Synthesizing System Dynamics and Geographic Information Systems in a new method to Model and Simulate Environmental Systems

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Dissertation for the degree philosophiae doctor (PhD)
System Dynamics Group, Social Science Faculty
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Supervised by Professor Pål I. Davidsen

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To My Mother's Soul

Abstract

A new method to synthesize system dynamics (SD) with geographic information systems (GIS) is presented in this research. This new method employs the Object Oriented Paradigm (OOP) as a common platform for the integration process. Recently, GIS software such as ArcGIS has become fully Object-Oriented software, providing the ArcObjects developer kit as a collection of (COM-compliant) objects that can be linked/embedded within other OO software. Vensim® software is an Object-Based simulation environment that can be used to build simulation models that may be linked to other applications through its dynamic link library (DLL). We developed a new application, referred to as SDGIS Application, using Microsoft Visual Basic to tightly couple the SD model components with their counterparts in the GIS model (i.e., stocks and flows with the associated geo-referenced features).

Initially, the GIS model provides the spatial information to the SD model. The SD model, through simulation, identifies the changes in the spatial features over time and communicates them back to the GIS model. These changes in space in turn impact the decisions taken by the user. Thus, processes can be modelled in time and space in an integrated way while capturing underlying accumulation process, the feedbacks, and nonlinearities.

The underlying approach, resulting in creation of the SDGIS application, provides a much-needed capability to model spatially distributed, dynamic feedback processes in time and space, while facilitating an understanding of the interactions between different components within the system. The main strength of this approach is the two-way simultaneous exchange of data between the SD and GIS, providing feedback in time and space. The technique used to build the SDGIS application is different than existing techniques for dynamic modelling such as Cellular Automata; Agent-Based simulation and GIS Model-Builder, and addresses most of the limitations present in these techniques. This approach, and the associated techniques, can be used to build similar applications like the SDGIS to model a variety of natural and social processes where the main concern is the space–time interaction. This is true in cases that concern environmental processes, water and/or natural resources management, and disaster management. In this research, the applicability of the SDGIS Application is demonstrated with an application to the irrigation system in the Nile Delta region in Egypt.

Key words: System dynamics; Geographic information systems; Object Oriented; Environmental systems; Water resources management; spatial distribution; Irrigation system; the Nile Delta.

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My deepest gratitude is dedicated to the memorial of my mother, who passed away before seeing the fruits of her unflagging dedication and absolute confidence in me. My gratitude also goes to my brother Dr. Maged Gharib, my sisters Rama and Marwa, and my extended family for their perpetual care and support.

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Sameh Gharib
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List of Abbreviations

AML	Arc/Info Macro Language
ArcGIS	is the name of a group of GIS software product lines produced by Environmental Systems Research Institute (ESRI), Redlands, California.
BCM	Billion Cubic Meters
CBP	Component Based Programming
CLD	Causal Loop Diagram
COM	Component Object Model. Microsoft COM technology in the Microsoft Windows-family of Operating Systems enables software components to communicate. COM is used by developers to create re-usable software components, link components together to build applications, and take advantage of Windows services. The family of COM technologies includes COM+, Distributed COM (DCOM) and ActiveX® Controls.
DBMS	Database Management Systems
DDE	Dynamic Data Exchange
DLL	Dynamic Link Library. DLL is Microsoft's implementation of the shared library concept in the Microsoft Windows and OS/2 operating systems. These libraries usually have the file extension DLL, OCX (for libraries containing ActiveX controls), or DRV (for legacy system drivers). The file formats for DLLs are the same as for Windows EXE files, that is, Portable Executable (PE) for 32-bit Windows, and New Executable (NE) for 16-bit Windows. As with EXEs, DLLs can contain code, data, and resources, in any combination.
DSS	Decision Support System
ESRI	Environmental Systems Research Institute (ESRI) is one of the world leaders in GIS technology and software providers.
esriCore.olb	is the name of ESRI Object Library that contains all classes, co-classes, and interfaces needed to perform the ArcGIS functionalities from within a standalone application.
FAO	Food and Agriculture Organization (United Nations)
FPP	Functional Programming Problem
GIS	Geographic Information System
GUI	Graphic User Interface
IWMI	International Water Management Institute, Colombo, Sri Lanka
MALR	Ministry of Agriculture and Land Reclamation (Egypt)
MCM	Million Cubic Meters
MWRI	Ministry of Water Resources and Irrigation (Egypt)
OO	Object Oriented
OODBMS	Object Oriented database management systems
OOGIS	Object Oriented Geographic Information System
RDBMS	relational database management systems
SD	System Dynamics
SDGIS	is our new application developed
SDGIS	System Dynamics Geographic Information System. It is our new application developed using Microsoft Visual Basic 6.0, Vensim DSS 5.2, and ArcGIS 8.3 to demonstrate our new method of integration.
SDSS	Spatial Decision Support System
VB	Visual Basic
VBA	Visual Basic for Applications
VCL	Visual Component Library
WNPL	Water needed plus leakage

Chapter 1

Introduction

Background Information related to the research in prospect

1.1 Background

The primary goal of this research is to develop a new ***method*** that enables us to understand: (1) The structure of complex, spatially distributed, dynamic systems. (2) The behaviour of such systems over time resulting from the interaction between their structural components across space. (3) The relationship between structure and behaviour.

We intend to develop the new method by way of a ***technique*** that allows us to model and simulate complex dynamic systems that are characterized by a spatial distribution of its components. Consequently, we need a set of ***tools*** that facilitate building and analysing models that reflect the structure of such systems (i.e. represent the causal relationships between system components including the rules governing those relationships, and relationships span across time and space). In this research, we will therefore make use of tools developed in the areas of system dynamics (SD) and geographic information systems (GIS).

Environmental systems are a good example of a class of spatially distributed dynamic feedback systems. The feedback structure of such systems includes accumulation processes as well as nonlinear stochastic relationships that span time and space. SD is well suited to address such complexity while GIS can be used to layout the system across the spatial dimension.

System dynamics may be defined as a powerful method providing a modelling and simulation based technique for framing, understanding, and discussing complex issues and problems. SD was originally developed to help understand industrial systems. Over the past three decades, SD has been applied more broadly in a wide range of disciplines, in areas of social science including management, and in natural science including engineering, medicine, and psychology. Perhaps more importantly, SD has been applied across discipline to address multidisciplinary issues. Among the many issues addressed we find urban decay, social unrest, economic development, renewable/non-renewable energy management, ecological and environmental change.

Environmental simulation models provide diagnostic and predictive outputs that can be combined with socio-economic data to assess local and regional environmental risk or natural resource management issues. Such assessments may involve air pollution, water quality, the impact of human activities on natural ecosystems; or conversely, the effects of climate variability on water supplies, agriculture, ecosystems, or other natural resources.

More recently, the importance of scientific models for the assessment of potential global environmental problems, including regional response to global change, has been illustrated by the National Research Council (NRC) (1986, 1990), Earth System Sciences Committee (ESSC) (1986, 1988), International Council of Scientific Unions (ICSU) (1986), International Geosphere-Biosphere Program (IGBP) (1990), and Committee on Earth Sciences (CES) (1989,1990). Eddy (1993) has discussed several environmental issues and suggested various courses of action, including the need for environmental simulation models, to help understand the current behaviour and to project the future state of the complex Earth system processes. These simulation models are necessary to help differentiate between environmental changes that are due to natural variability in the environmental system versus possible changes due to human impact. Although much progress has been made, research is still needed to model and understand environmental processes in natural science.

Fundamentally, the spatial dimension is essential in environmental modelling; and the integrated systems approach for developing and testing environmental simulation models suggests coupling with Geographic Information Systems (GIS) technology. Conceptually, GIS seem well suited to address spatial data and modelling issues that are associated with a modelling environment that includes multiscale processes (i.e., at different levels of aggregation), all within both heterogeneous landscape domain and complex terrain. GIS can help address data integration issues associated with multiscale data from ground-based and remote sensing sources. GIS could potentially support exploratory analysis of complex spatial patterns, including environmental processes. Finally, advanced environmental simulation models require detailed spatial data that provides an opportunity for innovative thematic mapping and error analyses with GIS.

From an environmental perspective, there are three primary reasons for why there is a need for integration of SD and GIS. These reasons are:

1. It is important to retain a spatial representation in models designed to address and solve environmental problems. GIS enables us to examine the spatial aspects of such problems and to make use of the results of such analysis in the proposed solutions. But current GIS lack the capability of representing a complex causal structure underlying the dynamics of such problems and to relate that structure to the resulting problem behaviour. Moreover, in GIS none of the relationships span time, there are no accumulations represented. Current GIS are typically limited to analytic compromises that include static representations of dynamic spatio-temporal processes, use of simple logical operations to explore complex relationships, and non-stochastic treatments of uncertain events. SD Models, in particular, could allow GIS to function beyond the limits of a static and planar domain where complex, often nonlinear, relationships that span over time and form feedback loops, may be explicitly expressed such that change and even uncertainty can be addressed in a direct way. GIS are currently very limited in their ability to examine any dynamic processes unless they are "wired up" in advance by analysts having a particular objective in mind and a very good understanding of both the technical aspects of GIS and the operation of a given model. This probably requires more knowledge than many users possess.

2. SD Modelling tools typically lack sufficiently flexible GIS capabilities like the spatial analytical tools. In addition to the rich visualization, GIS could offer SD modelling, in part, a flexible environment with a standardized array of spatial operators based on mathematical principles that describe meaningful properties of spatially distributed entities (motion, dispersion, and transformation for example). Sufficient intelligence could be built into such a tool to prevent some forms of misuse by the uninformed. Such an approach offers the benefits of a potentially

common analytic medium in which more comparability would be possible and through which it might be possible to improve communications among modellers working in different disciplines.

3. SD Modelling and GIS technology can both be made more robust by their linkage and co-evolution. Regardless where the new SDGIS modelling co-functionality comes to reside, in or out of the GIS or the SD software environment, the effort to combine the strengths of the associated tools will be mutually beneficial. Naturally, it is impossible to foresee all such benefits; but one can speculate (with confidence) that SD Modelling, at least, would benefit from a better engagement of the visual senses in evaluating the assumptions, operations, and results of models. Surely, many readers could recount experiences wherein the better mapping/ visualization of spatial properties brought new and sometimes startling understanding to those previously confident that they fully understood a target system by way of their methods of analysis.

It is not difficult to imagine that a conclusive synergy may combine the spatial representations of GIS with the temporal characteristics of SD models and the ability to characterize uncertainty and error. It is challenging, however, to find out how these tools should be made more interdependent and interactive. To solve pressing environmental problems, we will need different tools that work effectively together that are easy to use, and may be employed in a flexible manner to address complicated problems that arise in the context of multidisciplinary dynamic, spatially distributed feedback systems. These objectives will need to be harmonized in order to make rapid progress. Without taking the first step, the allure of constantly improving technologies will continue to draw both SD and GIS along separately. Without formalization of an effort to achieve integration, only the very fortunate will be able to incorporate the benefits of SD and GIS in their work because only they will have sufficient understanding and/or resources to overcome the difficulty of coupling tools that remain quite dissimilar.

1.2 Motivation

The motivation and justification for such a research emerge from the fact that there is a need for integration of SD and GIS that is driven by our need to make environmental choices. System Dynamics and GIS originated in, and still represent, substantially different domains of expertise, yet their integration will benefit both of them as well as the community of scientists, politicians, and public at large engaged in environmental problem solving.

In system dynamics we seek to understand the relationship between the structure and the behaviour of complex dynamic systems. The behaviour over time results from the interactions between the system's components. Therefore, the time dimension is a significant characteristic of the behaviour; behaviour unfolds over time. On the other hand, the system components coexist in the space across various geographic locations. In other words, the structure of the system is often spatially distributed and the behaviour that unfolds is, in part, determined by that location (in absolute or relative terms). Therefore, the spatial structure may be considered a significant part of the structure at large. Consequently, to understand the relationship between structure and behaviour we must concern ourselves with the spatial dimension the same way we consider the time dimension.

With the exception of few instances, the spatial dimension is not represented explicitly in system dynamic models. It has not been given the attention it deserves relative to the significant role it often plays in real life. One reason for this insufficient representation may originate from the fact that the SD modellers focus on the behaviour of the system over time. Another reason could be the lack of a mechanism that represents the spatial dimension properly and efficiently in system dynamics. Developing such a mechanism is a major challenge.

Our intention is to develop a conceptual framework for modelling spatial dynamic systems. The underlying concept is to "tightly couple" the "basic SD building blocks" with their counterparts of "GIS features". In that sense, we will enhance the SD method with the GIS capabilities (e.g., spatial analytical tools and rich visualization) and vice versa; in other words, to add the spatial dimension to SD, and the temporal dimension to GIS. This conceptual framework will then be used to create the spatial simulation data model (i.e., the SDGIS Application), which in turn will be applied to the irrigation system in the Nile Delta, Egypt as a proof of concept.

1.3 The Research Approach

This research is a multidisciplinary effort that crosses a number of scientific fields including environmental sciences, system sciences (system dynamics), geography (GIS technology), and information science (object orientation). Therefore, we assume that the reader has the essential knowledge about these domains.

The approach applied in this research is composed of three stages: (1) in-depth analysis and assessment for the state of SD, GIS, and object-orientation; (2) design of the conceptual framework and the development of the SDGIS application; (3) apply the new system (SDGIS) in a real environmental problem. The three stages (appearing with cyan in Figure 1-1) are described in the following paragraphs.

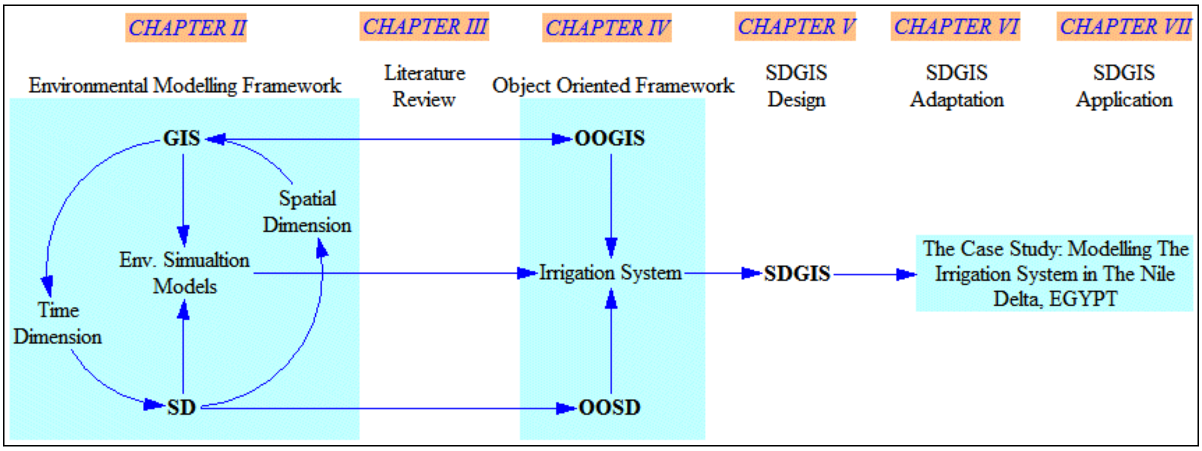

Figure 1-1: The research approach diagram

The first stage includes in-depth analysis and assessment of the current SD, GIS, and Object-Oriented paradigm, respectively. We study system dynamics to identify the relevance and significance of space in the SD. We study the GIS technology to examine the relevance and significance of the temporal dimension in GIS. The object-oriented paradigm will be introduced to serve as a common platform that facilitates the integration process. Then we identify the state of the environmental simulation models, we assess the diverse methods to add the temporal dimension to GIS (e.g. prior work such as the *Time geography path*), and finally, we illustrate and examine the prior attempts of integrating SD with GIS (e.g., SME application, GRASS applications, etc.).

The second stage is the design of the *conceptual framework* for the integration process. This design process includes the selection and utilization of techniques within simulation modelling (i.e., continuous or discrete), GIS (i.e., raster or vector based GIS), as well as Object Orientation (i.e., Bian or Booch method) that are appropriate to our research. Within this conceptual framework, we build a simulation model and a GIS model using synthetic datasets. We use illustrative examples to explain the coupling procedure that facilitates the synthesis between the two models. The implementation process includes building a GUI for the new SDGIS application to enable the users to access and handle models and performs the simulation.

In the third stage, we apply the SDGIS prototype in our case study. This implementation is undertaken as a “proof-of-concept” for the ideas developed in this research. The case study concerns the water scarcity problem that might emerge in the Nile Delta region in Egypt during the next twenty-five years. We employ the SDGIS to model and simulate the water accumulation, release, and flow through the irrigation network. The ultimate goal is to design policies for water preservation and management. This stage encompasses fieldwork activities such as data collection and direct communication and collaboration with a several authorities and jurisdictions.

1.4 The Aim of This Research

This research aims at demonstrating that synthesizing SD with GIS is not only feasible, but also produces a result beneficial to both SD and GIS practitioners. Based on the concepts developed in the spatio-temporal GIS, Time Geography, and object-oriented approaches, we develop a conceptual framework (the spatial simulation data model) that enables us to integrate the space and time domains and to make use of this integration within the context of environmental modelling. In this research we aim at attaining five different goals:

1. We want to define the space-time entity representation as a new means of characterising complex spatial dynamic systems in system dynamics.

2. We want to provide a deeper understanding of the spatial relationships and use this understanding to develop a suitable way to deal with the passage of time and the mechanisms of change within the environmental simulation models.

3. We want to synthesize the two approaches; modelling the environment with SD and modelling the environment with GIS, by associating the spatial simulation framework with the model construction tools of SD (Diagram, stock and flow) and the spatial representation capabilities and analytical tools of GIS (map features, overlay functions, and spatial queries).

4. We want to contribute to the development of the water preservation policies by providing a different perspective on the causal and spatial relationships underlying the water scarcity problem.

5. We want to undertake the implementation of the SDGIS Application into the irrigation system in the Nile Delta region, Egypt as “proof-of-concept”.

1.5 The Original Contribution of This Research

Phillips and Pugh (2000) identified nine characteristics to consider the original contribution of any PhD dissertation if the dissertation covers one of them. These characteristics are:

1. Carrying out empirical work that has not been done before.
2. Making a synthesis that has not been made before.
3. Using already known material but with a new interpretation
4. Trying out something in this country that has previously only been done in other countries.

5. Taking a particular technique and applying it in a new area.
6. Bringing new evidence to bear on an old issue.
7. Being cross-disciplinary and using different methodologies.
8. Looking at areas that people in the discipline haven't looked at before.
9. Adding to knowledge in a way that hasn't been done before.

The innovation of this work lies in the utilization of the object-oriented paradigm to incorporate the two technologies. In this thesis, we synthesis the system dynamics methods with the methods associated with GIS within object-oriented framework and apply the resultant application into the irrigation system. This synthesis has not been made before. Above, we have underlined five ways in which we believe that this research contributes to the science, i.e. is original in its nature.

First, the empirical work presented in chapter six and seven concerning the water scarcity problem and the current irrigation system in the Nile Delta region; the analysis of the water stress conditions (the driving forces for water scarcity problem) utilizing simulation models combined with spatial analytical tools of the GIS, and the evaluation of the water preservation policies, and the assessment of their feasibility in the case of Egypt, this empirical work is original.

Second, synthesizing SD models with GIS (in particular, the vector-based GIS) in a tightly coupled way using Object-Orientation, compared to the prior attempts (that described in the literature review, in chapter three), we believe, to our best of knowledge, that this synthesis has not been made before.

Third, the technique used to tightly couple the SD model components with the spatial features as explained in the conceptual framework, and implemented in the SDGIS and its application in the irrigation system, this work is original.

Fourth, in terms of cross-disciplinary, it is obvious that this research crosses several disciplines including system dynamics, geographical information systems, and object orientation in the context of Environmental modelling. This is explained in chapter two where we cover the essential literature of the environmental modelling domain, the Geographic Information System (GIS), simulation-modelling techniques focusing on System Dynamics (SD), and the Object Orientated paradigm as a common platform that facilitates synthesizing SD with GIS. In terms of methodology, we developed two different models for the study area (SD model and GIS model) and developed the SDGIS application that integrated both models and applied this application for the water scarcity problem. As Phillips put it "Being cross-disciplinary and using different methodologies is considered original".

Fifth, within the discipline of system dynamics, perhaps a considerable number of SD modellers have studied the water resources management, and simulation models in general have been utilised in hydrology domain. On the other hand, geographers, environmental scientists, and GIS specialists may have developed several models for hydrography, drainage basins and watersheds, and rain-fall/run-off processes. Remarkably, the two communities of modellers in both disciplines work separately. We were able to incorporate the benefits of SD and GIS in our work because we were fortunate to study both disciplines in previous education stages and gained sufficient understanding and have the resources to overcome the difficulty of coupling tools that remain, in many respects, dissimilar.

1.6 Thesis Outline

This thesis is divided into eight chapters. This first chapter briefly explains the research topic, our motivation, the research approach, and how the research has been organized.

The second chapter provides a theoretical background and an overview regarding the main disciplines related to this research: the Environmental Modelling domain, the Geographic Information System (GIS), System Dynamics (SD), and the Object Oriented Paradigm. We review the foundations of object-oriented methods of analysis and design, and the associated principles of software construction and user interface design.

In the third chapter, a literature review on the prior attempts to integrate SD with GIS is presented. The aim is to understand the difference between this previous work and our work presented in this research.

In chapter four we explain the conceptual framework and the procedures that we apply to synthesise the SD model components with their counterpart features in the GIS. We use an irrigation system as an example that can be modelled separately in system dynamics and GIS. Then, the two models are coupled through the development of an object-oriented based application. In this chapter also we introduce the software packages used to build the SD and the GIS models (Vensim® DSS and ArcGIS) and the Object components associated with them used to build the SDGIS application (Vensim® DLL and ArcObjects developer kit).

In chapter five we develop the SDGIS application. We describe in detail the steps of creating the application, the connection between the SD model and the GIS model, and the representation of the simulation results. A number of custom tools were built to: (1) facilitate access to and communication between the two pieces of software used to build the models, (2) controlling the simulation performance, and (3) handle the display of the results in two ways (i.e., on maps and graphic charts).

Chapter six is the first part of our case study that deals with the application of the SDGIS to the irrigation system in the Nile Delta, Egypt. In this chapter, we first describe the water scarcity problem that may emerge in the near future in Egypt, analyse its driving forces and highlight the factors that tend to intensify and possibly escalate the problem. Second, we describe the geographical and topological characteristics of the study area focusing on the irrigation system. Third, we explain the adaptation of the SDGIS application to the present irrigation system. Finally, we document the results of running the SDGIS application to test its operability and performance.

In chapter seven, that is the second part of the case study, we demonstrate the capabilities of the SDGIS application through illustrative examples for employing the SDGIS as: (i) an interactive learning environment for the educational purpose of explaining the complex irrigation system behaviour and management to non-technical individuals; (ii) an optimization tool for the irrigation network and the agriculture lands to attain the ultimate utilization of water and land resources; (iii) a spatial decision support system (SDSS) for supply, demand, and water allocation management and as a policy assessment tool for the water preservation measures.

In chapter eight we document the research conclusions and suggest future work. The implementation of the SDGIS Application and its adaptation to the case study has many consequences. It improved our analytical capabilities and enhanced our understanding of the dynamics of the water scarcity problem. Incorporating the spatial dimension in the SD model and the temporal dimension in the GIS model, and integrating both models in one system evidently proofed the significance of considering *Time* and *Space* when we model spatially distributed dynamic systems. Such results are being discussed in the last chapter.

Chapter 2

The Background Theory

The Theoretical Foundation &
Research Context

2.1 Introduction

This research crosses several disciplines including system dynamics, geographical information systems, and object orientation in the context of Environmental modelling. This chapter covers the essential literature of the environmental modelling domain, the Geographic Information System (GIS), simulation-modelling techniques focusing on System Dynamics (SD), and the Object Orientated paradigm as a common platform that facilitates synthesizing SD with GIS.

The chapter is divided into four main parts with respect to the disciplines involved in this research. In the first part we describe the state of the environmental modelling domain. We list a number of environmental problems confronting different countries and discuss the differences in attitudes pertaining such problems. The objective is to understand how different people perceive these problems in different ways and why environmental simulation models are significant to analyse and predict the environmental impacts and their immediate and long-term consequences and the associated risks.

GIS, as a powerful analytical tool, has been utilized in environmental modelling to perform sophisticated spatial analysis. The resulting data from such analysis is used as an input to the simulation models. Therefore, in the second part of this chapter, we introduce the field of GIS and describe the state-of-the-art in spatial modelling and briefly review the various approaches to incorporate the temporal dimension in GIS. The objective is to highlight the significance of time in GIS applications and to shift the dominant idea of organizing space over time to represent a real world phenomenon in space and time.

In the third part of this chapter, we describe the major paradigms in simulation modelling. The phrase “simulation modelling” used in this chapter is not limited to system dynamics. There are a number of simulation-modelling techniques such as Agent-based simulation and Cellular Automate. There is, to great extend, an overlap between these techniques that may create some confusion. Therefore, it is worthwhile to briefly describe the principles of each technique and the respective strengths and weaknesses. We exemplify fields of research and applications for each discipline that utilize one of these techniques, and demonstrate the broad overlap in research topics. This greatly helps to understand the difference between what we are doing in this research and the efforts done by others. It helps also to identify the best suitable technique for environmental problem solving.

Obviously, environmental modelling needs GIS to perform spatial analysis and needs simulation models to analyse and predict the environmental impacts. Remarkable, the two communities of modellers work separately, but have recently admitted that there is an urgent need for integration. One of the integration challenges is the lack of an appropriate mechanism to incorporate GIS and SD. Object orientation may serve as a common platform that facilitates such integration. Therefore, in part four of this chapter, we provide a historical background for the object-oriented paradigm and illustrate the diverse efforts involved in object-oriented methods. This helps to explain the main concepts of object-oriented methods that are essential for developing our spatial simulation data model (SDGIS) that explained in chapter four. The historical background summarises the chronological developments from object-oriented programming languages to object-oriented design methods, and finally to object-oriented analysis methods.

The concluding remarks of this chapter emphasise the need for integration and discuss the feasibility of such an integration given the available technology (software). Recently, GIS software (i.e. ArcGIS 8.1) has become fully object oriented, however, the available SD software (i.e. Powersim, Vensim) are object based. In the literature, there is a heavily debate among software expertise concerning the Object-Oriented versus Object-Based software. We briefly describe the main differences. This greatly helps understanding synthesizing procedures explained in chapter four.

Five references provide the framework for the subsequent discussion. First, Law and Kelton (2000) introduce the beginnings of the simulation modelling. Frenkiel and Goodall (1978) provide an excellent summary of early use of simulation models for environmental problem solving. A number of significant issues concerning the topic of modelling have been addressed by several global change documents [ESSC, 1988; IGBP, 1990; NRC, 1990]. Goodchild, Parks, and Steyaert (1993) introduced a remarkable volume concerning the state of the modelling environment with GIS. Finally, Sterman's book of business dynamics (2000) provides an overview of simulation and system dynamics.

2.2 Environmental Modelling

2.2.1 Human Activities and Environmental Problems

Different human communities are confronted with different sets of environmental problems, and even if they had the same problems they would probably see them differently. This is particularly true for the comparison between *developed* and *developing* countries. Most environmental problems are a result of intensive industrialization and advanced standards of living achieved with little regard to possible environmental effects. Although similar difficulties are now arising in the developing nations, many of their environmental problems are different and centre on the need to increase food production and resource utilization to match the requirements of the rapidly expanding population. Some of the most important environmental problems in these two groups of countries are listed in Table 2-1.

A number of the problems listed in this table for developing countries are of little or no importance in developed countries, but the reverse is not often true. It may be assumed, in fact, that problems in the first column either already exist in developing countries or are likely to appear as development proceeds unless measures are taken to avert them. At present, they are overshadowed by the problems listed in the second column.

Despite the listed problems associated with each group, there are environmental problems that threaten all mankind alike that have recently been recognized. Such problems include: (1) Possible long-term climatic change (in average, trends and variability) that may be associated with, for instance, increasing consumption of fossil fuels. (2) Exhaustion of non-renewable resources. (3) Changes in populations of animal and plant species. (4) Possible changes in atmospheric transmission of radiation, for instance, through use of aerosols and supersonic aircraft. Different countries perceive such environmental problems in different ways. Consequently, it is difficult (if not sometimes impossible) to generate international consensus on possible solutions.

Table 2-1: Environmental problems in *developed* and *developing* countries with respect to different fields of human activity[1]

Developed Countries	Developing Countries
1. Food Production	
Effects of strategies for planting, fertilizing, pest control, irrigation and storage. Development of unstable, monoculture systems. Reliance on energy-intensive practices. Effects of land allocation for crop types and/or grazing. Soil erosion and problems of water use.	Effects of strategies for planting, fertilizing, pest control, irrigation and storage. Effects of introducing fertilizers, pesticides, and mechanized methods. Spreading of weeds and pests through the introduction of new crop varieties. Effects of `slash and burn' practices, and of clearing scrub. Soil deterioration - erosion, salinization, water logging. Desertification of arid lands, resulting from overgrazing or unwise clearing and cropping.
2. Use of Forests	
Environmental impacts of planting and harvesting strategies. Environmental impacts of disease and pest control. Conflicts in providing for habitat preservation, recreation and multiple usages, including forests as energy sources.	Forest destruction. Poor forest management resulting in undesirable changes in species composition.
3. Pattern of land use	
Environmental effects of land allocation policies for cities, waste disposal sites, agriculture, forests, transportation, natural and recreational areas, etc. Problems of settlement on flood plains, geologically hazardous areas, etc. Spoiling of land by extraction industries (oil pipelines, strip mining, slag heaps, etc.) and lack of adequate measures of control. Long term effects of various land uses.	Effects of dense urban settlement - disease, sewage, pollution, etc. Untimely exploitation of non-renewable resources. Environmental results of land tenure systems leading to fragmentation. Penetration of little known areas, and resultant transport of disease, exotic species, etc.
4. Energy production and use	
Excessive energy use through an energy-intensive standard of living, and failure to adopt energy conservation techniques. Environmental impacts associated with production, storage, allocation and transmission strategies. Environmental hazards of some new energy sources (nuclear safety, oil shale exploitation, etc.) and lag times in the development of improved sources (solar, nuclear fusion, etc.)	Depletion of nutrients and deterioration of soil due to use of charcoal and dung as fuel. Impacts associated with developing supplies of energy to support increased levels of industrial and agricultural production.

[1] Source: Frenkiel and Goodall 1978.

Table 2-1 (continued)

Developed Countries	Developing Countries
5. Water supply	
Environmental impacts of developing, storing and allocating water supplies. Short and long term impacts of weather modification.	Difficulties of availability of water in quantity and quality necessary for urban settlement. Problems with rural water supplies. Adverse effects of new irrigation systems, including introduction or increase in diseases, and changes in soil composition and structure. Incidence of floods.
6. Pollution and waste disposal	
Air	
Impact of pollutants on health, property and food production. Introduction of synthetic trace chemicals. Transportation of pesticides and disease. Pollution impacts of traffic patterns. Thermal effects of power plants. Effects of weather modification efforts. Trapping of terrestrial radiation by gases; effect of changes in ozone layer. Depletion of solar input by particulates.	
Water	
Pollution by municipal sewage and industrial waste. Eutrophication of freshwater bodies from sewage and agricultural runoff (including intensive animal production areas). Thermal pollution by power plants. Contamination of ground water reserves by underground disposals, percolation from landfill, etc. Marine pollution by oil discharges and spills, and hazardous waste disposal.	Sanitary and pollution problems of villages. Air, water and land pollution are all increasing as the process of urbanization and industrialization get underway. Furthermore, they often pose special problems because of inadequate lead-time and preparation.
Land	
Uncontrolled erosion. Impacts of landfills and other above ground disposal sites. Irresponsible disposal of litter by individual citizens. Leaks from underground disposal of hazardous wastes.	
7. Social life	
Population density problems. Excessive noise. Impacts of social attitudes and consumer preference.	Problems of intensive urban migration and settlement. Rural depopulation.

2.2.2 Environmental Problems Perceptions[2]

In addition to differences between developed and developing countries, there are contrasts in perception of the prevailing problems between individuals within the single nation. These contrasts may arise from such individuals belonging to different population strata taking different roles in society, such as labours, decision makers, administrators, and scientists.

For the general public in over-crowded and underfed nation, one prime cause of environmental problems typically arise from shortage of food resulting from an increase in the population over and above the increase in the food supply. This call for a high degree of resources utilization that eventually may be environmentally harmful (say because of resources depletion). Although one may obtain a more efficient utilization of these resources, for example, by employing a higher level of technology, the level of education and income typically does not allow the majority of the population to take advantage of such opportunities. The need for food, often amounting to a daily life-or-death struggle from an individual perspective, tend to sideline or allow for only a very short-term perspective on the environmental consequences of such an intensive and often inefficient utilization of resources. Long-term perspective catches the popular attention only when given prominence in publicity. Otherwise, an individual's foresight is generally limited to days or weeks, and to environmental consequences directly and immediately affecting their own life.

Decision-makers in governmental bodies vary in their outlook on environmental problems depending on the role they play. Politicians give their main attention to those environmental problems that are most prominent in the mind of the voters. Consequently, the time-scale for politicians is too often limited by the next election. Decision-makers in the public service may have longer-term views of such problems, particularly if their positions require them to remain working with, or affected by, the same problems over an extended period of time. As a result, long-

[2] The significance of this part will be obvious when we come to our case study in chapter six.

term responsibility for the environment, on behalf of the public, will often fall upon their shoulders and be dealt with in the form of policy development and the implementation of regulations that affect both the public and the private sector.

Private corporations whose decisions affect the environment may operate on a time-scale similar to the permanent public service decision-makers (long-term). However, their motivation may be somewhat different. The focus will be on what best serves their business interests. Environmental concerns are therefore in focus because they constitute business opportunities or because not being concerned about the environment may hurt the business, say, in the form of a loss of reputation or governmental or private premiums to be paid in the future.

Usually, decision-makers who are in the public eyes, whether in private corporations or in governmental bodies, and whether elected or appointed, would take account of public reactions to their decisions. Among the problems which may confront them are the activities of “action groups” (stakeholders), usually local but often vocal and even aggressive.

Scientists generally view environmental problems on a longer time-scale than that of the decision-makers. However, their focus maybe narrower, since the training and career structures for scientists do not usually encourage them to become familiar with subjects outside their own area of expertise. Therefore, the physical scientist presumably would concentrate solely on climatic change, while the biologist is more interested in the fate of endangered species. The social scientists are likely to give more attention to the problems of the population explosion, high-density housing, or rural depopulation. Only recently, means for encouraging interaction among these disciplines tend to be developed.

There is no absolute measure for the relative importance of different environmental problems. The views of all groups, from the public to the scientist, from the least to the most highly developed country, are all relevant within their own frame of reference. It is not the responsibility of an environmental scientist or a modeller to try to reconcile or resolve these differences in attitudes. Rather, he should see his role as the determination and clarification of all likely consequences of any action that may be contemplated. It is in this context the main value of environmental modelling field lies. If causal chains and networks of relationships can be established in complex systems, simulation models are the tools whereby these interconnections can be explored. Hence, the effects of modifying one part of the system can be discovered and related to the consequence for other, more remote, parts. This provides a better understanding of the dynamics of the system, and thus enables to predict the results of proposed actions, and to select the action that seems to be most desirable among a set of possible options.

2.2.3 Environmental Modelling Domain Overview

Environmental modelling, as one of the scientific tools that facilitates the prediction and analysis of the environmental impacts and the associated risks, is a well-established field of research. We can find a number of analytical approaches dating back to Lotka (1924). In the field of hydrology for example, we can look back at more than a hundred years of modelling history [Maidment, 1993]. Although these studies were conducted over a wide variety of time scales, none of them explicitly accounted for the spatial dimensions. In limnology, oceanography, and plant sociology for example, concepts such as patchiness were discussed, however, not referenced to a fixed coordinate system, as is the case in GIS.

Computer-based mathematical models that realistically simulate spatially distributed, time-dependent environmental processes in nature are increasingly recognized as fundamental requirements for the reliable, quantitative assessment of complex environmental issues of local, regional, and global concern. These environmental simulation models provide diagnostic and predictive outputs that can be combined with socio-economic data for assessing local and regional environmental risk or natural resource management issues. Such assessments may involve air and water quality; the impact of man's activities on natural ecosystems; or conversely, the effects of climate variability on water supplies, agriculture, ecosystems, or other natural resources.

More recently, the importance of the scientific models for the assessment of potential global environmental problems, including regional response to global change, has been illustrated by the National Research Council (NRC) (1986, 1990), Earth System Sciences Committee (ESSC) (1986, 1988), International Council of Scientific Unions (ICSU) (1986), International Geosphere-Biosphere Program (IGBP) (1990), and Committee on Earth Sciences (CES) (1989,1990). Eddy (1993) has discussed several environmental issues and suggested various courses of action including the need for environmental simulation models to help understand the current behaviour and to project the future state of the complex Earth system processes. These simulation models are necessary to help differentiate between environmental changes that are due to natural variability in the environmental system versus possible changes due to human impacts. Although much progress has been made, research is still needed to understand and model environmental processes in natural science.

In the literature, the environmental modelling domain is extremely influenced and overwhelmed by the dynamical simulation models that are evolved through global climate change research programs, specifically as noted by the Committee on Earth and Environmental Sciences CEES (1991), NRC (1990), and IGBP (1990). These types of advanced models are also applicable to issues within the areas of land and water resource management, environmental risk assessment, and other applications. This section addresses the status of research on the development and testing of models, not the use of models in an applications or an assessment mode.

In the following paragraphs, we highlight some of the general research themes that tend to characterize the state of environmental simulation modelling within, and particularly across, natural science disciplines. Then, we describe the state of the GIS for environmental problem solving. For the purpose of this research we focus on hydrologic modelling. The goal of these remarks is to help facilitate the understanding of the models subsequently discussed in chapter three, as well as to establish further potential integration between environmental simulation modelling and geographic information systems (GIS).

Environmental Simulation Models

The phrase *environmental simulation model* in the following paragraphs is used as a general term, not limited to system dynamics simulation models only, to characterize the types of models found in the environmental modelling literature. There is no one definition or all-encompassing term that will adequately describe this type of modelling. In fact, most of these models are more commonly referred to as an Earth science model, atmospheric or hydrological model, ecosystem dynamics model, or some other type of model. The term by which a model is named is frequently associated with the particular scientific discipline, spatial and temporal scale, application, or type of bureaucratic program.

General Concepts

Environmental processes in the real world are typically three dimensional, time dependent, and complex. Such complexity can include nonlinear relationships, stochastic variables, and feedback loops over multiple time and space. There may be significant qualitative understanding of a particular process, but the quantitative understanding may be limited. The ability to express the physical process as a set of detailed mathematical equations may not exist, or the equations may be too complicated to solve without simplifications.

Furthermore, computer limitations or the manner in which mathematical equations are converted for numerical-processing on a grid (discretization) lead to the parameterisation of sub-grid small-scale complex processes that cannot be explicitly represented in the model. In some cases, these sets of equations can be viewed as a collection of hypotheses, concerning physical processes, whose inputs and outputs are linked. This set of parameterised equations represents the modeller's best approach to account for these processes, given these collective constraints. (This concept is illustrated in the subsection on Simulation Models.)

Therefore, it is important to recognize that environmental models are usually, at best, just a simplification of real world processes [IGBP, 1990]. Reality is only approximated within the model. In spite of all these qualifications, models in the hands of a skilled user do, in fact, provide useful information of scientific and applied interest.

The phrase "*environmental simulation model*" can be dissected (from environmental domain viewpoint) and examined word by word to help understand these types of models. In fact, other key terms such as "parameterisation" or "discretization" permit even more understanding of the modelling process, as well as the current state of the models.

Types of models

Steyaert *et al.*, (1993) classified models into three major categories: scale, conceptual, and mathematical. An example of a ***scale*** model would be a scaled-down replica of a mountain range or an airplane wing for use in wind tunnel experiments. There are also analog scale models such as a topographic map. (Note: GIS deal with analog models. hence, integration implies links between scale models and mathematical models). ***Conceptual*** models are frequently used in the modelling process in block diagrams that show major systems, processes, and qualitative interrelationships between subsystems. ***Mathematical*** models can be further classified as either deterministic or statistical (i.e., non-deterministic). Statistical or probability models contain at least one stochastic process represented by one or more random variables. A deterministic model does not have any random variables. Thus, a stochastic model has output data that are also random variables, and a deterministic model has a unique set of output data for a given input set [Law and Kelton, 1982]. (In this categorization, deterministic models are associated with environmental processes, and statistical models are based on empirical analysis of observations.)

Both deterministic and statistical models can be further subdivided into either "steady-state" or "dynamic" models, where dynamic models contain at least one term that is a function of time. In the case of deterministic relationships, steady-state models can be represented by algebraic expressions for diagnostic study. Similarly, the deterministic-dynamic model is represented by differential equations that include at least one time derivative or by algebraic relationships that include a time term. Both total and partial differential equations are used.

Diagnostic models may represent the interrelationships within a system that is in a static or steady-state condition (that is no temporal component) or for some fixed point in time given a quasi-steady-state assumption. Prognostic models are used for prediction and depict a dynamic system that is a function of time [IGBP, 1990].

Simulation models

An environmental simulation model may be defined as a computer-based technique to imitate, or simulate, the operations of various kinds of real-world processes [Law and Kelton, 1982]. Examples of real-world environmental processes are hydrodynamic fluid flow, radiating and heat transfer, biological growth mechanisms, and ecological development. Physically based laws describing these processes may not be known.

To study these types of processes, either individually or as part of a system, physically based laws (e.g. Newton's laws of motion) or other types of assumptions are usually made on how the processes actually work. These laws or assumptions can be expressed as mathematical or logical relationships; collectively they represent a model.

There are *no* fixed rules, but typically the environmental simulation model will include time-dependent partial differential equations and algebraic equations. The model is a dynamic model because of the time dependency. In some cases, these may be based on assumption or may be derived empirically through statistical analysis of observed data. For complex processes, there may be an extensive number of equations. Frequently, the goal is to make prognostic projections based on the simultaneous solution of a set of equations (with the same number of unknowns), as discussed by Lee *et al.*, (1993). Frequently, assumptions must be made to simplify the set of equations.

For a very simple deterministic model, it may be possible to calculate an exact solution for idealized conditions (e.g. couette flow). However, real-world processes are typically so complex and nonlinear that an analytic solution is not possible. In such cases, the model is converted so that a numerical solution can be calculated on a computer.

In the case of numerical solutions, the system of mathematical equations that make up a model is usually converted to run on a two- or three-dimensional grid. The methodology for restructuring a system of equations to run on a grid is termed “discretization”. There may be small-scale processes, termed sub-grid processes, which must be accounted for at the grid level, usually by a method that is termed “parameterisation” [Steyaert *et al.*, 1993].

Parameterisation may be viewed as a method for scaling sub-grid processes up to the grid level. However, the concept of parameterisation is also used to link models across space and time scales. For example, detailed data and models near the process level at small scales are used to parameterise relationships at the next higher scales. Such an approach is of interest to scaling instantaneous biophysical data at the plant leaf level (evapotranspiration and photosynthesis) to annual regional estimates of net primary production or evapotranspiration [Running, 1991] through multiple parameterisations. These parameterisations can be quite elaborate, for example, the land surface parameterisation for a global climate model. (To complicate matters, the terms "model" and "parameterisation" are sometimes used interchangeably.)

Lee *et al.,* (1993) provided additional information concerning the meteorology numerical models. Because the equations are discretized, only portions of the equations are based on fundamental physical quantities (for example, the pressure gradient and advective terms in the equation of motion). The remainder of the terms are parameterised and generally are not based on fundamental concepts. Lee *et al.*, (1993) provide examples of such parameterisations for meteorological models: cloud physics, long- and short-wave radiative flux divergence, sub-grid turbulent fluxes, and soil and vegetation effects.

There are several reasons for uncertainty in model results: (1) Only a limited number of processes can be treated; (2) Processes may not be well understood or, for some other reason, may be treated inadequately; and (3) The spatial and temporal resolution is inadequate [IGBP, 1990]. Also, the solutions may be very sensitive to initial conditions if the interactions in the models are sufficiently nonlinear (see for example [Lorenz, 1967]).

Finally, the term "modelling" may be referred to as the research process that leads to the development of a "model". The modelling process typically involves the development and testing of complex, interrelated hypotheses as a part of the scientific method. This process may include the collection and analysis of observations that may be used to formulate a model or to test the hypothesis. The modelling process can include steps to develop, test and evaluate, validate, and apply the model.

Recent works by several authors support the use of dynamic modelling in environmental analysis. Macgill (1986) provided an assessment of different modelling styles including the system dynamics models and their capabilities for scenario testing. Sampson (1985) presented a view of modelling and simulation based on systems methodology. Sheldon (1984) suggested the use of system simulation techniques for determining optimum production strategies for natural resources. Couclelis (1985) also suggested the use of Cellular Automata (CA) in modelling geographic systems. Itami (1988) and Gimblett (1989) applied the cellular automata concept within a GIS. Green (1989) studied the utility of cellular automata and percolation theory in spatial patterns and dynamics in forest ecosystems. All these efforts indicate a trend toward the use of system dynamics as a decision support tool in environmental management and decision-making.

More sophisticated environmental models need system dynamics approach to deal with the temporal dimension, feedback loops and overall dynamic and complexity of the environmental systems. They need also a GIS to represent the spatial dimension. Simulation, Spatial distribution, increased dimensionality, and *resolution are one straightforward way of "improving" environmental modelling domain.*

Classification of Environmental Simulation Models

Apart from the possible varieties of approach in the technical construction of models mentioned in the previous paragraph, models may also vary greatly in subject, in scale, and in the purpose of use/study. Frenkiel and Goodall (1978) set a detailed list of attributes that specify an environmental simulation model in different respects. From these attributes we found that environmental simulation models can be classified into three major categories as shown in Table 2-2.

Table 2-2: Classification of Environmental Simulation Models.

(a) The Subject	(b) The purpose of use/study	(c) Environmental system being studied
Environmental conservation	Decision-making (political, operational).	Type (atmosphere, river-stream, lake, groundwater, coastal-estuarine, ocean, land, soil, primary production, agriculture, forest, urban, etc.).
Pollution control	Scientific research	Size (local, regional, national, global).
Resource utilization.	Educational and training	Time horizon (hour, day, week, month, year, decade, century).
	Public information	

Modelling the Environment with GIS

Environmental problems do have an obvious spatial dimension. Within the environmental modelling domain, this is addressed by spatially distributed models, which describe environmental phenomena in one dimension (for example, in river models), two dimensions (land, atmospheric, and water-quality models, models of population dynamics), or three dimensions (again air and water models). The increasing development and use of spatially distributed models replacing simple spatially aggregated or lumped parameter models is, at least in part, driven by the availability of more and more powerful and affordable computers [Fedra and Loucks, 1985; Loucks and Fedra, 1987].

Fundamentally, environmental processes operate at multiple space and time scales. Multiple spatial scales are evident in the fields of hydrology (networks of small watersheds scaling up to large river basins), and ecology (patches, landscapes, and biomes)[3]. The use of Remote Sensing RS and GIS technologies to extend and extrapolate local results to the regional level is one approach. Another is the use of nested modelling concepts, sometimes in combination with remote sensing and GIS.

GIS, as described in detail later in this chapter[4], provides representations of the spatial features of the Earth, while hydrologic modelling is concerned with the flow of water and its constituents over the land surface and in the subsurface environment. The connection between the two subjects is obviously clear. Hydrologic modelling has been successful in dealing with time variation, and models with hundreds or even thousands of time steps are common, but spatial disaggregation of the study area has been relatively simple. In many cases, hydrologic models assume uniform spatial properties or allow for small numbers of spatial subunits within which properties are uniform. GIS offers the potential to increase the degree of definition of spatial

[3] It is evident also in the field of atmospheric science (hemispheric long-wave patterns, synoptic waves, surface layer fluxes, and eventually the dissipation of micro scale turbulence fluctuations near the land surface)

[4] See section 2.3

subunits, in number and in descriptive detail, and GIS-hydrologic model linkage also offers the potential to address regional or continental-scale processes whose hydrology has not been modelled previously to any significant extent.

The goal of this section is to outline an intellectual basis for the linkage between GIS and hydrologic modelling. Its specific objectives are to present a taxonomy of hydrologic modelling; to understand the kinds of models that are used and what they are used for; to indicate which kinds of models could be incorporated within GIS and which are best left as independent analytical tools linked to GIS for data input and display of results; to examine the object-oriented data model as an intermediate link between the spatial relational model inherent in GIS and the data models used in hydrology; and to look at some future directions of hydrologic models that have not been possible before but that might now be feasible with the advent of GIS. The scope is limited to a fairly abstract discussion looking over the field as a whole rather than to one or other types of models within the field.

General concepts

A hydrologic model can be defined as a mathematical representation of the flow of water and its constituents on some part of the land surface or subsurface environment [Maidment, 1993]. In this sense, hydrologic modelling has been going on for at least 150 years. Darcy's Law (the fundamental equation governing groundwater flow) was discovered in 1856, the St.Venant equations describing unsteady open channel flow were developed in 1871, and a steady stream of analytical advances in description of the flow of water has occurred in the succeeding decades. Transport of constituents in natural waters was sparsely treated before about 1950; after that time, first for transport in pipes, and then later in rivers, estuaries, and groundwater systems, transport issues gradually assumed a greater prominence and are now a major factor in hydrologic modelling. Computer models began to appear in the middle 1960s, first for surface water flow and sediment transport, then in the 1970s for surface water quality and groundwater flow, then in the 1980s for groundwater transport. There are literally hundreds of public domain computer programs for hydrologic modelling; however, the most frequently used models in the United States, for example, are produced or endorsed by the Federal government, and these are much fewer in number (not more than a few dozen in total). Table 2-3 summarizes some of the models commonly used in hydrology.

Hydrologic modelling depends on a representation of the land surface and subsurface because this is the environment through which water flows. There are also interactions with biological and ecological modelling because the transport of constituents in natural waters is influenced by biological activity that may increase or decrease the amount of constituents in water, and because the amount and condition of water flow can affect habitats for fish, plants and animals. The degree of saturation of the soil is a time-varying hydrologic parameter that impacts biological and ecological processes.

Hydrology is closely tied to weather and climate too. So, in principle, modelling of atmospheric processes should be linked to hydrologic modelling, but in practice a close linkage between these two types of models is difficult to achieve because the large, grid-square spatial scale of atmospheric modelling, especially global climate modelling, is so much larger than the watershed or aquifer scale normally used for hydrologic models.

There are three basic issues: *pollution control* and mitigation for both groundwater and surface water; *water utilization* for water supply for agriculture, municipalities, and industry and the competing demands for in-stream water use and wildlife habitat; and *flood control* and mitigation. Most hydrologic modelling is directed at solving problems in one of these three areas.

Table 2-3: Some commonly used computer codes for hydrologic modelling. and the sources from which they can be obtained.

Surface Water Hydrology Models	
(1) Single-event rainfall-runoff models	
HEC-1	U.S. Army Corps of Engineers, Davis, California
TR-20	Soil Conservation Service, U.S. Dept. of Agriculture, Washington DC
ILLUDAS	Illinois State Water Survey, Champaign, Illinois
DR3M	U.S. Geological Survey, Reston, Virginia
(2) Continuous stream flow simulation	
SWRRB	Agricultural Research Service, U.S. Dept. of Agriculture, Temple, Texas
PRMS	U.S. Geological Survey, Reston, Virginia
SHE	Institute of Hydrology, Wallingford, England.
(3) Flood hydraulics	
Steady flow:	
HEC-2	U.S. Army Corps of Engineers, Davis, California
WSPRO	U.S. Dept_ of Transportation, Washington, DC
Unsteady flow:	
DMBRK	U.S. National Weather Service, Silver Spring, Maryland
DWOPER	U.S. National Weather Service, Silver Spring, Maryland
(4) Water quality	
SWMM	University of Florida Water Resources Center, Gainesville, Florida
HSPF	USEPA Environmental Research Laboratory, Athens, Georgia
QUAL2	USEPA Environmental Research Laboratory, Athens, Georgia
WASP	USEPA Environmental Research Laboratory, Athens, Georgia
Subsurface Water Hydrology Models	
(1) Groundwater flow	
PLASM	International Groundwater Modelling Centre (IGWMC), Colorado School of Mines, Golden, Colorado
MODFLOW	U.S. Geological Survey, Reston, Virginia
AQUIFEM-1	Geocomp Corporation
(2) Groundwater contaminant transport	
AT123D	IGWMC, Golden, Colorado
BIO1D	Geotrans, Inc., Herndon, Virginia RNDWALK IGWMC, Golden, Colorado
USGS MOC	U.S. Geological Survey, Reston, Virginia
MT3D	S.S. Papadopulis and Associates, Inc, National Water Well Association
MODPATH	U.S. Geological Survey, Reston, Virginia
(3) Variably saturated flow and transport	
VS2D	U.S. Geological Survey, Reston, Virginia
SUTRA	U.S. Geological Survey, Reston, Virginia; National Water Well Association

Source: David R. Maidment, 1993.

State of Hydrologic Modelling Independent of GIS

All of the waters of the Earth can be classified into three types: atmospheric water, surface water, and subsurface water [Maidment, 1993]. Atmospheric water includes water vapour in the atmosphere and also water and ice droplets being carried by clouds or falling as precipitation. Surface water is water flowing on the land surface or stored in pools, lakes, or reservoirs. Subsurface water is water contained within the soil and rock matrix beneath the land surface. Hydrologic modelling is largely concerned with surface and subsurface water. When modelling of "atmospheric water processes" is considered, such as precipitation or evaporation, it is generally to supply input information needed for some aspect of the surface or subsurface water balance. The dynamics of atmospheric processes are so complex that models of precipitation and evaporation are more analogies to the real processes rather than precise physical descriptions.

In modelling the flow of water, the main issue is to determine the disposition of rainfall: how much of it becomes runoff, infiltration, groundwater recharge, evaporation, and water storage? Once the discharge of water is determined at particular point, the hydraulics of flow is sometimes also considered, such as the flow velocity and water surface elevation in a channel, or the Darcy flux and piezometric head field in an aquifer. Transport issues are also important. These include transport of material floating or suspended in water such as sediment; constituents dissolved in water, such as toxic chemicals or pesticides; and biological constituents in water, whose effect is measured by their consumption of dissolved oxygen. The objective in modelling pollutant flows is to be able to predict how far and how fast a pollutant will travel in a water body, what will happen to it as it travels, and what will be its ultimate fate. If remedial activities are being undertaken to clean up pollution, modelling of the extraction of polluted waters is also sometimes undertaken, such as in the design of pumping schemes to extract contaminated groundwater. Obviously, physical processes such as adsorption of the pollutant onto the soil or rock matrix, or chemical processes, such as the oxidation or reduction of chemical species, are important in assessing the pollutant fate and transport.

In a general way, hydrologic modelling can be divided into four components: Vertically, there is a distinction between modelling surface or subsurface waters; sequentially, there is a distinction between modelling flow and transport, or equivalently between modelling water quantity and water quality. Thus, one can speak of a surface water flow model or a surface water quality model, and likewise a subsurface flow or transport model. It is necessary to model or map the flow field before modelling the transport of constituents since their motion is driven by the motion of the flow field.

One can also distinguish three major variables for which hydrologic models are constructed: Q (units of volume per unit time) for flow or discharge; h (units of length) for water surface elevation or piezometric head; and C (units of mass per unit volume of water) for constituent concentrations. Once the time and space distribution of these variables has been determined, a hydrologic modelling exercise is usually complete. It may be noted that while h and C are scalar variables, their gradients are vectors. The discharge Q is also a vector and is oriented in the direction of declining head gradient. The product of concentration and discharge produces the constituent or contaminant loading (in units of mass per unit time) that is being carried by the flow, such as the sediment load of a river.

Spatial Components in Hydrologic Modelling

There are four basic spatial components used in hydrologic models: surface watersheds, stream channels, lakes or estuaries, and subsurface aquifers. Each of these components is a three-dimensional object, but they can be approximated satisfactorily for many purposes with a model of lesser dimensions. The first three components are described in more details elsewhere (see for example Arc Hydro data model developed by ESRI). What is important here to remember is that in each of the four flow systems mentioned, the same physical principles govern water flow and transport and similar equations are used to describe these phenomena. The most fundamental principle is the conservation of mass-water or constituent mass cannot be created or destroyed. This principle is expressed as the continuity equation, which states that the rate of change of storage in a system is equal to the inflow minus the outflow. To complete the description of water motion, an additional principle is usually employed-either the momentum principle (for fairly rapidly varying flow with time steps of the order of hours or days) or the energy principle (for long-term studies with time steps of the order of months or years). The momentum principle is contained in Newton's second law of motion, which states, “If a body is acted upon by an unbalanced external force, its motion will change in proportion to the magnitude of the force and in the direction of the external force”. The energy principle is contained in the first law of thermodynamics, which states, “The change of energy of a body is equal to the amount of heat input it receives minus the amount of work it does”; work being measured by the product of force applied by the body and the distance through which it moves.

From the previous discussion, it is apparent that similar physical principles and various spatial representations can be used for hydrologic modelling. It is thus possible to propose taxonomy of hydrologic modelling that classifies available models. There are a number of ways such taxonomies can be built up, but the following way (next paragraph) may serves as a basic framework within which more detailed classifications can be made.

Hydrologic phenomena vary in all three space dimensions, in time, and are random or uncertain because they are driven by rainfall and because many of the properties of the flow domain are unknown, especially for subsurface flow. There are thus five sources of variation that one can consider in a hydrologic model: time, three space dimensions, and randomness. All hydrologic models can be classified according to the assumptions made about these three factors. The simplest case is a deterministic (no randomness), lumped (processes are assumed spatially uniform), steady flow model (no variation in time). This is typical of steady, uniform flow in a channel, or aquifer system, for which the mechanics are well understood and modelled. Allowing any one of the factors (time, one space dimension, or randomness) to be accounted for explicitly, is also commonly handled, and good models with computer programs for this purpose have existed for about 20 years (e.g. steady, non-uniform flow in rivers, radial flow towards wells in groundwater, regression modelling, and statistical analysis of extreme floods); modelling variation with respect to any two of these factors taken as independent variables has become possible with standardized computer programs within the last 10-15 years (e.g. unsteady, non-uniform flow in rivers, two-dimensional steady flow and transport in groundwater systems; time series and geostatistical analysis of hydrologic data). Allowing any three of these factors to be explicitly varying is really still largely in the research realm (e.g. two-dimensional, unsteady flow in rivers and estuaries, three-dimensional steady groundwater flow models; geostatistical studies with randomness explicitly characterized in two dimensions on a spatial plane). Models with four or five independent variables are even more in the research realm [Maidment, 1993]. The state of flow modelling is more advanced than that of transport modelling, both for surface and subsurface waters. Often the flows are computed first, and then transport is modelled using the pre-computed flow field. In subsurface waters, flow in saturated groundwater below the water table is better understood than is unsaturated flow above the water table, especially near the soil surface.

GIS can make a contribution to hydrologic modelling by solidifying the treatment of spatial variation. In so doing, it is likely that models with three independent variables will become capable of general application in the near future; and those with one or two independent variables will become more accurate and less costly to implement than they are now.

State of Modelling Coupled With GIS

Several levels of hydrologic modelling in association with GIS can be distinguished: hydrologic assessment, hydrologic parameter determination, hydrologic modelling inside GIS, and linking GIS with hydrologic models.

Hydrologic assessment means mapping, in GIS, the hydrologic factors that pertain to some situation, usually as a means of risk assessment. **Hydrologic parameter** determination is currently the most active area in GIS related to hydrology. The goal is to determine the input parameters of the hydrologic models by analysing the terrain and land cover features. Thus land surface slope, channel lengths, landuse, and soil characteristics of a watershed are starting to be extracted from both raster and vector GIS systems. A simple way for a GIS to supply hydrologic parameters is through linkage to a library of geo-referenced parameter values. For example, SWRRB model [Arnold *et al.*, 1990] for simulation of the water resources of rural basins has a library of weather parameters defined for about 100 weather stations in the United States, so that in application of the model without local weather data, the analyst chooses parameters from the weather station closest to the study area. Likewise, for soils information, SWRRB has detailed information on soil properties for hundreds of soils classified on county soil maps. If these maps were likewise stored in GIS, then the linkage of these parameters as attributes of the soil polygons would be a straightforward matter. In Canada a similar georeferenced parameter library is used for modelling pesticide movement in soils.

It is possible to do some **hydrologic modelling directly within GIS systems**, as long as time variability is not needed. This is the case when considering annual averages of variables, such as annual average flow or pollutant loadings from a watershed. One can then implement spreadsheet-type models in which flows or loadings are computed as flow or load per unit area times the area; one can also capture some more complex equations, such as those for pollutant loadings derived from the regression, where the independent variables in the regression equations are mapped in coverage and then the loadings are worked out based on a mathematical combination of coverage data.

Another way of eliminating time as a variable is to take a snapshot at the peak flow condition and model that by assuming the discharge is at its peak value throughout the system. It is thus possible to route water through GIS networks using analogies to traffic flow routing in which each arc is assigned an impedance measured by flow-time or distance and flow is accumulated going downstream through the network. A limitation of this type of modelling is that for water flow, the impedance to flow into the arc is related to the amount of flow; that means, one cannot specify the impedance without first knowing the flow, and cannot calculate the flow without first knowing the impedance. But this problem has been known in hydrology for many years, and the well-used rational formula for storm sewer design gets around this by working successively downstream, so that the amount of flow is being accumulated as the computations proceed and thus the impedance to be assigned to the next arc can be determined.

Linking GIS and hydrologic models through Object-oriented linkage

Figure 2-1 shows a concept of GIS representation of the real world, proposed by Scott Morehouse of ESRI [Morehouse, 1978]. He suggests that: starting with image processing, building through raster GIS, then through vector GIS, one can obtain raster and tabular representations of reality. He indicates that the next step beyond tabular modelling is semantic modelling, in which one attempts to capture the functional interrelationship of the objects located on the land surface. Semantic modelling is a very familiar concept for hydrologists, as it is the prime way that the data structures for lumped hydrologic models are organized. In such models, geography serves a starting point for building up the semantic representation of the system, but once it is constructed, the semantic representation becomes the primary *mental model* that the hydrologist uses when thinking about the system.

Building semantic models in hydrology requires an abstraction of spatial features into spatial objects to form a schematic representation of the flow system. An object-oriented model, such as that used in some expert system programs, appears to be a good linkage between GIS and hydrologic models for these types of models. Each line in the input code of the hydrologic model can be conceived of as an object whose properties are the various fields in that line. Djokic and Maidment (1991) were conducting some research along these lines at the University of Texas using a linkage between the ARC/INFO GIS and the expert system Nexpert Object [Djokic and Maidment, 1991].

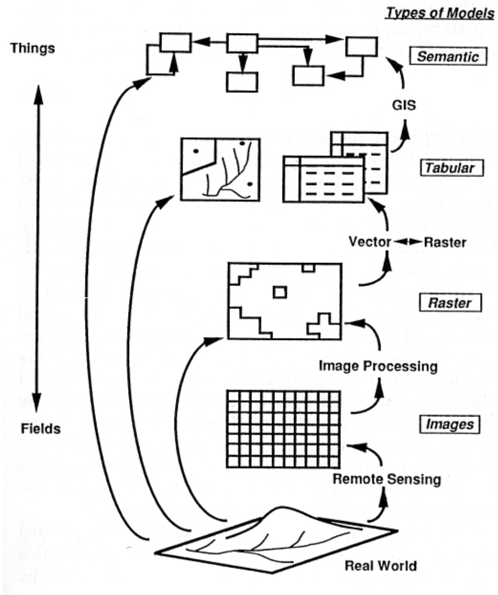

Figure 2-1: A hierarchy of models for knowledge about the real world
Source: [Morehouse, 1978].

Concluding Remarks on Environmental Modelling

It goes without saying that many hydrologic analyses are time-varying, particularly for surface water flow (less so for groundwater). **GIS really does not lend itself to time-varying studies because there is no explicit representation of time in the data structures.** One cannot readily model the evolution through time of spatial variation in a phenomenon within GIS for this reason. But such variations are often needed in hydrology, for example, to look at tidal variation of flow and transport in an estuary. **Until GIS explicitly integrate time variation in its data structures, its role will largely be limited to an input data provider and an output display and mapping device.**

As Maidment put it " Because most surface water hydrology flows are time varying and because much of the concern about groundwater flow deals with tracing out the motion of contaminants over time, it would be very helpful to have in GIS some explicit data structures that resemble the space-time domain. With such data structures for point, line, and area primitives, it would be realistic to begin thinking about doing numerical modelling within GIS instead of keeping it in a separate code, as is now necessary. There is no doubt that computation is more efficient if it can rely on a single set of data structures instead of having data passed back and forth between different data structures".

2.3 The Geographic Information Systems

2.3.1 The Origins of the GIS

GIS has a longer history than most realize. Depending of what lineage one traces, one can find hints of what was to come in GIS perhaps 45 years ago or more, through computer-assisted cartography [Tobler, 1959], in civil engineering [Horwood *et al.*, 1962], and solid vestiges in geography [Wellar and Graf, 1972]. There was clearly some sense of what a GIS was in 1972 as indicated by the publication of the proceedings from the Second Symposium on Geographical Data Handling [Tomlinson, 1972]. Tomlinson and Petchenik (1988) edited a series of articles that treat computer-assisted cartography as one of the core lineages, particularly analytical cartography [Tobler, 1977] with its focus on the transformation of spatial data geometries.

The Canadian Geographic Information System developed between 1960 and 1969 has often been called the first production GIS. In mid-1970s, the design for spatial data manipulation (in the Odyssey system) was developed at the Harvard Laboratory for Computer Graphics and Spatial Analysis. Industrial-strength commercial GIS first took root in the early 1980s when spatial data managers were teamed with relational data managers to provide the spatial and attribute data management [Tomlinson, 1988].

Remote sensing has had a significant impact on GIS, but the major focus in remote sensing has been on the development of image processing systems. As early as 1972, Tomlinson has discussed the use of remote sensing data in GIS. The link between image processing systems and GIS has also been maturing for quite some time [Marble and Peuquet, 1983].

Recent developments in GIS are too voluminous to review in this limited space. However, the number of software packages in the commercial marketplace and the number of GIS textbooks and reference volumes of collected papers published recently give an indication of recent growth and development. Not less than 55 commercial products are available worldwide according to the GIS sourcebook [GIS world sourcebook, 1996]. Overall, the data, the software, and the hardware market are estimated to be in the multi-billions of dollars.

GIS has now become a large field so that no single basic reference source has it all. Thus, the state of knowledge must be taken as an aggregate of references. Several books have appeared that are useful for environmental problems, each with a particular perspective on GIS. For example, Burrough (1986) text focuses on GIS for land resource assessment, with a large portion dedicated to database issues. Starr and Este (1990) text deals with GIS from a remote sensing perspective, but emphasizing the importance of satellite imagery as well as point, line, and polygon vector-structured data. Tomlin (1990) text treats GIS from an analytical, map algebra perspective, dealing principally with data analysis rather than data entry or map product displays. Clarke (1990) text, although focusing on analytical cartography, provides a very valuable perspective on the algorithmic transformations of space.

Collections of articles for basic-readers have also appeared. Peuquet and Marble (1990) provide an introductory collection of papers. Ripple (1987) provides a compendium of natural resource management topics. Such a compendium was warranted for environmental issues. As early as 1991, Maguire, Goodchild, and Rhind introduced the most ambitious reference on the general principles and applications of the GIS. The two-volume reference was indicative of both the wealth of knowledge and the maturation of certain GIS topics, but certain topics like human factors issues and network GIS remain largely untreated in texts.

Although it is true that there has been a tremendous growth in knowledge related to GIS, there is still considerable room for improvement. Improvements would occur on several fronts, including issues related to institutional arrangements, data, software and hardware [Frank *et al.*, 1991]. A major part of those improvements, related to the study of the environment, will be the linking of the GIS and the environmental simulation models. Although analytical models have been a part of the GIS for some time [Wheeler, 1988] and have been linked to the GIS for topics like resource assessment [Burrough *et al.*, 1988], **the cross-fertilization between environmental simulation models and GIS is not started yet, and here our original contribution lies.**

Finally, we have to mention that much of the current experience in environmental modelling comes from hydrological modelling, particularly as performed by the Water Resources Division of USGS. This is one of the main reasons motivated us to select our case study in this research. We have to remember that Environmental modelling as a broad topic can place some of the heaviest demands on GIS because of its need to handle many kinds of data in both space and time in a more dynamic way than has been demonstrated to date. These requirements will help GIS evolve, perhaps in ways not currently envisioned. The current state of GIS should not be viewed so much as a hindrance, but as an opportunity that needs both direction and steps for progress. Realizing this opportunity involves putting GIS to use in creative ways. This might be considered as another contribution for our research.

2.3.2 The Nature of Geographic Information System

People come to understand the nature of the GIS from three basic perspectives: functional, procedural, and structural. Cowen (1988) identified several ways to define the GIS found in the literature and stated that definitions often arise due to a perspective on a topic. However, all seemed lacking, and he proposed to describe the GIS as a "decision support system", although this phrase did not receive much elaboration. Fundamentally, three perspectives are important for GIS:

- A functional perspective concerning what applications the GIS is used for (the nature of the GIS use).
- A procedural perspective concerning how the GIS works with regard to the various steps in the process to perform this work (the nature of the GIS workflow); and
- A structural perspective concerning how the GIS is put together with regard to various components (the nature of the GIS architecture).

All three perspectives add a different insight into the nature of the GIS, and any comprehensive definition should incorporate all three. Although no single definition says it all, a definition that combines a procedural and structural perspective and has had some discussion and agreement is: “A system of hardware, software, data, people, organizations, and institutional arrangements for collecting, storing, analysing, and disseminating information about areas of the Earth,” particularly in this case for understanding environmental processes [Dueker and Kjerne, 1989]. Such a definition is in keeping with the most popular rendition given by those with considerable experience in the field (e.g. [Marble, 1990]), but is slightly broader in scope because it admits the institutional considerations that give flavour to the GIS. A single definition of GIS is too limited to offer a full functional description, and if our intention is to integrate the GIS with any other technology we should understand the three perspectives to realize where the integration will reside. Consequently, each of them will be discussed in turn in the following overview to provide a comprehensive understanding.

Functional Perspective: The nature of the GIS use

There are many dimensions that can be considered in the use of GIS. There have been recent attempts through the National Centre for Geographic Information and Analysis (NCGIA) at developing taxonomy of use [Obermeyer, 1989]. The framework for such taxonomy can include many dimensions, such as [Onsrud, 1989]:

- Type of task: resource inventory, assessment, management and development.
- Application area: environmental, socio-economic, etc.;
- Level of decision: policy, management, and operations;
- Spatial extent of problem: small, medium, or large study area size; and
- Type of organization: public, private, or non-profit.

All five dimensions are pertinent for any particular use of the GIS. A generic treatment of use can only hope to focus on a couple of dimensions. Of particular interest here are the dimensions that concern tasks and environmental applications.

Environmental tasks include those tasks for inventorying, assessing, managing, and predicting the fate of environmental resources. An environmental inventory is an accounting of the state of a resource environment, what exists and what does not in particular areas. This can be accomplished with a GIS at different levels of spatial, temporal, and thematic resolution as deemed necessary by the group interested in the inventory. Such an accounting is a very traditional, descriptive approach to "doing geography”. An assessment can be used to determine what has been lost due to environmental influences. The relationship between what exists and what no longer exists is a difference in two maps over time. The difference is computed through use of a change detection technique. Environmental management is a task requiring certain policy controls to determine what resources should receive protected-use. Environmental prediction is a task requiring a thorough understanding of the “causal mechanisms” of change, and is the most difficult of all tasks, as it requires assumptions about many unknowns.

The second dimension concerning “application area”; GIS can provide support for several different environmental modelling applications. These include: hydrological modelling [Maidment, 1993], ecological systems modelling [Kessell, 1990], plus policy considerations for risk/hazard assessment [Hunsaker *et al.*, 1990] involving these models. Another of the dimensions of use is the decision-making level. Different GIS processing environments *support* different levels of decision-making (but it is not a DSS itself, this issue is discussed in chapter seven).

GIS usage in terms of tasks, applications, and levels of decision-making, takes particular meanings when we understand whom the users are. Several types of users can be identified: scientists, managers, technical specialists/analysts, clerks, and the general public. At the current time the largest group of users are mainly specialists with a background in both GIS jargon and their own disciplinary jargon.

Three primary modes of GIS use can be identified: map, query, and model [Nyerges, 1991a]. The map mode provides referential and browse information, when a user wishes to see an overview of a spatial realm, and needs to get a sense of what is there. A query mode is used to address specific requests for information posed in two ways. One is that the user could specify a location and request information on phenomena surrounding that location or nearby. A second is that a user could specify a kind of phenomenon (or phenomena) and request to see all locations where the phenomenon occurs. However, there are several other renditions of these basic questions [Nyerges, 1991a]. Questions dealing with "when" and "how much" can be added to the "what" and "where" in queries about the geographic phenomenon under study. Model invocation is the third mode of use. After having prepared the nature of the inputs to be retrieved for a model, the model is run and an answer is computed. More realistic data with a locational character do have an impact on model results. In addition, geographical displays interactively depicting the nature of the sensitivity of certain parameters can be very useful in support of model initialisation (parameterisation). The model brings together the locational, temporal, and thematic aspects of phenomena in a geographic process characterization.

GIS operate in all conceivable modes for information processing. There are systems that are standalone, and there are systems that are wholly integrated. In the standalone mode the GIS is the entire workhorse for problem solving, whereas with integrated systems GIS is only one part of a comprehensive solution [Nyerges, 1991c]. To consider such issues more thoroughly, we can view GIS from a procedural perspective.

Procedural Perspective: The nature of the GIS workflow

The GIS workflow process consists primarily of four steps: (1) problem definition (and software/hardware setup if needed); (2) data input/capture (with subsequent data storage/management); (3) data manipulation/analysis; and (4) data output/display. Data storage/management functions support all the others.

Tasks and applications that solve problems require functions (sometimes called operations) to make use of the GIS. The major functions that support use of the GIS include data entry/capture, data storage/management, data manipulation/analysis, and data display/output. Data entry/capture functions support all other processing steps. There is no question that data entry/capture functions can support environmental modelling. In fact, this is the most obvious of the support functions, and unfortunately sometimes the only function that is recognized. Data management functions focus on characterizing the state of the data environment for each context. Complete data records for geographic phenomena would include an observation of thematic attribute character, an observation of location, and an observation of time. The tendency has been to characterize the present, forgetting about the past. In many instances new data replace old data, with the record of old data being eliminated (except for database backup and archive). As a result of this view of the value of old data, current systems can only handle the character of phenomena as time slices for past, present, and future observations.

Current inventories may or may not constrain analyses, depending on the functions available for transforming data into a suitable form for analysis. Langran and Chrisman (1988) describe the value of retaining old data, and some of the conceptual issues underpinning design requirements for spatio-temporal inventories.

Functions that support GIS data manipulation focus on preparing data for the analysis phase of processing. Conversion from one structure to another is often necessary to support spatial data analysis. Functions that support GIS data analysis focus on developing and synthesizing spatial relationships in geographic data to provide answers. They range from simple models developed wholly within the GIS context to elaborate coupled models linked into the GIS environment. Examples of such functions for river network modelling appear in Table 2-4. These functions produce answers that take the form of single numbers or words, perhaps in response to a query, or they take the form of several thousand numbers or words as the basis of a map display.

Many of the current concerns with analytical functions are with the design tradeoffs for integrating and/or linking spatial process models into the GIS context, that is, the model structuring function in this table.

The advantage of the GIS is that it provides interactive data processing support. Consequently, the four steps described can occur in rather rapid succession. However, for some projects, days rather than minutes are required to proceed through all of the steps. The ease with which these necessary steps are carried out is influenced by the GIS architecture.

Table 2-4: GIS data analysis functions to support river network modelling

Function		Description
Spatial Data Analysis		
	Spatial intra-object measurement:	Individual object calculations for line length, polygon area, and surface volume, polygon perimeter, percent of total area.
	Spatial inter-object measurement:	Inter-object calculations for distance and direction point to point, point to line, polygon perimeter, percent of total area, percentiles, range, and midrange.
	Descriptive spatial statistics:	Centroid (weighted, geometric).
	Inferential spatial statistics:	Trend analysis.
Attribute Data Analysis		
	Descriptive non-spatial statistics:	Frequency analysis, measures of dispersion (variance, standard deviation, confidence intervals), measures of central tendency (mean, median, mode), factor analysis, contingency tables.
	Inferential non-spatial statistics:	Correlation, regression, analysis of variance, discriminant analysis.
Spatial and Attribute Data Analysis		
	Overlay operators:	Point, line, area object on/ in point, line, area object.
	Network indices:	Compute network indices for connectivity, diameter, and tree branching structures.
	Significance tests:	t-test, chi-square, Mann-Whitney, runs.
	Simulation:	Test the interaction of flows on the network over time. Test modal choice over time.
	Model structuring:	A model-structuring environment that provides linkages between parts of models and the GIS environment through a special language interface.

Structural Perspective: The nature of the GIS Architecture

Another way to describe the general nature of the GIS is to examine the nature of the software architecture. As mentioned in the definition, GIS is composed of data, software, and hardware used by personnel to develop and disseminate geographic information. In a sense, each of the components of data, software, and hardware has architecture (a framework for how it is put together). For this discussion, and from a systems design point of view, perhaps the most fundamental of these three is the software architecture. GIS architecture can be described in terms of generic modules as shown in Figure 2-2. Many authors [Calkins and Tomlinson, 1977; Clarke, 1986; Guptill, 1988) list the following modules that are of significance: input/capture, data management, manipulation/analysis, output/display. Not surprisingly, these modules are a reflection of the use and processing activities in the GIS.

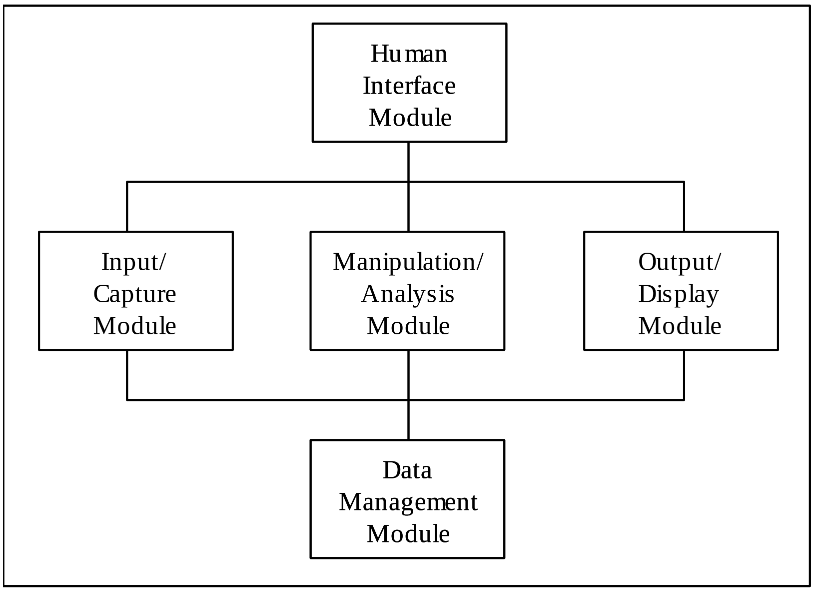

Figure 2-2: GIS as architecture of modules from a structural perspective.

Each of the modules has been described in terms of functions that the respective module performs. The data capture module provides operational functions for acquiring data. The data management module stores and retrieves the data elements. The manipulation and analysis module handles the transformation of data from one form to another and the derivation of information from data. The data output and display module provides a way for the user to see the data (information) in the form of diagrams, maps, and/or tables, etc.

The architecture of the data management module determines the design of the descriptive constructs used for data storage. As such it is the fundamental mechanism for determining the nature of data representation as presented to applications, whether these be integrated functions in the GIS or models linked to the GIS. The architecture of the module is based on the types of data models used. A data model determines the constructs for storage, the operations for manipulation, and the integrity constraints for determining the validity of the data to be stored [Nyerges, 1987]. The data model concept is often misunderstood; many authors including only the data construct aspect of this concept. Goodchild (1992) reviewed the different data structuring approaches used in the GIS data models. Together with the various functions described in Table 2-4 and the integrity constraints for keeping data valid, these aspects of the GIS data model determine the architecture of a system.

Among the more common GIS data models are the layer, object, and network data models [Goodchild, 1992], together with a relational data model (Figure 2-3). Layer models consist of spatial data constructs (location samples) with attached attribute data constructs. Object models consist of culturally defined attribute descriptions (attribute data constructs) with attached spatial data constructs. The principal difference between layer models and object models is that layer models do not bundle spatial and attribute data for data management, where object models do bundle spatial and attribute data for management. Network models can be developed like layer-based or object models, but with the additional stipulation that the linear geometry along the phenomenon must be part of the spatial description. The network model in Figure 2-3 indicates this through the use of the linear address construct, which can be thought of as a sequence of river sampling stations. Relational data models carry the attribute information for layer-based, object, and network models. Consequently, the difference in the data modelling approach is whether the spatial, attribute, and temporal characteristics are bundled as described phenomena or not.

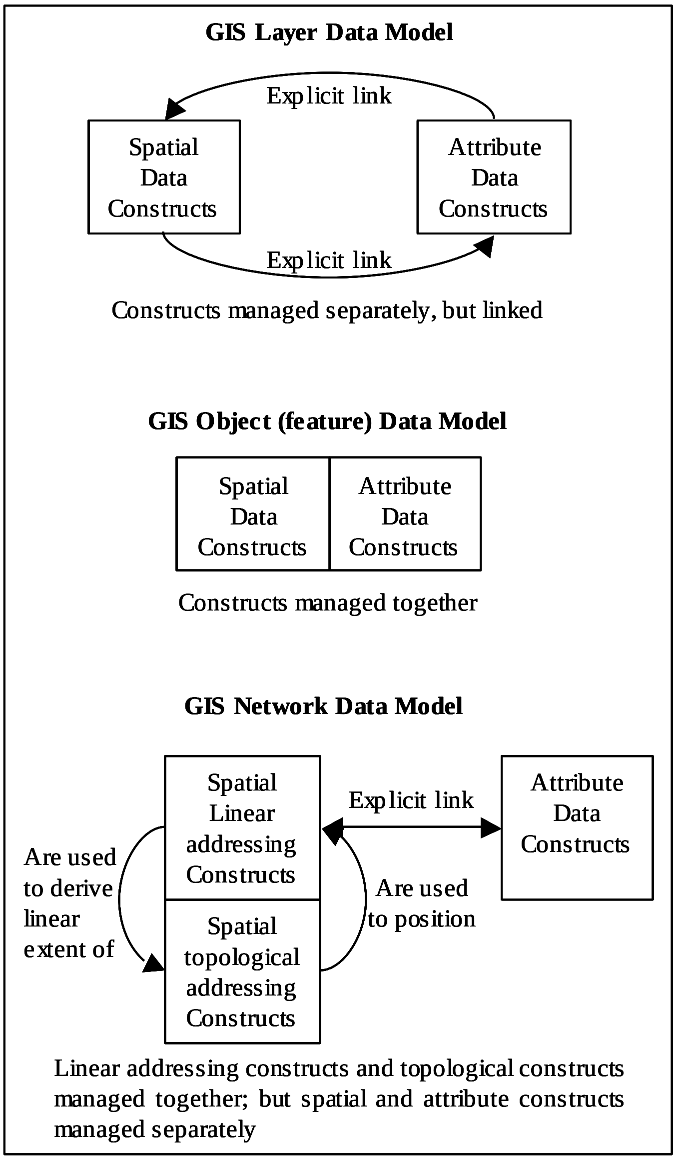

Figure 2-3: Common GIS models

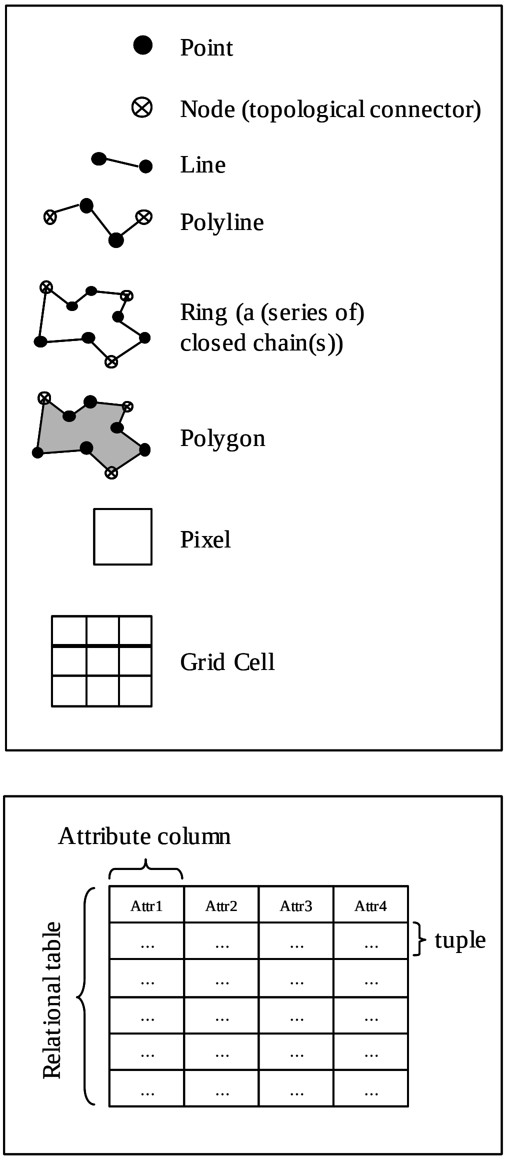

Figure 2-4: Data representation in GIS.

Top: Graphic depiction of spatial data constructs.
Down: Graphic depiction of attribute data constructs.

Bundling characteristics allows for easier data manipulation. Not bundling them allows for easier data management. The primitive spatial data constructs in layer, object, and network models include: point, node, segment, chain, ring, polygon, cell, and table (Figure 2-4). The primitive data constructs in the relational data model include: table (relation), tuples, and columns. These basic constructs are combined in various ways to form the layer, object, and relational models.

There are six different types of layer models. These types include: irregular or regular sampled points, contours, polygons, grid cells, and triangular nets. The irregular or regular sampled points are composed usually of points in *X, Y, and* Z space with an attached attribute. Contours are (X, Y) points with implicit segments, the aggregate sequence of points having an attached attribute, usually for terrain elevation or water depth. The polygon model is composed of topological chains (also called arcs or edges in some systems) that form a ring (closed boundary) around individual areas, with all areas together exhaustively covering a spatial extent, having no overlaps or gaps between polygons. The grid cells are areas (usually of the same rectangular size) exhaustively covering a surface. Triangular nets are (usually) irregularly spaced points that form vertices of triangles, whose sizes are optimised to cover a surface (with no gaps or overlaps) for the most effective representation. Goodchild (1992) discussed the layer models in more detail.

The data management module is connected directly to the data/capture, manipulation/analysis, and output/display modules (Figure 2-2). It provides the clearinghouse function to pass data between the various modules. One of the major reasons that GIS has been so useful is because it provides a mechanism to manage large volumes of spatially related data in a systematic fashion. Originally the graphics were acceptable, but computer-assisted cartography was better. The analytical capability was acceptable, but spatial models (in many different disciplines) provided for better analysis. For this reason the GIS often had been referred to as a database engine. With the advances in graphics and analysis incorporated into many GIS in recent years, this view has changed. Some organizations look at the GIS as a graphics engine, while others look at it as an analytical engine. Nonetheless, the GIS cannot do everything; it would be too expensive if it did.

One of the functions that are still poorly performed in GIS (if not missing) is those functions deal with time (temporal dimension). Geographic phenomena are depicted as a 'static' map displaying information of the real world at a particular time, but geographic processes are dynamic. Although the concept of storing unique attribute information linked to objects within a GIS is fundamental, adding the time element raises some intriguing questions and presents new difficulties. There have been many attempts to add the temporal dimension to the GIS. In the following section we explore the concept of the temporal GIS and review its strengths and weaknesses. The aim is to understand the significance of time in GIS and the feasibility to perform simulation modelling.

2.3.3 Significance of Time in GIS

Time has fascinated humans for generations, serving as the eternal medium through which we pass. It is also a dimension in the GIS field that is getting more attention now than ever. Throughout the geography literature, many researchers have studied temporal progressions in an analytic manner. There are for example the studies of innovation and diffusion [Hägerstrand, 1952], which in turn led to the ideas of "Cellular Geography" [Tobler 1979] and "Cellular Automata" [Couclelis 1985].

Furthermore, there is Hägerstrand's more qualitative study of the effects of time and space on people that he termed "Time Geography" [Hägerstrand 1962; 1970]. He examined space and time within a general equilibrium framework, in which it is assumed that every entity performs multiple roles; it is also implicitly admitted that location in space cannot effectively be separated from the flow of time. In this framework, an entity follows a space-time path, starting at the point of birth and ending at the point of death. Such a path can be depicted over space and time by collapsing both spatial and temporal dimensions into a space time path. Time and space are seen as inseparable.

In the last 15 years, there has been a fair amount of research and debate on the subject of time-integrative GIS, predominantly from a technical perspective. Many design proposals and even some intriguing prototype software solutions were presented. However, not much has been accomplished in the real world, although potential applications of temporal GIS abound.

Although most conventional texts on GIS still try to avoid the complex issues raised by the integration of time into GIS, there are a few exceptions to the rule. Gail Langran (1992) wrote a seminal work on "Time in Geographic Information Systems", reviewing and discussing many of the possibilities and technologies in detail. Other substantial contributions continue to come from Peuquet and MacEachren (1998), the members of the GeoVISTA centre at Penn State University. The discussion on temporal GIS has profited from the GIS-Data initiative sponsored by the European Science Foundation and the national research councils of 14 European countries.

In general, a temporal GIS maybe defined as an attempt to store and analyse spatial objects and changes in their attributes through time [Castagneri 1998]. Every spatial object used in a GIS has a temporal validity as well as one or many attribute values. The entity of a spatio-temporal process may change its spatial representation over time as well as its spatial relationship to other entities. In addition, the related attribute information may be subject to changes throughout time. All spatial objects in a GIS are in the first instance defined by their spatial representation. This concentration on the spatial aspect of an object as the focal point of the conceptualisation of a spatio-temporal process in a GIS neglects the fact that *Time* and *Space* are equivalent dimensions.

Thomas Ott and Frank Swiaczny (2000), Monica Wachowicz (1999), and May Yuan (1996) gave an overview of different approaches of the conceptualising of time related to spatial objects in a GIS. In this context "the concept of time implies that changes occur throughout the present, the past and future of the life span of a real-world phenomenon. The temporal GIS would aim at understand these changes and their effects over time rather than simply reproducing them by displaying a sequence of snapshots" [Wachowicz and Healey 1994]. According to Langran (1993) the following major functions of a temporal GIS can be distinguished:

- *Inventory:* Storing a complete description of the study area, and accounting for changes in both the physical world and computer storage.
- *Analysis:* Explaining, exploiting, or forecasting the components contained by and the processes at work in a region.

- *Updates:* Superseding outdated information with current information.
- *Quality control:* Evaluating whether new data are logically consistent with previous versions and states.
- *Scheduling:* Identifying or anticipating threshold database states, which trigger predefined system responses.
- *Display:* Generating static or dynamic map, or a tabular summary of temporal processes at work in region.

To realize these functions in the conventional GIS, temporal information for objects must be added to the logical data models used in GIS. Different approaches to do so are discussed in [McBride *et al.*, 2002]. "Thus, while great progress has been made in developing data models for GIS that go beyond the time slice approach, the creation of a truly spatio-temporal GIS remains an unmet challenge" [Couclelis 1999]. The integration of time in existing desktop GIS packages is an even greater challenge today. As a prerequisite for this attempt, basic concepts have to be utilized. These basic concepts are explained in the following paragraphs.

Temporal Data representation in GIS

Many GIS data models have been proposed to involve temporal information. Their general frameworks use a set of geometry-based spatial objects to represent reality. Thematic characteristics are represented as attributes of spatial objects. Temporal information is either associated with time-stamped individual layers, such as the Snapshot Model [Armstrong, 1988], or individual spatial objects, such as the Space-Time Composite Model [Langran and Chrisman, 1988].

In the snapshot model, every layer is a collection of temporally homogeneous units of one theme (Figure 2-5). It shows the states of a geographic distribution at different times without explicit temporal relations among layers. Time intervals between any two layers may vary and there is no implication for whether changes occur within the time lag of any two layers. The Temporal Map Sets (TMS) [Beller *et al.*, 1991] model can be seen as extensions of the snapshot model. The design of TMS purports to model geographic events in a defined area (Figure 2-6). Events are defined as binary TMSs, specifying whether each cell is in or out of the event. These snapshot approaches always result in a large amount of data duplication with unchanged properties in space and time. The major drawback is data redundancy and the risk of data inconsistency.

The Space-Time Composites model (STC) represents the world as a set of spatially homogenous and temporally uniform objects in a 2D space (i.e., a layer) Figure 2-7. Every space-time composite has its unique temporal course of changes in attributes. Apparently, space-time composites can be derived by temporal overlays of time-stamped layers (snapshots). A space-time composite conceptually describes the change of a spatial object through a period of time. Attribute changes are recorded at discrete times, although its temporal resolution is not necessarily accurate. The STC model is able to record temporality within the largest common units of attribute, space, and time (i.e. change in site), but it fails to capture temporality among attributes across space (i.e. motion or movement). In addition, updating a database of STC requires reconstruction of STC units. Consequently, geometrical and topological relationships among STC units change and the whole database, both spatial objects and attribute tables, needs to be re-organized.

The spatio-temporal object model (ST-Object model) represents the world as a set of discrete objects consisting of spatio-temporal atoms by incorporating a temporal dimension orthogonal to the 2D space (Figure 2-8). Spatio-temporal atoms are the largest homogeneous units in which certain properties hold in both space and time. A spatio-temporal object can possess changes in both space and time, although there is no change occurring within each of its spatio-temporal atoms. Therefore, the ST Object model is able to record changes in attributes of a ST-object in both spatial and temporal dimensions, together or separately, by projecting its ST-atoms to the spatial and/or temporal space. However, gradual changes in space through time are unable to be represented in the ST Object model since its ST-atoms are discrete. Though the ST Object model is similar to the snapshot model and STC model, it only represents sudden changes upon an independent, discrete, and linear time structure. None of them are able to portray the concepts about transition, process, or motion.

The above attempts indicates the fact that although the debate on temporal data models for GIS continues, one thing is clear, that is, GIS users no longer are satisfied with static data. From wildfire management to urban growth models, scientists and GIS users are wondering of what GIS can do. Despite the potential benefits from spatio-temporal GIS applications, current limitations in basic understanding of temporal datasets continue to hinder the development of truly useful Temporal GIS data models and tools.

Although the computer technology for spatio-temporal analysis exists, the GIS community must undergo a paradigm shift to fully appreciate "spatial dynamic GIS" benefits. It is not just a matter of collecting time-based data within a GIS, but also developing: A new way of thinking about time in a spatial sense; A new way of thinking about feed back loops and delays; A new vision to the cause and effect (causality relationships) that draw changes in geographic processes.

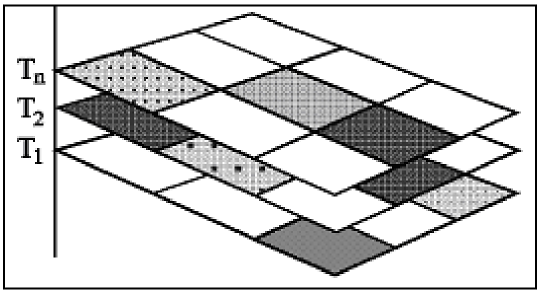

Figure 2-5: An example of the snapshot model [Armstrong, 1988]

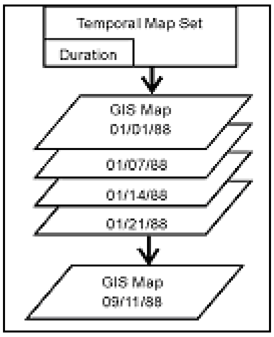

Figure 2-6: An example of a TMS [Beller *et al.* 1991]

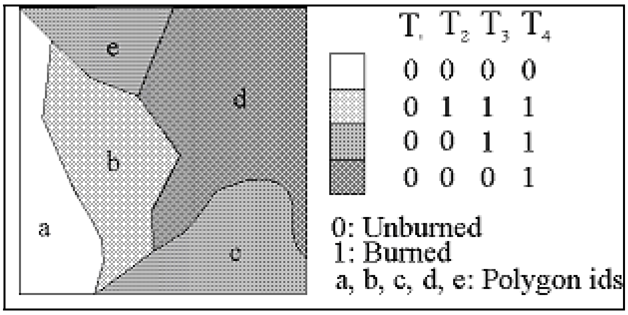

Figure 2-7: An example of an STC layer for burns [Langran and Chrisman, 1988]

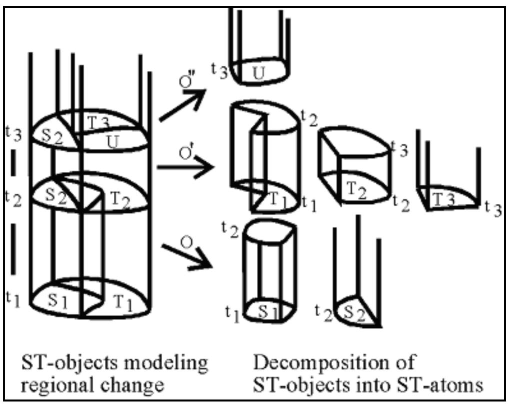

Figure 2-8: An example of a spatio-temporal object model [Worboys, 1992]

2.4 Simulation Modelling Techniques

The Latin verb *simulare* means to imitate or mimic. The purpose of a simulation model is to mimic the real system so that its behaviour can be studied. The model is a laboratory replica of the real system, said another way: a *microworld*. By creating a representation of the real system in the laboratory, a modeller can perform experiments that are impossible, unethical, or prohibitively expensive in the real world [Sterman 1991].

In principle, modelling is a way of solving problems that occur in the real world. Modelling allows one to optimise systems prior to implementation. Modelling process includes: *abstraction* (the process of mapping real problems into virtual world); analysis and optimization; and mapping the solution back to the real system. We can distinguish between *analytical* models and *simulation* models. In *analytical* or static models the result functionally depends on the inputs (a number of parameters). It is possible to implement such a model in a spreadsheet. However, analytical solution does not always exist, or maybe very hard to find. Then simulation or dynamic modelling may be applied. A *simulation* model may be considered as a set of rules (e.g., equations, flowcharts, state machines, cellular automata) that define how the system being modelled will change in the future given its present state. Simulation is the process of model "execution" that takes the model through *discrete* or *continuous* state changes over time. In general, for complex problems where time dynamics is significant, simulation modelling is the best answer.

In the simulation modelling literature, there is a mix of use regarding the terminology. We found terms are used in different ways that create some confusion. Thus, to make sure we all agree on terms, we consider the following paragraph:

There are two theories underlay the simulation modelling paradigms, the control theory and the complexity theory [Scholl, Hans J. 2001]. These theories stand behind two major *nonlinear* modelling methodologies, the System Dynamics and the Agent-based modelling respectively (Scholl called them modelling *techniques*).

Simulation models use two different techniques, *continuous* simulation and *discrete-event* simulation (some references identified Cellular Automata as a third technique, while others consider it as a *method*). Models can fall in two types, deterministic and stochastic. Finally, the three popular SD modelling tools are Stella, Powersim, and Vensim, whereas Swarm, Echo, and Xraptor are three development toolkits that help developing and implementing Agent-Based models.

Despite the distinctions between the simulation models, all of them share a common approach to modelling [Sterman 1991; 1994]. As Sterman stated “A simulation model does not calculate *what should be done* to reach a particular goal, but clarifies *what would happen* in a given situation”. The purpose of the simulation may be *foresight* (predicting how systems might behave in the future under assumed conditions) or *policy design* (designing new strategies or organizational structures and evaluating their effects on the behaviour of the system). In other words, simulation models are “What-If” tools. Often, such “What-If” information is more important than knowledge of the optimal decision [Sterman 1991].

Frenkiel and Goodall described the relationships between the major simulation techniques as shown in Figure 2-9. For situations where the system being studied contains a number of separate items each of them has its own characteristics and period of existence within the system, *discrete-event* simulation is often appropriate. In discrete-event technique, changes in the state of the system are conceptualized as taking place in discrete jumps corresponding to the arrivals, departures, or other critical changes in status of the individual items. This approach could, for instance, appropriately be used in modelling demographic processes in a small population where each birth and death is to be noted separately [Frenkiel and Goodall 1978]. This contrasts with the *continuous* simulation technique where the changes are *thought of* as taking place in a continuous manner (although they may be programmed in terms of discrete equations). System Dynamics models are continuous models, they do not model discrete events, rather they "view separate events and decisions as riding on the surface of an underlying tide of policy, pressures, and dynamic pattern" [Richardson, G. P., 1991 p. 323].

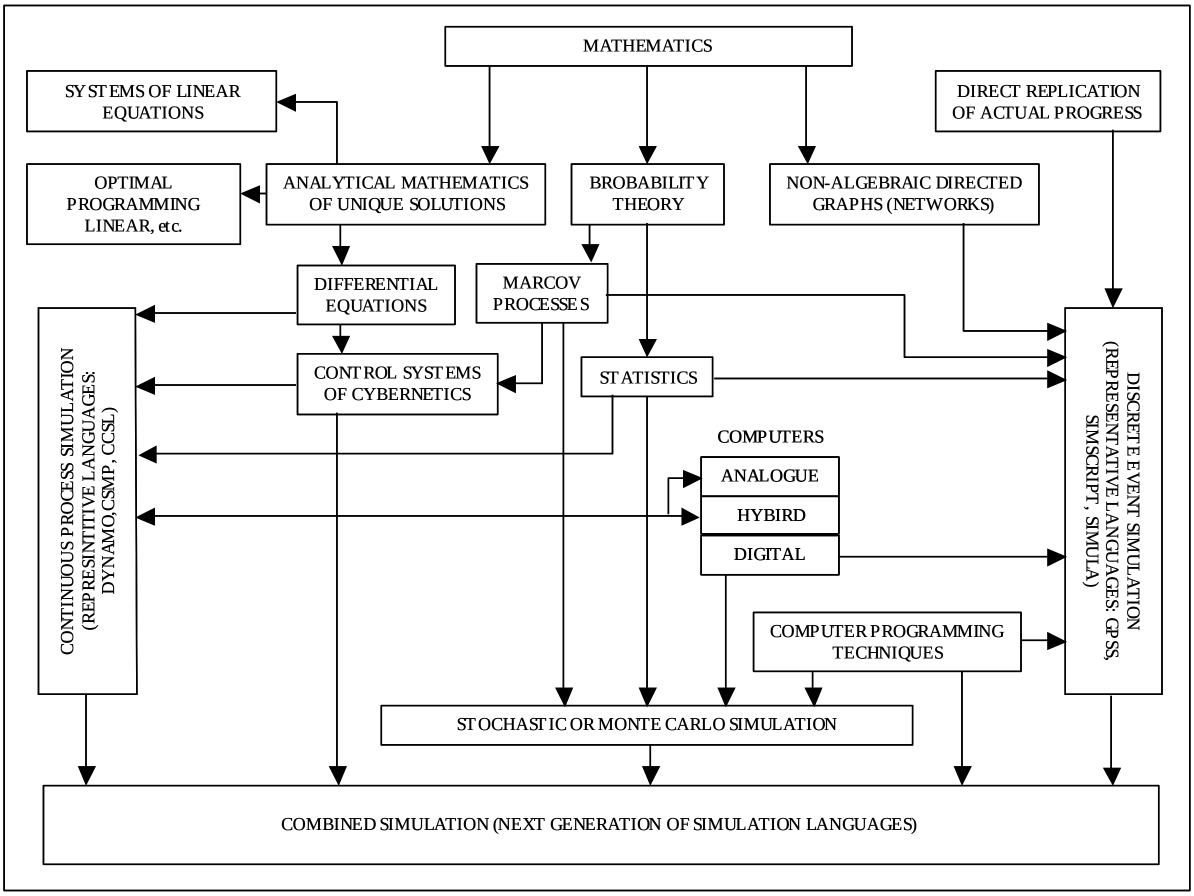

Figure 2-9: Relationships between the major simulation approaches.
Source: Frenkiel and Goodall 1978.

Where the number of separate items is sufficiently large, and only their average or groups' behaviour is of interest, a continuous simulation model may still be appropriate. But where it is essential to follow the fortunes of each item and preserve its individuality, the discrete-event form is usually necessary. So far, *continuous simulation models have been the choice in the majority of environmental applications*, but recently more use of discrete-event simulation introduced through Cellular Automata and Agent-based simulations as well.

Simulation models can be typified as deterministic or stochastic. In a deterministic model the state of the system at the next time step is entirely defined by the state of the system at the current time step and the transfer functions used. In a stochastic model there may be several future states corresponding to the same current state. Each of these future states may occur with a certain probability [Radzicki, Michael J. 1990a, 1990b: U.S. Department of Energy, 1997].

2.4.1 Major Paradigms in Simulation Modelling

Borshchev and Filippov (2005) identified the major approaches (paradigms) in simulation modelling as shown in Figure 2-10. The approaches are arranged on a scale with respect to the typical level of abstraction of the corresponding models. The approaches are: System Dynamics (SD), "Discrete Event" (DE) (they consider it as an approach), and Agent Based (AB). There is also Dynamic Systems (DS) field, but it stays a bit aside as it is used to model "physical" systems. Technically, SD and DS deal mostly with continuous processes whereas DE and AB work mostly in discrete time (i.e. jump from one event to another).

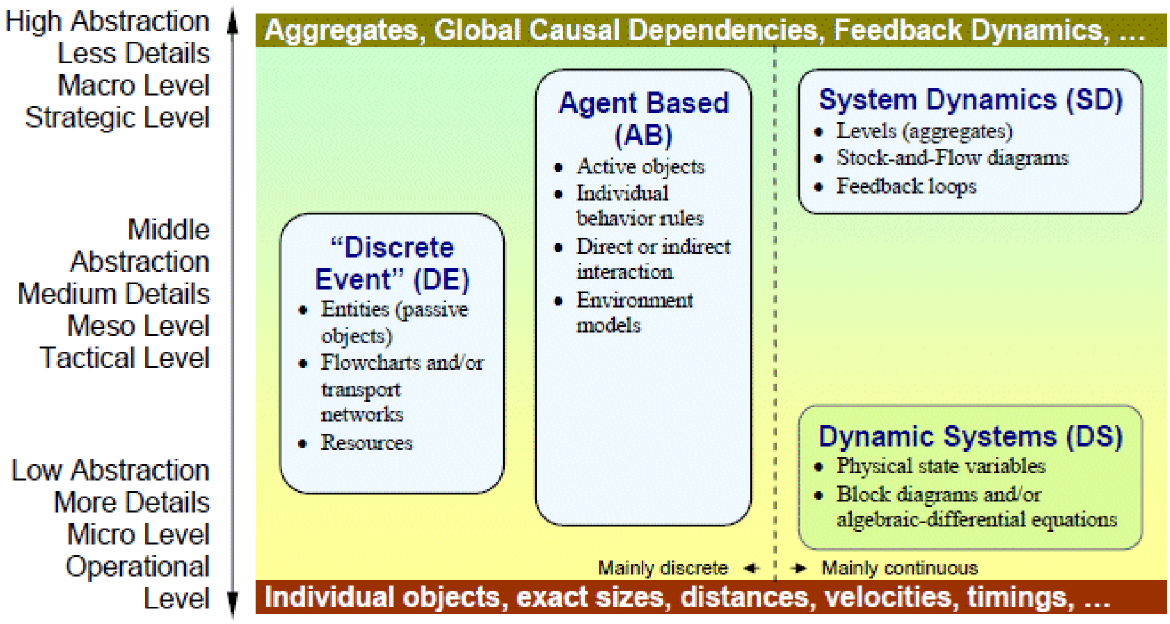

Figure 2-10: Approaches (Paradigms) in Simulation Modelling on Abstraction Scale. Source: Andrei Borshchev and Alexei Filippov (2005)

Based on how approaches correspond to abstraction, Dynamic Systems or "physical" modelling is at the bottom of the chart. System Dynamics (dealing with aggregates) is located at the highest abstraction level. Discrete Event modelling is used at middle-low abstraction. As for Agent Based modelling is used across all abstraction levels.

Historically, SD, DS and DE have been taught at universities to very distinct groups of students such as management, control engineers, and industrial engineers. As a result, they currently exist as three separate practitioners' communities (three different worlds) that never talk to each other. AB until recently has been almost purely academic topic [Borshchev and Filippov, 2005]. Borshchev and Filippov claim that: “the increasing demand for global business optimization have caused modellers to look at AB and combined approaches to get deeper insight into complex interdependent processes having very different natures. Therefore, there is a request for platforms that would allow for integration and efficient cooperation between different modelling paradigms.”

Scholl (2001) pointed to the same issue, as he put it: “Agent-based and System Dynamics modelling, Rather than benefiting from one another, the two disciplines ignored each other’s literature almost entirely. This is even more remarkable since the study areas significantly overlap. Still, results were seldom compared nor shared.” Scholl called for closing this gap and for bringing the two literatures into contact.

We believe that the reason of this deviate maybe because the theories behind these disciplines are different (as we will see in the coming paragraphs). Another reason could be the purpose of each approach (the ultimate goal). However, combining or merging the approaches and inspecting how they can fit together is beyond this research. What is important here is to understand the relative strength and weaknesses, similarities and distinctions among the major modelling disciplines. This would: (1) remove the confusion that one might fall in due to the similarity; (2) answer the question that one might ask (or may raise) about the difference between our research objectives (our new method developed) and the prior work that have been made by others; (3) provide insight understanding and strengthen the theoretical background regarding the simulation modelling. The major simulation modelling disciplines described next are System Dynamics, Agent-Based simulation, and Cellular Automata.

2.4.2 System Dynamics Modelling

System dynamics approach uses a perspective based on the scientific concept of information feedback and mutual or recursive causality to understand the dynamics of complex physical, biological, and social systems [Forrester, 1968]. System Dynamists attempt to understand the basic structure of a system, and thus understand the behaviour it can produce. The underlying concept of feedback is its loop structure, or the notion of circular causality. It is worthwhile to recall how traditional science establishes causality: "(1) the cause precedes the effect in time, (2) there is an empirical correlation between them, and (3) the relationship is not found to be the result of some third variable" [Babbie, 1998]. Only relationships satisfying all three criteria are recognized as causal by traditional researchers.

The existence of **causal relationships** governing the behaviour of the system is the core of the System dynamics modelling [Saleh, M. 2000]. Thus, a closed loop of circular causality can be formed.

The second concept in system dynamics is the **accumulation process** that is a fundamental process in Nature. "Nowhere does Nature differentiate; in real systems, dynamic change arises only from accumulation, that is, integration" [Forrester, 1980]. Thus, the focus is on the accumulation (integration) process, rather than the differentiation process.

The Endogenous Origin of Cause is the third concept. This implies the existence of other concepts such as: closed causal boundaries, feedback, and nonlinearity. This concept dictates that *the root causes of a "solvable problem" associated with a particular system are contained within the internal structure of the system itself*. A solvable problem means that behaviour can be adjusted (controlled) by human intervention. As long as the problem of interest is a solvable one, then the root causes of the problematic behaviour are not a consequence of unavoidable exogenous disturbances, but rather arise from the complex relationships of the structure of the system.

The endogenous concept necessitates the presence of a **closed causal boundary** for the system. This closed boundary separates the dynamically significant inner workings of the system from the dynamically insignificant external environment. While, in general system theory a closed system is defined as a materially closed one, in system dynamics a closed system is defined as a causally closed one. A system dynamist looks for the boundary that encompasses the smallest number of components within which the dynamic behaviour of the problem is generated. Those components are capable by themselves, without exogenous aid, to reproduce the essential characteristics of the problematic behaviour. A problem focus acts as a critically important filter that screens out unnecessary details and focuses the attention on the significant aspects of the system.

The **feedback view** of system dynamics can be seen as a consequence of the closed causal boundary and the endogenous concept. If feedback loops would not presented in a closed boundary system, then all causal links would (at the end) have to be connected to exogenous factors outside the boundary of the system. This will make the behaviour of the system a result of those exogenous factors. Since system dynamists have an internal perspective to problems, the existence of the feedback loop concept is inevitable. A **feedback loop** is defined as a closed sequence of causes and effects (circular causality), a closed path of action and information. Also, in system dynamics, a feedback system is defined as a one of an interconnected set of feedback loops.

A common feature of a feedback loop is the presence of **delay** in the flow of information and material throughout the loop. For example, the release of water from the reservoir does not immediately result in a delivery of water to the last farm at the tail of the channel, crops planted cannot immediately be harvested, new ideas take time to spread, etc. Delays have the tendency to dramatically change the behaviour of the model. "Delays are crucial in creating the dynamic characteristics of information feedback systems" [Forrester, 1961, 1985]. The delay in a negative feedback loop can exhibit oscillating behaviour, and usually attenuate the amplification power of a positive feedback loop.

Given the behaviour characteristics of the problems addressed by system dynamics, then the endogenous origin of cause concept forces system dynamists to include **nonlinearities** in the structure of their models. To understand the reason, we must first understand the behaviour characteristics of the problems that the system dynamics program attempts to solve.

Many problems that the program addresses are characterized by an unstable, non-linear, self-limiting behaviour, or in short, complex behaviour. Complex behaviour is a typical characteristic of many *natural phenomena* in the universe. Complex behaviour can never be generated, without exogenous aid (the endogenous origin of cause concept), by a linear feedback model. A typical control model (recall that the control theory is the parent program of system dynamics) will be a linear feedback one. That is because most engineering applications do not exhibit such kind of complex behaviour. Yet, Forrester [Forrester, 1969] had to step out of the linear world into the nonlinear universe to be able to address the problems in real world exhibiting complex behaviour.

In such kinds of complex behaviour, no static view of the feedback loops of the model is therefore sufficient. It is necessary for the feedback loops to change endogenously their relative strength of influence as conditions (states) change to generate such complex behaviour.

In system dynamics terminology, we call this the ability of the model to endogenously shift its dominant loops. Dominant loops are loops that are primarily responsible for the behaviour of the model over an interval of time. Loop dominance usually shifts among a number of loops in the course of time. For example, the self-limiting behaviour (the so-called S-shaped behaviour) can be generated by two coupled feedback loops. One loop is positive and the other one is negative. In the beginning the positive feedback loop is dominant and this generates the exponential growth behaviour and then, as the model changes its state, the negative feedback loop dominates and the saturation behaviour results.

The endogenous shift in loop dominance takes place as a consequence of **nonlinearities** in the equations defining the model's structure. If these equations were linear, no such shift in loop dominance would occur, and only one fixed set of loops will continuously dominate the model. In system dynamics, we expect models to change their dominant structure over time. Consequently, the focus is on nonlinear models [Forrester, 1987].

Structural changes are considered to be significant and are handled quite differently in cybernetics and in system dynamics modelling. In traditional cybernetics, structural changes are captured linguistically and sometimes diagrammatically, for example by redrawing the system structure. In the more quantitative program, the system dynamics program, structural changes are represented by endogenous shifts in loop dominance, which are capable of changing the active structure over time [Forrester, 1987].

It is assumed that there is a hidden meta-loop between structure and behaviour [Davidsen, 1991]. Shift in loop-dominance is a result of the dynamic behaviour of the model itself. These shifts in loop dominance change the active structure of the model. As the active structure changes, so does the dynamic behaviour of the model, which in turn further shifts the dominance of the loops, and so on. Understanding the mechanisms of this meta-loop is the principle outstanding problem in the system dynamics program. The goal is to understand the mechanisms of this hidden meta-loop in the model first (i.e. assuming that the model is our virtual world), then to reflect our understanding of the model on the real system. As Davidsen (1991) put it: “System dynamics has a great potential in describing the complexity of the real world (something that many modelling programs lacks), yet currently the explanatory power of system dynamics is not adequate. The major challenge, in future, for the system dynamics program, is to develop new concepts and tools that can enhance the explanatory power of the program through innovative ways of *"tracing"* in depth the mechanisms of this hidden meta-loop; otherwise the program is under the threat of reaching a *crisis* state”.

Finally, in the context of the model structure and complexity, the system components may coexist in the space. Environmental systems for example do have an obvious spatial dimension. In other words, the structure of the system is often distributed geographically. Consequently, space maybe substantial part of the structure and maybe considered as a *structural component* in the system, and to understand the environmental processes, and the relationship between the structure and the behaviour, we must concern ourselves with the spatial dimension which is significant and prominent aspect of the structure of the system.

Despite the fact that spatial dimension is crucial for environmental modelling, the spatial dimension has not explicitly represented in system dynamics. It has not been given the attention it deserves with respect to its significant role; presumable it plays often in real life. The system dynamists focus on the behaviour of the system, but when focusing on the structure of the system, relatively few system dynamists concern themselves with the space as a structural component; and take the spatial dimension explicitly into consideration, the way we typically do when we utilize geographical information systems. The reason for that might be the lack of a mechanism that represents the spatial dimension explicitly, properly and efficiently in system dynamics. Creating such mechanism is a major challenge.

2.4.3 Agent-Based Modelling

As opposed to the concept of feedback and circular causality in system dynamics modelling, is the concept of emergence and Agent-Based modelling. The aim of the Agent-Based (also known as Entity or Individual-based) modelling is to look at global consequences of individual or local interactions in a given space [Reynolds, 1999]. Agents are seen as the generators of emergent behaviour in that space [Holland, 1999]. Interacting agents, though driven by only a small set of rules that govern their individual behaviour, account for complex system behaviour whose emergent dynamic properties *cannot* be explained by analysing its component parts. In Holland's words "The interactions between the parts are nonlinear; so the overall behaviour *cannot* be obtained by summing the behaviours of the isolated components. Said another way, there are regularities in system behaviour that are not revealed by direct inspection of the laws satisfied by the components". Emergence, thus, is understood as the property of complex systems where "much (is) coming from little" [Holland, 1991, 1999]. Emergence is the focal point of what now is called the theory of *Complexity* [Phelan, 1999].

Agent-Based models consist of a space, framework, or environment in which interactions take place and a number of agents whose behaviour in this space is defined by a basic set of rules and by characteristic parameters [Reynolds, 1999a]. Some Agent-Based models are *spatially explicit* meaning that agents are associated with a location in geometrical space. Some spatially explicit agent-based models also exhibit *mobility*, where the individuals can move around their environment. This would be a natural model, for example, of an animal in an ecological simulation, whereas plants in the same simulation would not be mobile. Spatially explicit models may use either continuous (real valued) or discrete (integer valued, grid-like) space. However, not all models need to be spatially explicit (i.e. location does not play any role in computer networks simulations).

Agent-Based models are subset of *multi-agent systems*, which includes any computational system whose design is fundamentally composed of a collection of interacting parts. For example an "expert system" might be composed of many distinct bits of advice that interact to produce a solution. Individual-based models are distinguished by the fact that each "agent" corresponds to autonomous individuals in the simulated domain. The emergent dynamic behaviours resulting from Agent-based models can be linked with those of other models forming an even higher level of complexity and emerging behaviours. In summary, Complexity Theory is the "science of emergence" [Waldrop, 1992], and agent-based models are a key element for modelling emergent phenomena.

2.4.4 Cellular Automata

Similar to the Agent-Based modelling is the Cellular Automata concept that was first introduced by John Von Neumann in the late forties [Von Neumann, 1966]. This concept gained popularity three decades later through John Conway's work in the game of Life [Fogelman *et al.*, 1987; Toffoli and Margolus, 1987).

Cellular Automata models of dynamic systems consider a lattice of cells on a line (one-dimensional cellular automata) or a uniform grid (two or three-dimensional cellular automata), with a *discrete* variable at each cell. The state of a cellular automaton is completely specified by the values of the variables at each cell. A cellular automaton evolves in discrete time steps, with the value of the variable at one cell being affected by the values of variables at cells in its *neighbourhood* on the previous time step. The neighbourhood of a cell is typically taken to be the cell itself and all immediately adjacent cells. The variables at each cell are updated simultaneously (synchronously), based on the values of the variables in their neighbourhood at the preceding time step, and according to a definite set of *local rules* [Wolfram 1983; 2002]. Since they are based on microscopic behaviour, the transition rules are generally quite simple. However, the resulting overall behaviour of the system can appear to be quite complex.

An example for two-dimensional Cellular Automata is shown in Figure 2-11. Each cell has two possible states (black and white) and the local *neighbourhood* of the cell is defined by two adjacent neighbouring cells. The transition rules simply specify that the state of a cell at time ($t+\Delta t$) is equal to the state of its two neighbours at time (t) if these have the same state, otherwise the state of the cell will remain unchanged. In terms of structure, this computational scheme is similar to the scheme employed in the numerical manipulation of partial differential equations. The difference is that the state variable at each cell of the lattice is only allowed to assume a small set of values, typically, two states per cell and that the transition functions do not assume an algebraic form [Hogeweg, 1988] but may be deterministic or stochastic.

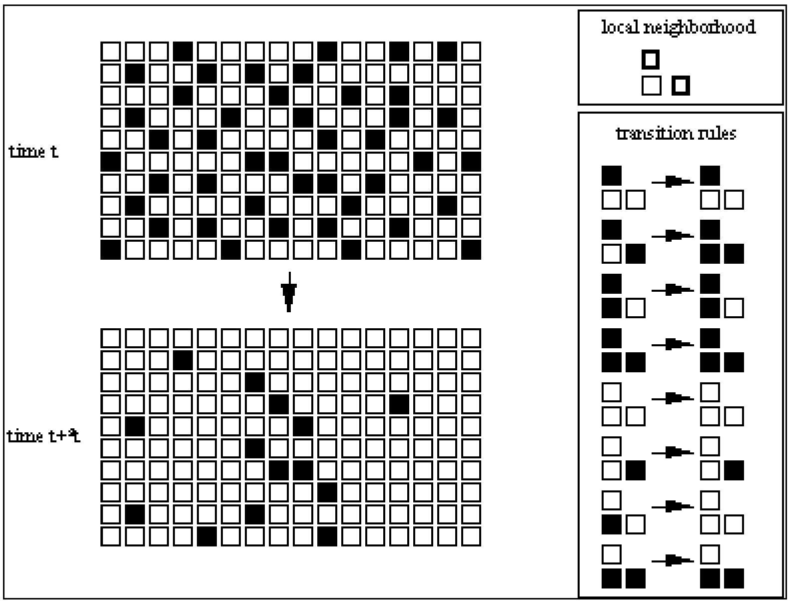

Figure 2-11: 2D Cellular Automata example

Cellular Automate Applications Example

Camara *et al.* (1996) have modelled the predator-prey relationship using a cellular automata formulation and compared the results with a traditional differential equation based model. A regular time steps were considered for both models. Predators and preys were assigned locations in cells in a mosaic representing a territory (Figure 2-12). Cyclic boundary conditions were also considered. To simulate species growth, a random reproduction and death rules were assumed. Probabilities for these rules for both predators and preys were determined based on birth and death rate constants. Predators and preys could meet in the same cell. Then, for a certain probability, the prey could die. This cellular automata model was implemented on personal computer using software that allows the consideration of a spatial representation as a background. Objects in this background may interact with the predators and preys following appropriate rules.

Another predator-prey model was developed using iThink [Richmond, 1991], considering an initial number of individuals, birth and death rates, for both species identical to the ones used in the cellular automata model (Figure 2-12). The results from the two approaches are compared in Figure 2-14. Notice that while the cellular automata model continues to perform oscillations, the iThink model stabilizes.

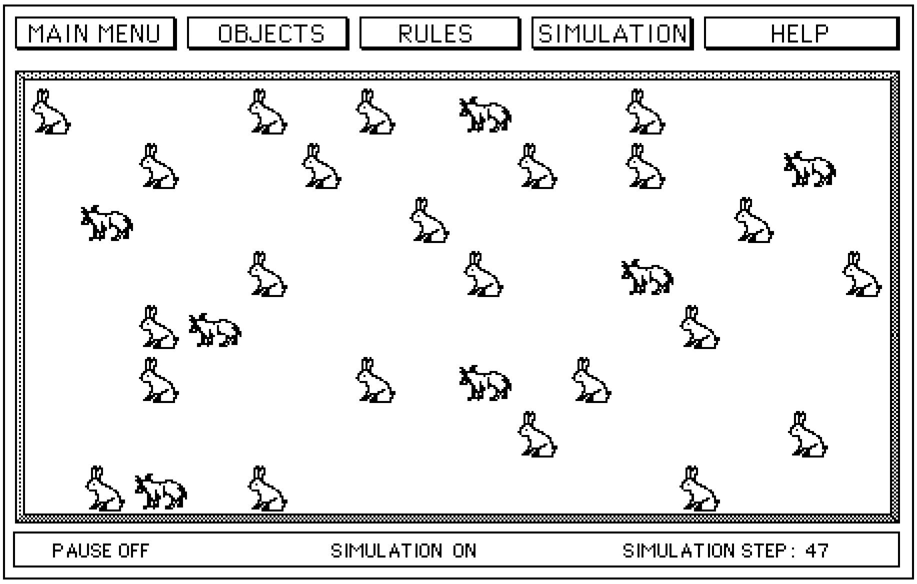

Figure 2-12: Object representation of a predator-prey Cellular Automata model.

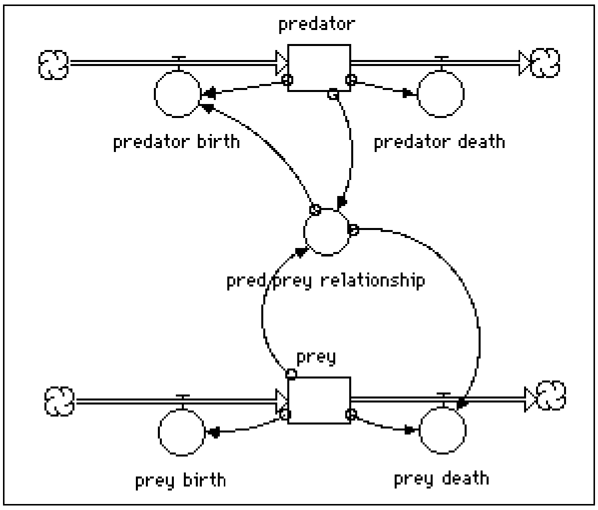

Figure 2-13: iThink predator-prey model.

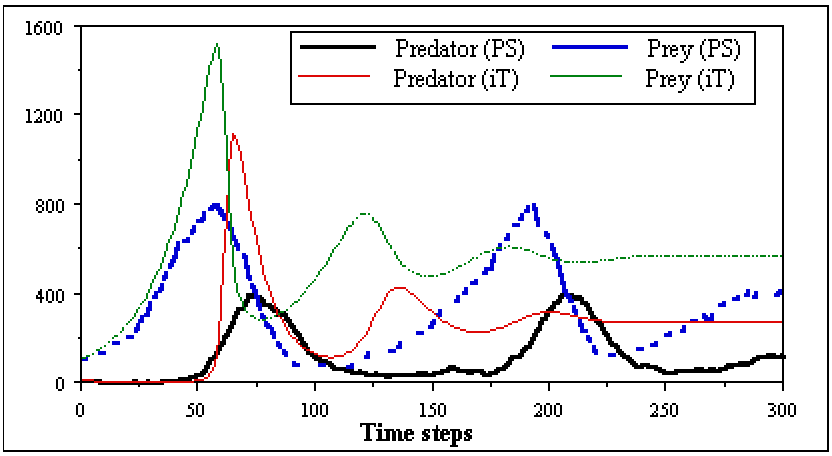

Figure 2-14: A comparison between CA model run and the iThink model run.

The distinctions between CA and Agent-Based modelling can be seen in many parts. First, Agents have more freedom to navigate and explore their spatial environments than the individual finite state machines that comprise CA are, simply because their spatial behaviour is not constrained by a lattice and interaction can be mediated beyond the neighbourhood.

Second, Agents possess true mobility within their virtual spaces, some discrete confines that separate them from the environment in which they exist. This boundary need not be cellular, although this is one of the forms that agents may take. In this way, agents can be designed to mimic, for example, any urban entity (e.g., individual inhabitants, businesses, vehicles, etc.), allowing for a much richer range of spatial processes to be represented than is possible in CA.

Third, in CA, information exchange is mediated through the neighbourhood. While in Agent-Based models, the exchange of information is much more explicit (Figure 2-15). Agents can communicate with other agents as well as with their environments. Indeed, specific computer languages and protocols have been devised to cater to agent communication, e.g. Knowledge Query and Manipulation Language (KQML). The potential channels for interaction are therefore much greater within Agent-Based models when compared to CA.

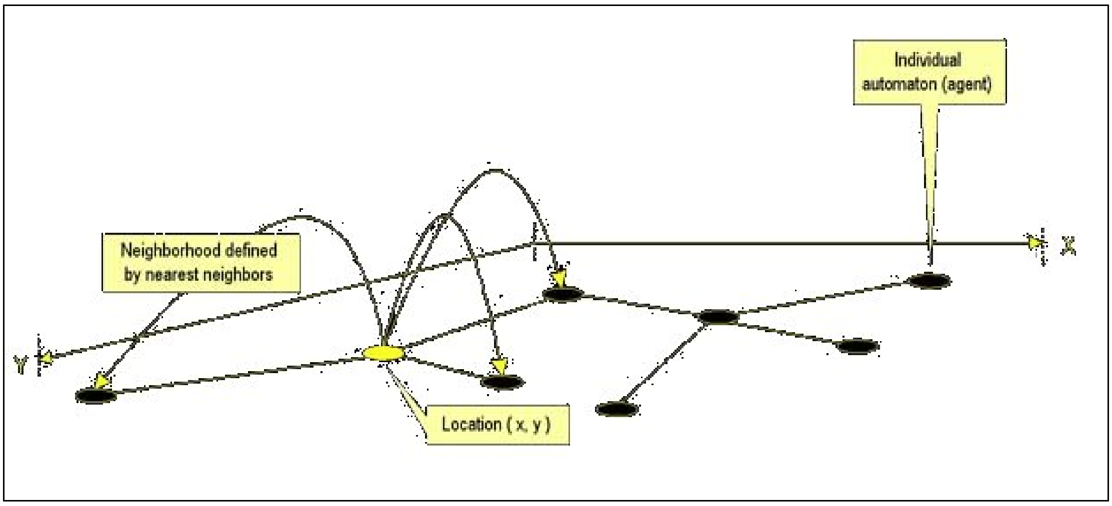

Figure 2-15: The exchange of information in Agent-based models.

Reynolds also makes clear the relationship between Agent-Based systems and CA by stating that "There is an overlap between individual-based models and cellular automata. Certainly, cellular automata are similar to spatially explicit, grid-based, immobile individual-based systems. However, CA models are always homogenous and dense (all cells are identical), whereas a grid-based individual-based model might occupy only a few grid cells, and more than one distinct individual might live on the same grid. Perhaps the significant difference is whether the simulation's inner loop proceeds cell-by-cell, or individual-by-individual. The philosophical issue is whether the simulation is based on a dense and uniform dissection of the space (as in a CA), or based on specific individuals distributed within the space" [Reynolds, 1999].

Challenges Facing Cellular Models

Camara *et al.*, (1994) stated that Cellular Automata appear to be a promising approach to simulate spatial phenomena. They concluded that in some situations (e.g. water quality and forest fire propagation modelling) the results obtained with cellular automata were similar to the ones obtained with the traditional models. They proposed cellular automata models to replace differential equation based models [Toffoli and Margolus, 1987]. However, these attempts show that for process-based models, the definition of cellular automata transition rules might be cumbersome. Future practical application of cellular automata in these cases will certainly require built-in transition rules.

For a predator-prey problem, the cellular automata model has used a simple transition rules. For this problem, transition rules such as attraction and repulsion will have to be developed. Naturally, the spatial nature of the cellular automaton model made it produce different results from the conventional differential equation lumped model.

Future developments should not be centred only on transition rules. The modelling of more complex systems will require the handling of a larger number of interacting bit planes. Extensions to three dimensions may be also relevant for a number of environmental applications.

Finally, cellular automata concepts may be extended to simulate real or symbolic multidimensional objects. Camara’s work points towards that direction by simulating pictorial objects defined by position, size and colour. Future work should also take into account the shape of objects (basically a set of connected cells).

2.4.5 Fields of Application and Tools

System Dynamics modelling has been used in a wide range of fields such as biology, ecology, economics, education, engineering, medicine, public administration and policy design, law, business administration, psychology, sociology, the military among others. System Dynamics has become popular when its general principles of feedback thought were presented to a wider audience under the label of systems thinking [Senge, 1990]. However, systems thinking can ultimately not be applied without rigorous modelling.

The three popular SD modelling tools are Stella, Powersim, and Vensim. **Stella** is one of the older simulation packages that widely used in K-12 to graduate education. Students, teachers, and researchers use Stella "to render, then test, their mental models of everything from how a bowl of soup cools to how a galaxy expands…and everything in between" [STELL URL]. A second modelling package is **Powersim** that is "used to create models of processes and competitive markets, demonstrate strategies and identify leverage points for managing change" [Powersim URL]. The modeller can also "import historical information, experiment with future scenarios and develop the best long-term strategy". A third modelling software package is **Vensim**, which is used for developing, analysing, and packaging high quality dynamic feedback models [Vensim URL]. Models are constructed graphically or in a text editor. The features provided by Vensim include: dynamic functions, subscripting (arrays), Monte Carlo sensitivity analysis, optimization, data handling, and application interfaces.

Agent-Based models are applied to an equally wide range of fields as System Dynamics modelling. Typical fields are ecology, biology, anthropology, artificial societies, psychology, sociology, economics, traffic and vehicle simulations, animation and interactive media, and the military applications. There are currently at least three development toolkits that help develop and implement agent-based models: **Swarm** was originally developed at the Santa Fe Institute. It is a package for multi-agent simulation of complex system and a "tool for researchers in a variety of disciplines, especially artificial life. The basic architecture of Swarm is the simulation of collections of concurrently interacting agents" [Minar *et al.*, 1996]. **Echo** is another package widely used for ecological simulations. It is a simulation tool developed to investigate mechanisms that regulate diversity and information processing in systems comprised of many interacting adaptive agents, or complex adaptive systems (CAS) [Echo URL]. **XRaptor** is a third tool, which is an environment for simulation of scenarios in continuous virtual multi-agent worlds. It is written in C++. XRaptor allows studying the behaviour of agents in different 2D or 3D continuous worlds [XRaptor URL].

2.4.6 Relative Strength and Weaknesses

The major differences between the modelling disciplines also mark their relative strengths and weaknesses. In SD modelling, the feedback loop is the unit of analysis as seen earlier. Dynamic systems are deductive, in that, they are described by their feedback structure at an aggregate level. That is, individual agents or events do not matter much in SD models, since the dynamics of the underlying structures are seen as dominant. Feedback structures, for example in social science fields of study, can become subject to controversy since perspectives on a problem and perceptions thereof may differ widely.

Constructing models, hence, is a process in which expert consensus regarding the feedback structure is essential to the credibility of any given model. If the feedback structure of a model captures the structure of a system insufficiently, the resulting insights may be faulty, even if the model matches historical data of the modelled system to some degree.

On the other hand, if the model does represent the systemic problem sufficiently, leverage points for intervention can be identified fairly effectively. This, however, is not possible at an individual rather than an aggregate level.

Agent-Based modelling focuses on individuals who interact on the basis of generally simple rules. The resulting emergent behaviour of such agents as a complex system is the basic unit of analysis. The approach is inductive. The researcher may modify rules and environmental parameters and then try to understand what the resulting outcomes are with regard to the emergent behaviour of the overall system.

As long as rules are known or can be discovered by some sort of observation, the modelling and testing of such emergent structures is a relatively straightforward process. However, once the reverse direction of study is employed, that is, a complex aggregate behaviour of a system has been observed, and now its agents and the rules by which they interact shall be identified, the process can be anything but straightforward. "Discovering" agents and rules and then building a model, which in turn is capable of mimicking the previously observed dynamic behaviour, may become a very tedious avenue of research. If rules and agents are identified, leverage points can be found at an individual level that may influence the complex aggregate behaviour of a system significantly.

Both techniques aim at discovering leverage points in complex aggregate systems, modellers of agent-based models seek them in rules and agents, while SD modellers do so in the feedback structure of a system.

2.4.7 Concluding Remarks

System Dynamics and circular causality on one hand, and Agent-Based and complexity theory on the other hand, have both produced rich bodies of research and literature on widely overlapping fields of application. Both have a high capacity of explanatory power. The cross study of these bodies of literature is overdue. Results on identical or neighbouring research topics must be compared.

Individual-based modelling and aggregate feedback modelling may complement each other in ways that are unimagined from today's perspective. The comparison of results in the same subject areas will most probably lead to some fine insights. It would also be desirable to see an Agent-Based implementation for some SD classic models such as the "beer game" which, in particular, may have the potential to become a classic in the agent-based modelling field as well. Testing techniques are a starting point for more active and mutually influential collaboration [Senge, 1990; Singe et al, 1994].

2.5 Object Orientation

“Object-oriented methods cover methods for design and methods for analysis. Sometimes there is an overlap, and it is really an idealization to say that they are completely separate activities” [Graham, 1994].

In searching for a more effective model to represent the dynamic world, Peuquet and Duan (1995) proposed an *Event based Spatial-Temporal Data Model* (ESTDM) for temporal analysis of the geographical data. The data model takes into consideration the changes to the location and/or other properties associated with the time-line.

Among many methodologies proposed, the approach that is repeatedly proposed as a better solution for modelling the dynamic world is the object-oriented paradigm. Tang *et al.,* (1996) proposed a system based on geographic features, in which the semantic feature objects form the basis of the system. Geographic locations are properties of the geometric objects that are encapsulated by the semantic features. Takeyama and Couclelis (1997) presented a similar design philosophy. Both were applied to a cellular automata system.

Raper and Livingstone (1995) outlined another design for modelling natural processes. The design bases the representation of real world on form, process, and material objects. Geographic location and time are treated as properties of the objects. They claimed that both feature-based and time-based designs allow easier handling of spatial and temporal dynamics of entities or phenomena. These designs, and especially the ones that focus on features in dynamic progress, are particularly adaptive to modelling processes. This design is consistent with the vision of the Open-GIS consortium as well [OGIS, 1996; Buehler and McKee, 1996].

Object-orientation is perhaps the most effective framework that can embrace both System Dynamics and GIS models in a single coherent information system because both geographical features (spatial entities) and system components can be represented as Objects that have properties and behaviours (methods).

Conceptually, within the Object Oriented framework, the entities of the phenomena of interest form the essential objects. These objects are linked through associations. The location (represented by geographical coordinates) and the time (represented by points in time and/or time intervals/step) are the properties of the objects. Methods are actions that object execute when certain event occurs. Thus, with the time advance, object may change/update its location (executed by way of its methods) that explicitly leads to state-change of an object. Issues such as incompatibility in data resolution, spatial-temporal handling, and dynamic (runtime) simulation can be adjusted due to the flexibility of this framework.

Practically, the Object Oriented framework supports reuse of object class libraries, effective spatial and temporal queries, easy interfacing with visualization, and flexible customization. These technical advantages support the realization of component ware, a concept and practice that is foreseen as the future of the GIS by many researchers (e.g. Open-GIS consortium), and the future of the environmental modelling as well [Buehler and McKee, 1996].

2.5.1 A Brief History of Object Orientation

Object Orientation appeared in the early 1960s as a result of the efforts of Dahl and Nygaard, at the Norwegian Computing Centre in Oslo, in creating and implementing new concepts for programming discrete simulation applications. By year 1965 they developed Simula[5] on the basis of the ALGOL-60 language, which was specifically oriented towards discrete event simulation [Dahl *et al.*, 1966]. Later, in year 1967, the same Norwegian team has developed the programming language Simula-67 [Dahl *et al.*, 1968], once again an extension of ALGOL-60.

Simula-67 introduced the basic concepts that characterise existing object-oriented programming languages. In particular, the notion of an object class defined by its type and the algorithms necessary to represent its actions. It also introduced the inheritance mechanisms through which an object class could inherit the data and the algorithms from other object classes.

The concepts introduced by Simula-67 were widely recognized after the mid-1970s. The programming language Smalltalk, a result of the work accomplished by Kay, Goldberg, Ingals and others at the Xerox Research Centre at Palo Alto (PARC), was established as the purest representation of object-oriented concepts [Wachowicz 1999]. In Smalltalk everything is perceived as an object, and objects communicate with each other by passing messages. Having its origins in Simula and the doctoral research work of Alan Kay, Smalltalk has evolved by integrating the notion of classes and inheritance from Simula as well as the functional abstractions flavour of LISP[6].

There have been five releases of Smalltalk running from Smalltalk-72, launched in 1972, to Smalltalk-80, launched in 1980. The other three releases were launched in 1974, 1976 and 1980. Smalltalk-V and Smalltalk-AT have also been created as dialects from the former Smalltalk developments [Krasner, 1981]. Generally, Smalltalk is a complete programming environment, offering features such as editors, a class hierarchy, browsers and many of the features of a fourth-generation language [Graham, 1994]. According to Booch, “Smalltalk is perhaps the most

[5] SIMULA [Dahl et al., 1970] - is the first simulation language and contains some constructs, which are embryonic forms of those found in the object oriented programming paradigms.

important object-oriented programming language, because its concepts have influenced not only the design of almost every subsequent object-oriented programming language, but also the look and feel of graphic user interfaces such as the Macintosh user interface and Motif.” [Booch, 1994]

Several object-oriented programming languages have been developed, most of them having their conceptual foundations based on Smalltalk. These attempts have tried to overcome the main inefficiency problems of Smalltalk (e.g. in interpretative language, for example, the code is not pre-compiled and executed; the lack of support for persistent objects and a distributed multi-user environment) but with the pitfall of compromising the purity and consistency of Smalltalk's features. Over 100 object-oriented programming languages have been developed over the past decade. However, as Stroustrup points out: “One language is not necessarily better than another because it has a feature the other does not - there are many examples to the contrary. The important issue is not how many features a language has, but that the features it does have are sufficient to support the desired programming styles in the desired application areas” [Stroustrup, 1988; 1998]. Object-oriented programming languages are still being developed and it is expected that new languages will emerge, acquiring new features rapidly.

The research and development in artificial intelligence (AI) programming environments (from mid-1970s) have also influenced the object-oriented paradigm. LISP is one of the main programming languages used in AI systems, and several object-oriented extensions of LISP have been created. LOOPS, Common LOOPS, FLAVOURS, KEE, ART and New FLAVOURS are some examples in which a semantically ample form of inheritance is proposed that differs from the one encountered in most object-oriented programming languages such as Smalltalk. In these cases, values, in particular default values, can be inherited as well as attribute names [Graham, 1994].

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[6] LISP stands for list processing, originally developed by John McCarthy in 1958 and more recently it has been used in artificial intelligence work.

With the maturing of the concepts in object-oriented programming languages and their practical use in various application contexts, research interests have diversified. Focusing on object-oriented design methods, Booch stated: *"Object-oriented design is a method of design encompassing the process of object-oriented decomposition and a notation for depicting both logical (class and object structure) and physical (module and process architecture) as well as static and dynamic models of the system under design."* [Booch, 1994]

Significant debate has arisen in this research area concerning whether an object-oriented design method can be intrinsically independent of any programming language, or whether current design methods are intrinsically associated with specific object-oriented programming languages. Most object-oriented design methods reveal the influence of Booch's pioneering work [Booch, 1986]. In his original proposal, Booch suggested a design method based on some features of the ADA programming language, using an object-oriented style. GOOD[7] and HOOD[8] are examples of ADA-derived methods that enforce the top-down hierarchical decomposition approach among objects but without the support of inheritance and polymorphism.

Also influenced by Booch's work, OOSD[9] provides a hybrid, low-level notation for logical design of object-oriented methods in general. Although designed to be an independent language, OOSD has not been extended to a consistent object-oriented notation due to its inability to deal with complex data structures and large numbers of methods. OODLE[10] is another example of a language-independent notation, which advocates four interrelated diagrams in order to support the Shlaer-Mellor approach to object-oriented design. Booch's revised design method [Booch, 1991; 1994] probably gives probably the most incisive and comprehensive prospect of an object-oriented design method. His method improves the concepts of

[7] General Object-Oriented Design method developed at NASA.
[8] Hierarchical Object-Oriented Design method developed at the European Space Agency.
[9] Object-Oriented Structure Design introduced by Wasserman, Pircher and Muller (1990).
[10] Object-Oriented Design Language is a design-specific component of the Shlaer-Mellor method (Shlaer and Mellor, 1988).

object orientation and their respective notations as a whole, overlapping with the concepts of object-oriented analysis.

Other research innovations have emerged from the synergy between object-oriented programming and database management systems. This has generated a potential mechanism for representing, storing, organising, sharing and recovering objects that include multiple complex data types and associated methods and functions. Object-oriented database systems (OODBS) have developed capabilities such as persistence, long transactions and versioning, unlike most traditional relational database management systems. By combining database functionalities with object-oriented programming, OODBS has become an expressive device for multimedia applications, client-server systems as well as GIS, CAD, engineering and manufacturing systems.

Object-oriented databases have emerged as commercial products. ONTOS,[11] O2,[12] GemStone,[13] ObjectStore[14] and ORION[15] are some examples of object-oriented databases, although their capabilities can differ widely. These object-oriented databases have in common basic characteristics such as methods associated with objects, inheritance of attributes and procedures from super-types (super-classes), and the ability to define the type (class) of objects, their attribute types and relationships. However, they differ substantially in their query languages. The significant differences between them probably result from the fact that OODBS have been elaborated using programming languages for their data models as points of departure. Sometimes declarative query languages are only introduced after the initial implementation. *"The lack of a standard or a formal background for object-oriented*

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[11] ONTOS is a product of Ontologic, Billerica MA, which enhances C++ with persistent objects.
[12] O2 is a commercial product of GIP Altair, Le Chesnay, France. It reveals strong Prolog influences.
[13] GemStone is a product of Servio Corporation, Alameda CA and Beaverton OR. It has been built onto an extension of Smailtalk-80 known as OPAL.
[14] ObjectStore is a product of Object Design, Burlington MA, based on C++ programming language.
[15] ORION is a commercial product of Itasca Systems, Minneapolis MN, which extends LISP with object-oriented capabilities.

query languages has caused differences in query language syntax, completeness, SQL compatibility and treatment of encapsulation" [Cattell, 1991].

Object-oriented databases also offer the possibility of storing and manipulating all data pertaining to a GIS application in the same manner. By contrast, in relational databases, spatial data cannot be so readily stored and their integration with other systems is cumbersome. Chance, Newell and Theriault (1992) advocate the benefits of object-oriented concepts in developing a seamless environment. In the case of ArcGIS, object-oriented database capabilities have been implemented by front-ending a version-managed tabular data store with an object-oriented language named VBA (Visual Basic for Applications). In this environment, system programming, applications development, system integration and customisation are all written using the same object-oriented programming language, VBA. *"Object-orientation does not just mean that there is a database with objects in it, but that the system is organised around the concept of objects which have behaviour (methods)"* [Chance, Newell, and Theriault 1992].

Following the proliferation of research on object-oriented programming and database management systems, object-oriented *analysis methods* have been gradually developed as an approach to improving our understanding of the concepts, activities, rules and assertions of the object orientation paradigm. *"Object-oriented analysis is a method of analysis that examines requirements from the perspective of the classes and objects found in the vocabulary of the problem domain"* [Booch, 1994]. Within the object orientation paradigm, methods developed for design are frequently applicable to analysis, and vice versa.

Computer Aided Software Engineering (CASE) has become increasingly important as a graphical tool for supporting object-oriented analysis and design methods. CASE tools have been variously regarded with enthusiasm or with scepticism regarding whether there is any advantage to be gained through their use.

An increasing number of software products for CASE tools are under development based on the composition of graphical symbols and notations depicting the semantics and features from the object-oriented analysis and design methods. The most important benefits of using CASE tools are their ability to generate code automatically and enhance productivity. However, CASE tools can restrict innovative kinds of application, where the rules and methods provided by CASE tools are inappropriate or even non-existent. The main examples of CASE tool systems available in several platforms and operating systems are the ROSE tool supporting Booch's method. Object Maker supports a vast range of conventional and object-oriented methods including Booch, Coad-Yourdon, Shlaer-Mellor, Rumbaugh-Hood. OOA-Tool supports Coad-Yourdon method.

Object-oriented paradigm (with its origins in computer simulation domain) is perfectly suited to the fundamental requirement for the GIS applications. A GIS should facilitate abstract representations of real world objects that are understandable and easy to use. It is natural to represent spatial entities as objects in the application. The paradigm also greatly reduces the problem of redundancy as it supports the usage of the same model in different phases of application development. GISs request persistence storage of objects. Therefore, the ideal solution is to use an OODBMS to store data.

2.5.2 Object Oriented Concepts

Object-oriented programming uses fundamental constructs called objects to represent real-world concepts. An ***Object*** is an abstraction of an entity in the real world. It reflects the information about the entity and methods for interacting with it. Objects possess both a data structure and behaviour. An object’s data structure is described by its properties or attributes. A *property* is a descriptor for an object that may take on different values. For example, a river object could be described by a width property. An object’s behaviour is also known as its methods or operations. A *method* is a task that an object performs in appropriate situations. For instance, a river object might have a method that routes a hydrograph through it. A ***Class*** is a description of a set of objects describable with a uniform set of attributes and methods. A class therefore represents a generalization of a set of objects with common properties and behaviour. Objects are instantiated (generated) from this description.

Object-oriented development is a *thought process* and is largely independent of its actual implementation in a programming language. By focusing first on the design of objects rather than implementation, designers can create objects that best model the relevant aspects of their real counterpart. An object-oriented approach generally includes four concepts: identity, classification, polymorphism, and inheritance [Rumbaugh *et al.*, 1991].

Identity refers to the quantification of data as discrete objects. Objects can represent both concrete entities such as a reservoir, or concepts such as a reservoir operating policy [Rumbaugh *et al.*, 1991].

Classification refers to the grouping of objects with the same properties and methods into a class. The class defines the properties and methods for the objects, with each object representing an instance of the class. In a water resources application, an example of a class might be a reservoir, while the High-Dam Lake would be example of reservoir object. Although each reservoir object contains the same properties, such as the name of its managing agency, the values of the properties may differ [Rumbaugh *et al.*, 1991].

Polymorphism means that different classes may implement the same behaviour in different ways. For instance, a reservoir object might perform a flood routing operation differently than a river object. Polymorphism allows new classes to utilize existing operations without the need for rewriting code, as long as each new class contains the code it needs to handle the operation [Rumbaugh *et al.*, 1991].

Inheritance refers to the hierarchical sharing of properties and methods among related classes. Properties and methods common to several types of objects can be grouped into a superclass, also known as a parent class. Subclasses, or child classes, can then inherit those properties and methods in addition to defining their own. For example, a waterbody could be modelled as a superclass, with subclasses of river, lake, and fishpond. Each subclass may have a fish count property, while the lake and fishpond classes may also define a surface area property. Some superclasses are useful for grouping properties and methods, but are never used to instantiate objects of their own. These classes are called abstract classes. By grouping common properties and methods into superclasses and then utilizing inheritance, repetition in a program is greatly reduced [Rumbaugh *et al.*, 1991].

From an implementation point of view, there are some other concepts that we consider fundamental. Here we briefly list them alongside with their definitions.

Object identification enables each object to be uniquely distinguished from all other objects in the database. An object identifier (OID) is generated by the system at the moment when the object is being created, independently of the values of its attributes. OID is immutable, that is, stable for the lifetime of the object. An OID is dropped only if the object is destroyed; furthermore, it should be used only once in the database in order to be associated with only one real-world object.

Encapsulation is the principle that enables an object to hide its structure and/or behaviour from other objects. Internals of an object are accessible only via its interface that is the operations known by the system. In this way, the external properties and methods of an object (those visible to other objects) are separated from the implementation details of the object (that are hidden from other objects). By internalizing the implementation details, a system becomes much easier to maintain. The designer can change the implementation (for instance to fix a bug or improve efficiency) of a particular object's methods without having to change the way those methods are called by other objects [Rumbaugh *et al.*, 1991].

Association enables specifying relationships that exist between various objects in the database. Associations may be expressed explicitly in some OO models, while in others they are represented as reference attributes. In the latter case, the value of a reference attribute is the OID of the associated object. Additionally, some OO models have the construct of *ordered association* that takes into account the order of the association objects.

Version control is often needed in non-traditional areas, where different "versions" of the same object may be important. For example, in GIS applications it can be the case that the boundary of some spatial object changes over time (e.g. agriculture area, lake, etc.), so information about the previous state (version) and the new state of the same object is required. Usually, versions are implemented as different objects, which means that they will have different OIDs

The main advantage of the Object-Oriented paradigm is how well it facilitates a systems understanding; it enables what many end-users consider a "natural" representation of real world objects, their mutual relationships and behaviour. Object-Oriented applications are easy to maintain because they are modular and objects are independent of each other; a change in one object should not affect other objects in the system. The paradigm supports reusability: objects are self-contained and may be reused in other similar applications. It also supports distributed and parallel processing.

Microsoft has taken the lead in creating and developing various object oriented applications. In order to make these applications communicate efficiently, they have to setup some standards and/or protocols. COM, that stands for Component Object Model, is a binary specification standard devised by Microsoft that allows compliant software to utilize the object libraries of other COM-compliant software. COM itself is not a programming language, although languages such as C++ and Visual Basic lend themselves towards COM-compliant software design. Rather, COM provides a standard set of rules for developing software such that components from a program with a COM-compliant design can access components from other COM-compliant programs, regardless of the language in which each program was developed.

COM may be most evident within the Microsoft Office applications of Excel and Word. Because each application can utilize the object libraries of the other application, each can incorporate useful components from the other application into its own documents. For instance, copying and pasting a range of Excel cells from a spreadsheet or a chart into a Word document is an easy operation and produces no error. In fact, Excel's charting capabilities are directly linked to Microsoft Graph, another COM-compliant object library distributed with Microsoft Office.

The COM-compliant design and encapsulation allow components of an object oriented system to be compatible with other programs, regardless of the programming language or implementation details of those components. One way in which this is accomplished is through the incorporation of DLLs into a software system. A DLL, or dynamic linked library, is a set of objects, functions, or routines that operate in the same process space as the calling application. By including a DLL from another COM-compliant application in a particular application's software design, that application can use components from the other application that are included in the DLL. For example, when a software-developer incorporates COM-compliance into his/her designed software, the software possesses the potential to utilize components from any other COM-compliant software. This means that a purely computational model could be extended to produce graphs, prepare reports, carry out spreadsheet operations, update databases, or even upload results to a web site, while keeping the core functionality of the model relatively simple. In chapter four, we describe in details the relationship between Object Oriented paradigm and GIS and with System Dynamics respectively.

2.6 Conclusions

Different human communities are confronted with different sets of environmental problems, and even if they had the same problems, they would perceive them in different ways. Even the perception of the prevailing problems within the single nation contrasts between various sections of the population. Consequently, it is difficult, if not sometimes impossible, to generate international consensus on possible solutions. Yet, there are environmental problems that threaten all mankind alike that are recently attracted attention worldwide. Such problems include: climatic change, non-renewable resources depletion, changes in atmospheric transmission of radiation, and changes in populations of animal and plant species. This makes the prediction and analysis of the environmental impacts and the associated risks, the bases for a rational management of our environment, a task of increasing global importance.

Environmental modelling, as one of the scientific tools that facilitates this prediction and analysis, is a well-established field of research with more than a hundred years of modelling history [Maidment 1993]. The environmental processes in the real world are typically three dimensional, time dependent, and complex. Such complexity can include nonlinear behaviour, stochastic components, and feedback loops over multiple time and space scales. With the advent of digital computers, numerical simulation models as well as spatially distributed models became feasible. Early linear models, applications of system dynamics to ecological problems, and ever more complex multi-compartment models like CLEANER and MS. CLEANER were developed [Fedra 1994].

Environmental problems do have an obvious spatial dimension. Within the environmental modelling domain, this was addressed by spatially distributed models, which describe environmental phenomena in one dimension (e.g., in river models), two dimensions (land, atmospheric, water-quality models, and models of population dynamics), or three dimensions (again air and water models). The increasing development and use of spatially distributed models replacing simple spatially aggregated or lumped parameter models is, at least in part, driven by the availability of more and more powerful and affordable computers [Loucks and Fedra, 1987; Fedra and Loucks, 1985]. This approach contributed significantly evolving the hydrological modelling, which is one of the active areas of research within environmental modelling domain.

The waters of the Earth are so extensive, their motion is so complex, and so much about what happens in hydrology is determined by the flow environment through which the water passes, therefore, GIS is extremely required. It is probably true that the factor most limiting hydrologic modelling is not the ability to characterize hydrologic processes mathematically, or to solve the resulting equations, but rather the ability to specify the values of the model parameters representing the flow environment accurately. GIS would help overcome that limitation.

Hydrologic phenomena are driven by rainfall and are thus always time dependent, even though by taking snapshots at particular points in time or by time averaging over long periods, a steady-state model can be created. To accomplish a complete linkage between GIS and hydrologic models would require GIS to have time-dependent data structures so that the evolution through time of the spatial distribution of hydrologic phenomena could be readily observed.

The concept of spatial analysis, as practiced by geographers and incorporated into GIS, has the goal of interpreting spatial data; that is, one is presented with a set of spatial features and associated descriptive data and one seeks to determine the patterns inherent in these data and by making intelligent queries of the data to define the optimal locations for activities. The concept of spatial analysis as practiced by hydrologists and incorporated into hydrologic models is that there are equations that govern the motion of water through the spatial domain, and one uses these to infer what the flow and transport patterns will be in a particular circumstance with a model. These are two very different concepts of spatial analysis, but they are complementary, and if they can be brought together more closely through the integration of GIS and hydrologic modelling, both GIS and hydrology will be strengthened.

One of the GIS functions that is extremely needed in the environmental modelling, and it still does not do well, is to perform simulation modelling. For that reason, linking simulation models with the GIS is seen as an area of interest to many researchers. This problem is part of the larger problem that deals with systems integration and linking applications to each other.

The architecture of the GIS data model determines how easy or difficult it is to couple GIS and environmental simulation models. [Nyerges 1991a; 1991c] and [Wehrend and Lewis 1990] described different coupling environments based on the nature of the models and the GIS involved. Coupling environments can range from loose to tight coupling depending on the compatibility of the data constructs and the software operations used to process them. A loose coupling involves a data transfer from one system to another. A tight coupling is one with integrated data management services. The tightest of couplings is an embedded or integrated system, where the GIS and models rely on a single data manager. Embedded systems have been shown to be either too superficial for solving problems or too complex in their development. Since embedded systems require a substantial amount of effort, and are developed for selected user groups, they tend to be rather expensive, and constraining when changes are desired.

Nyerges (1991b) also reviewed several trends in data, software, and hardware that collectively represent frontiers of GIS development. Whether or not these developments are fostered by frontiers of GIS use remains to be seen. One significant development involves temporal aspects, both for data representation and processing. Recent efforts [Armstrong, 1988; Langran and Chrisman, 1988; Langran, 1993] have produced valuable contributions, but concepts that form the basis of design suggestions for software architecture are still needed. When these developments are incorporated into commercial GIS then we will see substantial progress in pushing back the GIS frontier as related to environmental modelling. Such progress could in fact be almost as significant as the maturing of space-only based GIS. Coupling simulation models to the GIS is required at the current time because no GIS currently has the data representation flexibility for space and time, together with the algorithmic flexibility to build simulation models internally. Coupling models to GIS depends on the compatibility of the software architectures.

In summary, the integrated systems approach for developing and testing environmental simulation models suggests potential links to GIS technology. In conceptual terms, GIS seem well suited to address data and modelling issues that are associated with a modelling environment that includes multiscale processes, all within a complex terrain and heterogeneous landscape domain. GIS can help address data integration questions associated with multiscale data from ground-based and remote sensing sources. GIS could potentially support exploratory analysis of complex spatial patterns and environmental processes. Finally, these advanced environmental simulation models require detailed spatial data, which provides an opportunity for innovative thematic mapping and error analyses with a GIS. However, there is much to be done to meet the needs of the modelling community.

Chapter 3

Literature Review

The Prior Work Of Integration

3.1 Introduction

In this chapter we describe the efforts that have been made to integrate the simulation models with the geographical information systems in a number of knowledge domains using different methods and techniques. From a broader perspective, the basic concept (shared among these efforts) is to incorporate the temporal dimension with the spatial dimension to produce an integrated spatial simulation model (or system). In this context, two points should be made clear:

First, the “simulation models” in the coming examples are not limited to system dynamics models. In fact, the majority of the simulation models reported in literature are mathematical models (also known as dynamic simulation models). They are similar to SD models in that they are dynamic, nonlinear, and sometimes stochastic models. However, they differ from SD models in that they are physically based models which include sophisticated mathematical equations/formulations (e.g., second order partial differential equations, Markov chains[16], covariance[17] and/or Leslie[18] matrices, etc.), whereas SD models include a combination of differential equations (for stocks) and algebraic formulations (for auxiliaries). Furthermore, their ultimate goal is to gain more understanding of the physical processes within the modelled systems (although they may be used for prediction purposes like weather forecasting models) but they do not intend to be used for designing policies the same way as SD models do.

Second, the raster based GIS are extensively employed in theses attempts rather than vector based GIS. This is maybe because of the nature of the problems

[16] In mathematics, a Markov chain, named after Andrei Markov, is a discrete-time stochastic process with the Markov property. Having the Markov property means that the next state solely depends on the present state and doesn't directly depend on the previous states.
17 In statistics and probability theory, the covariance matrix is a matrix of covariances between elements of a vector. It is the natural generalization to higher dimensions of the concept of the variance of a scalar-valued random variable.
18 The Leslie Matrix is a discrete and age-structured model of population growth very popular in population ecology. It is used to model the changes in a population of organisms over a period of time.

that have been modelled and/or the best way of representation for the associated spatial features. Noticeable, the majority of these efforts have taken place in knowledge domains such as ecology, biology, oceanography, or atmosphere and biosphere at large. Social systems as well as urban and sustainable development problems have been rarely addressed.

In terms of classification, we can distinguish between two types of attempts: (1) the work that have been made by academic individuals (e.g., Master thesis, PhD dissertation, published papers, etc.) and, (2) the work that have been made by teams or organizations (e.g. as projects in research institutes, IT companies, and software vendors). The effort of an individual is commonly an academic activity and usually limited by time and budget, while the efforts by institutions have, in most situations, a larger budget and time may be extended. In this sense, it is not rational to compare between these two types of efforts and their outcomes, rather, the focus should be on the integration methods and techniques that have been used.

In terms of their relevance to this research, two types of attempts can be distinguished: (1) integrated systems that included System Dynamics simulation models and, (2) those systems that included mathematical simulation models (i.e., physically based process models). There is also a number of attempts aimed at developing specialized software (simulators) pertaining to hydrology and water resources management are being described in the last section of this chapter. Although one may argue the relevance of these examples, however, we believe that they have made a remarkable contribution to the integration methods and techniques. The objective is to understand the integration challenges and to highlight the difference between the work in this research and the work that have been done so far.

Therefore, the chapter is organized in the following way: in the first section, we list a number of individuals' attempts to integrate SD models with GIS and then the other simulation models with GIS. In the second section, we describe noteworthy software that has been developed at large research centres and federal organizations worldwide. In literature, the integration of simulation models with GIS (or say the integration attempts and the issues related to them such as integration methods, techniques, and strategies) has extremely influenced and overwhelmed by those models evolved through the environmental modelling domain (e.g., hydrologic, water resource management, oceanography, and weather forecast models) and the ecological modelling domain (e.g., landscape, marine, and ecosystem models). There is some degree of overlap between these models. For example, the issues of GIS integration in hydrologic modelling clearly share some content with those in land surface/subsurface modelling. Therefore, we intend to describe one example from each domain (i.e., SME for ecological modelling, GRASS-GIS and its associated models (AGNPS, TOPMODEL, and SWAT) for overlapped disciplines, IDLAMS for landscape modelling, and WaterWare for hydrological modelling). These examples are organized according to their relevance to our research too.

In the third section, we describe two simulators pertaining to hydrology and water resources management that, to some extent, have an interfacing with GIS maps. They are included in this chapter because they share the research area (i.e. water resources management) and the geographical extent (Nile basin and Delta) with our case study (i.e. the irrigation system in the Nile Delta).

Section 3.3 and 3.4 contain descriptions of some of the technical details that characterize various software packages of relevance to this work. We have found no reason to diverge in our description from the descriptions offered in the original documentation of these packages. In fact, that would easily introduce inaccuracies that would not benefit the reader of this thesis. To some extent, therefore, this section has been written as a composition of quotes from various sources. We have referred to these sources, but chosen not to use quotation marks in order to avoid making the text intransparent. The composition is made so as to establish a background for the description and evaluation of the development work documented in this thesis, including the comparison with existing software packages.

3.2 The Prior Work of Integration by Academics

The integration of the simulation models with the associated GIS capabilities for spatial data analysis and visualization has been the main concern of a number of researchers[19]. We can distinguish between two groups of researches depending on their perspective and ultimate goals. The first group consists of system dynamicists while the second group includes environmental scientists and geographers. Both groups have made considerable efforts in this area of research.

Hans D. Kasperidus (1988), a scientist among the first group of system dynamicists, has designed an integrated system dynamics model to analyse and evaluate possible future developments for high-mountain agriculture under challenging economical and ecological conditions in Berchtesgaden in Germany. The purpose of the model is to help understanding the relationship between farmers' economical activities, different landuse options, and the regional landscape attractiveness. Although he did not explain, in his paper, the procedure of linking the SD model with the GIS, he claimed that the link allowed for the translation of the dynamic pattern of landuse changes into spatial patterns. He added: "A decade after the first simulation runs, it was possible to look at the real development of the system. For this approach the original model adapted to Stella 5 environment. The predicted possible changes in landuse then compared with actual changes to prove the quality of scenario assumptions and model structures".

Singhasaneh and Eiumnoh (1991) described the gap between the GIS and the SD software as one that limits the study and in-depth understanding of any system falling into this gap. To fill this gap, they developed a system to demonstrate the integration of SD with GIS. Three SD models were used (two synthetic models and one of the Pattaya city of Thailand) to test the performance of the system. They aimed

[19] Note that system dynamics methodology utilizes simulation models and it aims at policy design and strategy development. Most of the simulation models described in this chapter are mathematical models and the integration aims at gaining insight into the analysis of spatial systems.

at demonstrating the importance of the integration by developing a complete system for the prediction of the landuse changes.

Grossmann and Eberhardt (1993) studied and compared a number of dynamic modelling techniques, including those that allowed for the representation and analysis of complex aggregated dynamic feedback models. The integration of the dynamic models and the GIS was applied in the context of "tourism and its interactions with the regional economy and the new agricultural strategies". The integration was on the conceptual level, where the dynamic model is used to describe the mechanism of attractiveness and the resulting deterioration of an area, and the GIS (that uses several different *base assessment maps)* is utilized to depict the areas where infrastructure is likely to be built and tourists are likely to reside.

Dmitri et al. (2000), at Moscow State University, developed a system dynamic based educational toolkit (called ECONET simulator) to train regional decision makers in Russia to manage the regional ecological nets of natural protected territories in a context of cross-sectional environmental-social-economical sustainable development. According to Dmitri, ECONET included 10 roles, 8 maps, and a number of software (Excel, Visual Basic, Delphi, and GIS), and offered the opportunity to run an integrated (ecological, social, and economy) model over 30 years, using three years as a time-step. ECONET embodied the ideas of SD simulation game "Poplysphere" designed by Sidorenko and Krjukov in 1997. Dmitri compared ECONET with similar existing SD-GIS-based models for sustainable regional and interregional development such as "Pangaia" developed by Kanegae and Kaneda (1995/1996), and claimed that ECONET enables the experts (i.e., federal and regional managers, and NGO leaders) to test some concepts of regional econet designs by means of simulation of spatial and temporal decisions in the three areas concerned. Dmitri claimed that: "compared to GIS-based cellular automata and artificial neural nets, this model is a new type of toolkit for researching and solving underlying problems".

At the University of Bergen, two Master students (Abraha Zewdie 1998 and Ling Shi 1999) attempted to integrate SD with GIS in their research. Zewdie studied the feasibility and the functionality of enhancing GIS with SD methods to support the understanding of the relationship between structure and behaviour of the dynamic spatial systems. He used Powersim to develop a simulation model to analyse the problem of forest depletion in Ethiopia; and PC ARC/INFO to develop the required maps. He employed Object-Oriented methods (analysis and design) to loosely couple the simulation model with the GIS through import/export Excel files. The temporal modelling techniques in system dynamics and the GIS perspective were combined. The main role of the GIS was to enhance the visualization of the dynamics of the SD model. The same way of integration (loosely coupling) has been used by Ling Shi (1999). Shi developed a "s*patial decision support system for land use planning*" to help planners to improve their policies. However, she used ArcView 3.1 and developed some scripts with Avenue (the ArcView 3.x customisation language) to facilitate the DDE (Dynamic Data Exchange) with the Excel files produced by Powersim. She applied her model to the urbanization problems in Shanghai, China.

Hallie Anthony (1998) integrated GIS with a system dynamics model of water flows in the Mono Basin [Ford 1999; Mono Lake website]. Anthony began with the Stella model of Mono Lake and re-built this model in Powersim to take advantage of Powersim's dynamic data exchange (DDE). The DDE facilitates the export of data from Powersim models to other applications such as Microsoft Excel. Anthony selected PC ARC/INFO as the platform for the GIS. She used a digital elevation data provided by USGS to create the coverage used to map the lake surface. To build an integrated system, Anthony used DDE in Powersim, VBA macros in Excel and SML (Simple Macro Language) macros in PC ARC/INFO. The initial step is to export the data originating from the Powersim model components, each representing a level of elevation in the mono lake area, via DDE to Excel. VBA macros in Excel were used to create symbol files needed by PC/ARC INFO to create lake surfaces. Each polygon in the final elevation coverage has an associated symbol, indicating water or land. The SML macros were then used to map the surfaces at the elevations found in the

Powersim model. The ARCPLOT subprogram was used to draw the elevation contours. (The resolution is one meter, the same as the resolution in the original USGS data.) The polygons were then shaded to represent land or water. The final product is a collection of maps associated with each of the elevation models emerging from the Powersim model. Anthony's maps were created and updated, one after another, so that the receding lakeshore is visually mapped at 25-year intervals in the Powersim simulation. She recommended that her system be improved for interactive studies (using the option available in Powersim to pause the simulation so as to facilitate an interaction to take place, i.e. an intervention on the part of the user of the system). The user could change a key policy variable (such as water export) during the simulation runtime, and the integrated system would respond with a new map at the next simulation step.

The second group, consisting of geographers and environmental scientists, includes Thomas Maxwell and Robert Costanza (1997). They established a research program aimed at developing a Spatial Modelling Environment (SME). Later, the University of Maryland sponsored the research and it became one of its major projects. The main purpose of the SME was to translate the set of difference equations describing an ecosystem model generated by STELLA into parallel-C code. Subsequently, several ecosystem models were developed using SME, including a non-linear dynamic Coastal Ecological Landscape Spatial Simulation (CELSS) model and the Everglades Landscape Model [Sklar and Costanza 1991]. The SME and both models are described in detail later in this chapter.

Despotakis, Giaoutzi, and Nijkamp (1993) subdivided the phenomena under investigation into two categories: geographical phenomena and economic, ecological, and social phenomena within the framework of sustainable development. They attempted to establish the missing link between these two categories by linking non-spatial models to spatial models (GIS). They developed a new system, called "dynamic GIS", and applied that system to the Greek Sorades Islands to study the conflicting objectives that appear in the area (the regional economic development and the environmental projection). They employed a non-spatial modelling tool, SPANS, for modelling spatial phenomenon while STELLA was used as a non-spatial dynamic modelling tool. To integrate these two models, a conceptual equivalence between the components of the two models was identified to facilitate the integration process. The stocks in the non-spatial model were related to each layer in the spatial model, in such a way that the spatial content of a specific layer was regarded to be stocks that change over time. The dynamic changes of the stocks over time are propagated in space using the corresponding layer in the spatial data model.

Betz *et al.*, (1998) attempted to integrate the landscape simulation model LANDSIM with GIS (ARC/INFO) to simulate the interactions between the forest fires and the forest succession, and to generate maps of predicted community types at the Bryce Canyon National Park in Utah.

Sui, Dianzhi (1993), in his PhD Dissertation, has investigated the opportunities for integrating the GIS-based spatial analysis with the dynamic modelling (i.e. he used Cellular Automata to examine the dynamics of urban spatial structures). He incorporated three urban models with GIS, to study the changes in the urban structure of Hong Kong between 1966 and 1986, and to predict the future development patterns by the year 2006 at a district level.

Gilruth et al., (1990) utilized GIS and Remote Sensing (RS) in modelling deforestation and land degradation in the Guinea Highlands of West Africa, (i.e., to simulate patterns of land clearing for shifting cultivation based on farmers' selection behaviour for new fields based on topography and proximity to village). Using GIS, the key model variables such as slopes, village proximity, site productivity, and labour are derived from maps, aerial photographs and ground data, to develop a dynamic spatial model of deforestation and land use changes. In addition, Gilruth pointed out the significance of the model in evaluating alternative strategies of landuse conversion.

From the examples illustrated above we conclude: First, the simulation models, whether SD models or mathematical models, have been used to represent the changes in the state of the system over time resulting from the dynamic interactions between the system components that may be spatially distributed. The GIS models, on the other hand, were used to represent the topological relationships between the spatial features and its attributes. Second, with the exception of the SME example, the coupling methods used in the above examples were implemented through data exchange (import/export) process utilizing an intermediate program such as Excel, Access, etc. This type of coupling is called loose coupling. Only rare efforts have been made to include the causal nature into spatio-temporal GIS. The work of Allen E., Edwards G., and Bedard Y. (1995) may be the only effort to be found in the literature, and this was merely carried through at the conceptual level. [Allen *et al*, 1995] developed a generic conceptual causal data model for explicitly representing the causal links within the spatio-temporal GIS.

3.3 The Work of Institutions and Research Centres

A number of environmental and ecological institutions and research centres have developed sophisticated software aimed at facilitating the spatial simulation modelling; some of which will be discussed in this section. One of these software is The Spatial Modelling Environment ***SME,*** developed by Thomas Maxwell and Robert Costanza at Ecological Economics Institute, University of Maryland. Moreover, there is ***GRASS*** **-** Geographic Resources Analysis Support System that has been under continual development since 1982 and has involved a large number of federal U.S. agencies, universities, and private companies. The Construction Engineering Research Laboratory (CERL) in Champaign, Illinois has developed the core components of GRASS (and later, the GRASS releases). Then there is the ***IDLAMS*** software, developed by Argonne National Laboratory, one of the U.S. Department of Energy's largest research centres. And there is the ***WaterWare*** software developed by Kurt Fedra at Environmental Software and Services (ESS) GmbH, Austria. WaterWare and a number of specialized software pertaining to hydrology and water resources management such as ***MFS,*** developed by the National Oceanic and Atmospheric Administration (NOAA), and ***NileSim*** developed by Maryland University, are discussed in section 3-4.

3.3.1 SME – The work of Ecological Economics Institute

The spatial modelling environment (SME) has been developed by Thomas Maxwell, Ferdinando Villa, and Robert Costanza at the University of Maryland to facilitate the development of ecosystem models [Maxwell et al., 1995]. SME links icon-based graphical modelling environments (e.g. STELLA) with parallel supercomputers and a generic object database. According to Maxwell, SME allows the users to create and share modular, reusable model components, and utilizes advanced parallel computer architectures without having to invest unnecessary time in computer programming or learning new systems [Maxwell and Costanza, 1995]. SME is free software that can be downloaded, including the documents, from the anonymous ftp site [ftp://iee.umces.edu/SME3]. It is associated with UNIX operating system, and there are five complementary components required in order to configure and successfully run the SME. These components are: Gnome xml, Java 1.2, Tcl 8.0 or later, NCSA Hierarchical Data Format (HDF), GRASS 4.1 or later, and the libraries MPI and SNI [SME user's guide, 2005]. The following paragraphs give a brief description of the design of the SME. A more detailed description can be found in the SME website [http://www.uvm.edu/giee/SME3/].

SME utilizes a grid-based approach to build the intended spatial landscape model. In this context, the space is represented as a uniform grid of cells[20], where each cell has an embedded SD model (i.e., STELLA) called the "unit model" which simulates the ecosystem dynamics for that cell. A variable of habitat type, for example, is used to parameterize the unit model in each cell, and the flux of information between cells takes place within the domain of the spatial landscape model as shown in Figure 3-1.

The main components of the SME have been described by its developers as the View, the ModelBase and the Driver components. Figures 3-2 and 3-3 illustrate the basic architectural modules and the flow of operations in the SME respectively.

The View component is used to graphically develop the simulation models (e.g., a number of unit models that collectively is called the front-end modules). The SME can utilize a number of graphic modelling tools such as STELLA, EXTEND, SimuLab, or Vensim [SME user's guide, 2005]. When the STELLA model, for example, is completed, the model can be run and the variables of interest can be plotted in various formats to help visualize the model behaviour. Maxwell stated: "Using iconographic modelling techniques greatly increase the ease with which the model can be changed and calibrated. The effects of changes made can be viewed immediately allowing the user to concentrate on modelling instead of computational details, greatly reducing model development time".

[20] The same approach used in Cellular Automate and Agent-Based discrete simulation models.

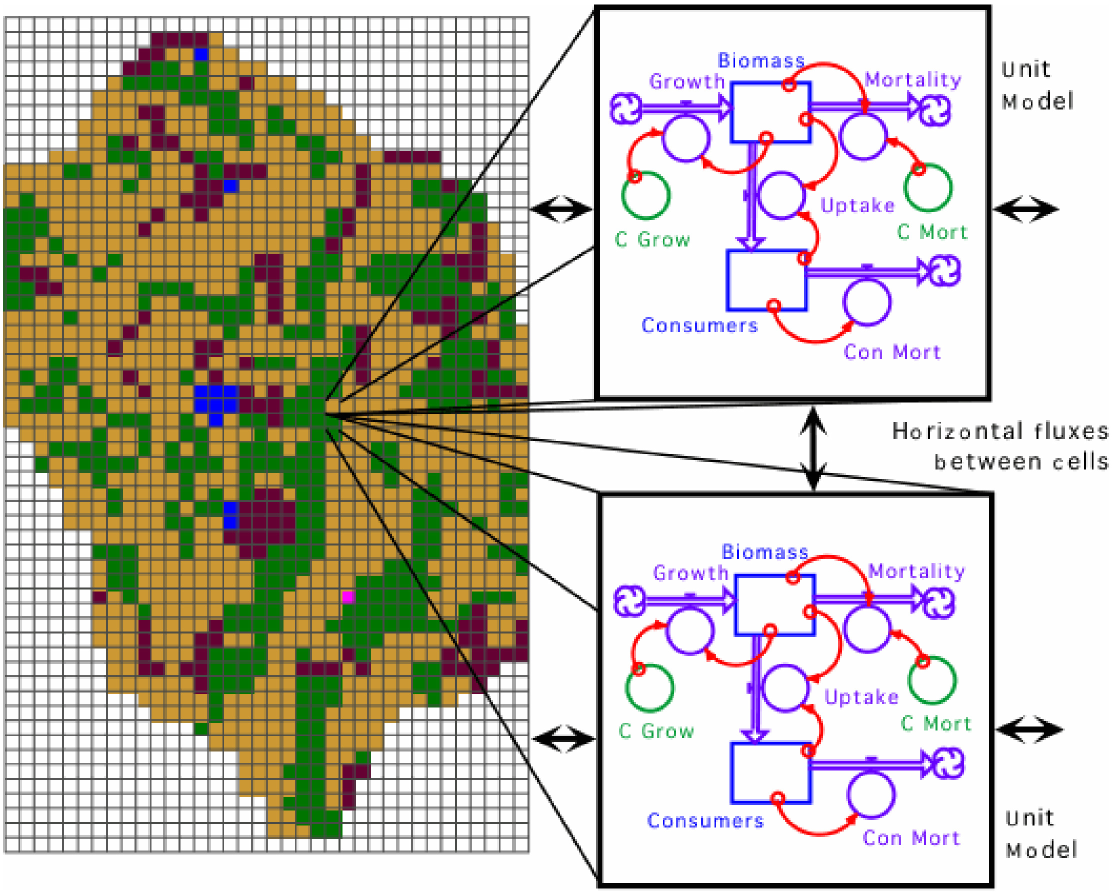

Figure 3-1: The basic structure of a spatial ecosystem model. [SME, 2005]

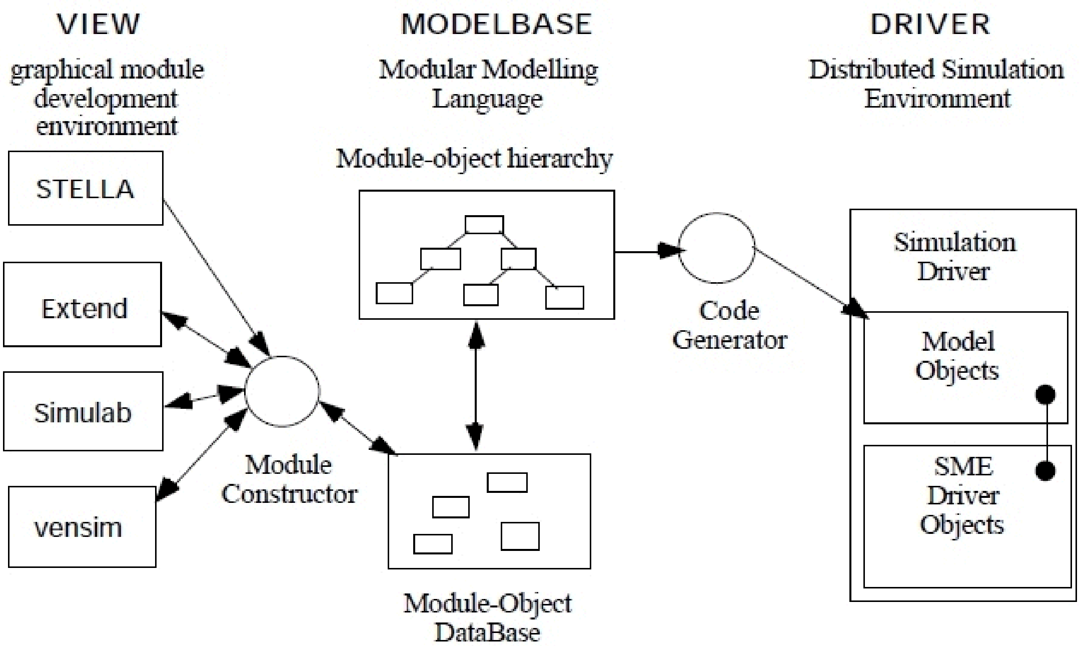

Figure 3-2: The main components of SME (View-Modelbase-Driver). [SME, 2005]

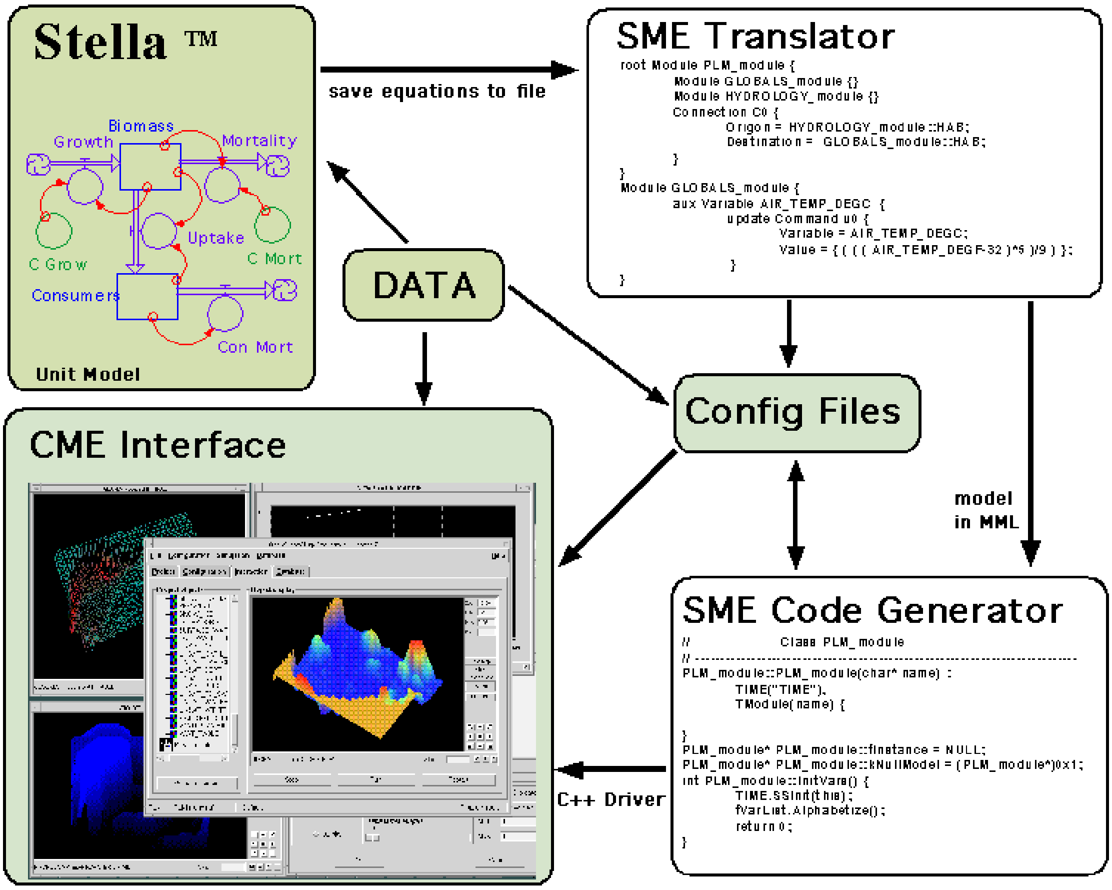

Figure 3-3: The SME Architecture. [SME users' guide, 2005]

When the front-end modules are complete, the Module Constructor translates them into a text-based Modular Modelling Language (MML). The MML modules can then be stored in the ModelBase component, or used immediately to construct a working spatial simulation.

The Code Generators convert the MML modules into a C++ object hierarchy which incorporated into the simulation Driver component. The configuration of the final spatial output takes place during this step. The configuration process includes selecting the intended variables to be displayed or mapped, and associating each MML object with a spatially oriented cell in the raster GIS map. The Code Generators also produce a set of simulation resource files that are used for runtime configuration of the model parameters, inputs, and outputs. The Driver then handles input-output of parameters, the link with the database, the GIS files, and the execution of the simulation.

Therefore, the development of the spatial simulation can be summarised in three steps. First, the SD *unit models* (front-end modules) are created in the View component, which means that the vast majority of the design work takes place in a non-spatial regime. Second, once developed and tested, the *unit models* are then linked together in the View or in the Modelbase components for a further round of tests. Implementing the spatial interactions takes place in this step by designing these interactions in the MML language, or by linking predefined methods from the Driver libraries. The Driver libraries contain methods that have been developed to implement common hydrologic scenarios including movement of water and constituents over and under the landscape surface. Finally, the assembled model (the spatial landscape model) is calibrated and verified spatially in the Driver component. The spatial aspects of the simulation are incorporated in this step. All calibration that can be accomplished without reference to the spatial nature of the system is completed in the prior steps.

SME Applications

The application of SME was first made to the Atchafalya Estuary in Louisiana in the early 1990's [Sklar et al., 1985; Costanza et al., 1990]. The model is called "the Coastal Ecological Landscape Spatial Simulation (CELSS) model". The initial modelling process began with dividing the Estuary waterscape into one square kilometre cells (the model included 2479 cells). A dynamic, nonlinear, ecosystem simulation model, with seven state variables of the waterway were then developed in each cell. The model is generic in its structure and can represent one of a six habitat-types by assigning unique parameter settings. Each cell is potentially connected to each adjacent cell by the exchange of water and materials. The simulation models were then compiled and integrated by the Spatial Modelling Environment (SME). The required spatial data varied with each location and was supplied by digital maps from a standard geographical information system. The completed model was used to predict the water depths of the estuary by determining the number and density of existing plant species distribution. Aerial photographs were used to calibrate and verify the accuracy of the model. It took the effort of four programmers for four years (16 person-years) to fully develop and implement the original CELSS model using a supercomputer. Maxwell and Costanza claim that the model has proved to be very effective at helping them understanding complex ecosystem behaviour and guiding policy and research [Sklar et al., 1985; Costanza et al., 1990].

More recent applications of the SME have been developed at the University of Maryland. The Everglades Landscape Model (ELM) was developed using the SME. The ELM is designed to be one of the principal tools in a systematic analysis of the varying options in managing the distribution of water and nutrients in the Everglades. Central to its objectives, is the prediction of vegetation change under different scenarios. Water quantity, and the associated hydro-period, has been a central issue in understanding changes to the vegetation of the Everglades [Davis et al., 1994; White 1994]. Nutrients from agricultural areas also appear to be important in understanding vegetation succession. The interaction of these factors, including the frequency and severity of fires, appears to drive the succession of the plant communities in the Everglades [Duever et al., 1994; Gunderson, 1994; White, 1994].

Within the ELM, the landscape modelled is partitioned into a spatial grid of 10,178 square unit cells, each of them covering one square kilometre surface area. An ecosystem "unit" model is replicated in each of the unit cells representing the Everglades landscape [Fitz et al., 1995]. The unit model itself is further divided into a set of model sectors that simulate the ecological (including physical) dynamics using a process oriented, mass balance approach. While the unit model simulates ecological processes within a unit cell, horizontal fluxes across the landscape occur within the domain of the SME. Within this spatial context, the water fluxes between cells carry dissolved nutrients, determining the quantity and quality of the water in the landscape.

3.3.2 GRASS-GIS and associated Simulation Models

GRASS (Geographic Resources Analysis Support System) is an open source, free GIS software, originally developed by the U.S. Army Construction Engineering Research Laboratories (CERL), between 1982 and 1995, as a tool for land management and environmental planning. GRASS was published in year 1989 and in 1997 CERL stopped developing GRASS and the Centre for Advanced Geography and Spatial Research at Baylor University became the sponsor for supporting and the development of further versions of GRASS. Because GRASS is an open source software, it gained a vast popularity and due to its rapid growth, the Development Team has grown into a multi-national team at numerous locations.

GRASS, as described by its developers, includes all the functions that are required in any hybrid GIS software package [Neteler, 2004]. It accommodates raster, vector and point data modules, in addition to a number of modules that are organized into groups to facilitate operations such as: display, general file functions, utilities to convert data from one format to another, satellite data processing, and 3D visualization. However, the strongest parts of GRASS are the raster analysis and image processing facilities. All analyses and modelling processes are done with raster maps. Vector and point data are used for input and output. In raster analysis, for example, weighted overlaying (with unlimited number of layers, and up to complex models like erosion modelling) can be carried out. The image processing module contains the standard functions like: rectification, supervised and unsupervised classification, image enhancement with digital filters, transformation, edge detection, and many other functions.

The modular concept, the internal language (FORTRAN), and the fully described programming library allow the users and programmers to: 1) write their own modules, which can make use of the database access functions and predefined standard GIS functions, and connect them to their own calculations; 2) create specific applications (e.g., AGNPS, SWAT, QUAL2EU) and couple them with GRASS. A number of examples can be found in the standard GRASS deployed package and on the Internet as add-in external modules associated with GRASS interface [Shepard, 2000].

The integration of GRASS-GIS with simulation models has been exhibited in several applications such as **erosion modelling** (e.g., AGNPS, ANSWERS, and KINEROS), **Rainfall-runoff modelling** (TOPMODEL, storm water), **hydrological modelling** (SWAT, CASC2D), **watershed calculation**, **floodplain analysis**, **landscape analysis,** and **wildfire spread.** For the purpose of this research, we briefly describe one example from relevant applications. More information can be found at: http://grass.itc.it/index.php *(or any other mirror site)* [Accessed Dec. 2007].

The AGNPS model

AGNPS (Agricultural Non-Point Source Pollution Model) is a single event based and parameter simulation model developed by U.S. Department of Agricultural Research Service (USDARS) [Young *et al.*, 1987]. The model is used to forecast surface run-off volume, peak flow rate, soil loss, sediment, nutrient and pesticide yield in a watershed. It is intended to provide basic information on water quality to be used to classify nonpoint source pollution problems in agricultural watersheds. For simulation purposes, the watershed is subdivided into homogeneous land areas (cells) with respect to soil type, land use, and land management practices. These areas can be of any shape, from square grid cells to hydrologic boundaries. Due to the large amount of input data required, the application of AGNPS is limited to watersheds not larger than 200 km^2 [Young *et al.*, 1989; Engel *et al.*, 1993]. However, AGNPS has been applied to large basins, by representing the study area by a grid of cells larger than 16 ha. For example, [Morse *et. al.*, 1994] applied AGNPS with 100 ha cells to calculate the nutrient and pesticide concentrations in a 1645 km^2 watershed. Several efforts have been made to integrate AGNPS with various GIS software packages to evaluate agricultural nonpoint source pollution. At least three attempts to integrate AGNPS with GRASS have been constructed: (i) at Michigan State University [He *et al.*, 1993], (ii) by Srinivasan and Engel [Engel, 1996], and (iii) by the Soil Conservation Service as a watershed planning tool in the Hydrologic Unit Water Quality Project (HUWQ) [Drungil *et al.*, 1995]. He *et al.*, (1993) used an integrated

AGNPS/GRASS system, known as WATERWORKS, to evaluate the impact of agricultural run-off on water quality in the Case River, a sub-watershed of Saginaw Bay. Mitchell *et al*., (1993) developed an integrated AGNPS/GRASS system to validate the AGNPS for predicting pesticide run-off from small watersheds of mild topography. Srinivasan and Engel (1995) developed a spatial decision support system using AGNPS and GRASS to assess agricultural nonpoint source pollution [Srinivasan and Engel, 1995]. In theses examples, GRASS was employed to perform the basic GIS functions of data input, storage, analysis and display [Drungil et al., 1995]. AGNPS has also been linked to other GIS software packages. For example, Jankowski and Haddock (1993) coupled AGNPS with PC-Arc/Info (ESRI product). The conjunction was constructed using Arc/Info macro language (AML), Pascal language, and batch programming. Another AGNPS-Arc/Info integrated system was constructed by Tim and Jolly (1994) to evaluate the effectiveness of several alternative management strategies in reducing sediment pollution in a 417-ha watershed located in southern Iowa. AGNPS has also been linked to: ERDAS Imagine, a grid cell-based GIS software package [Evans and Miller, 1988]; Geo/SQL, a vector-based GIS software [Yoon et al., 1993]; and IDRISI, a raster-based GIS software [Klaghofer *et al.*, 1993].

The TOPMODEL model

TOPMODEL (TOPography-based hydrological MODEL) is a rainfall–runoff model, originally developed by Beven and Kirby (1979) at University of Leeds, UK. The model requires data from a Digital Elevation Model (DEM) and a sequence of rainfall and potential evapotranspiration data to operate. The model is used to predict the catchment's water discharge and the spatial soil water saturation pattern. TOPMODEL has been validated with rainfall-discharge data [Hornberger *et al.*, 1985; Robson *et al.*, 1993; Obled *et al.*, 1994; Wolock, 1995] and several recent studies have examined its applicability to water quality problems [Wolock *et al.*, 1990; Robson *et al.*, 1992].

TOPMODEL makes use of a topographic index of hydrological similarity based on the analysis of the topographic data. For a long time, the calculation of the topographic index has been made manually, but with the advent of GIS and terrain analysis techniques this procedure is now automated [Quinn and Beven, 1993]. The GIS is normally used to produce the topographic index and the channel routing from the DEM.

Over the past two decades, TOPMODEL concepts have been implemented with various programming languages on different computer platforms (see, for example, Beven, 1997). The tools developed have been used widely in several catchments worldwide [Beven, 1997]. Efforts have also been made to integrate TOPMODEL with GIS, mostly from a hydrological perspective. For example, Chairat and Delleur (1993) used GRASS to determine the hydrological parameters and to link them with TOPMODEL. The linking method, however, was not explicitly described in literature although it has been mentioned that it belongs to loosely coupling methods as GRASS is mainly employed to access the input and output data from TOPMODEL. A second effort by Stuart and Stocks (1993) focused on the integration of a set of generic modelling tools into the SPANS GIS. Another application is AVTOP which integrates TOPMODEL into ArcView GIS [Huang and Jiang, 2002]. In AVTOP, the whole simulation process including stream network generation, topographic index map, and computation of soil saturation is implemented solely by the ArcView macro language (i.e., Avenue). The soil saturation status is visualized on top of a three-dimensional (3D) watershed surface layer for a better understanding of the predicted contributing area with respect to the distribution of the topographic index.

The SWAT model

SWAT (Soil and Water Assessment Tool) is a river basin (or watershed) scale model aimed at quantifying the impact of land management practices on water, sediment, and agricultural chemical yields, in large complex watersheds characterized by varying soil types, land use, and management conditions over long periods of time. The model components include hydrology, weather, sedimentation, soil temperature, crop growth, nutrients, pesticides and agricultural management.

SWAT divides the watershed into sub-watersheds. Each of them is connected through a stream channel and further divided into Hydrologic Response Unit (HRU). HRU is a unique combination of a soil and a vegetation type in a sub-watershed. SWAT simulates hydrology, vegetation growth, and management practices at the HRU level. Water, nutrients, sediment, and other pollutants from each HRU are summarized in each sub-watershed and then routed through the stream network to the watershed outlet [Neitsch *et al.*, 2005a; 2005b].

SWAT has been linked with GRASS [Srinivasan, 1992; Engel et al., 1993; Srinivasan and Arnold, 1994], Arc/Info [Bian et al., 1995], and ArcView [Arnold et al., 1998]. The **SWAT-GRASS linkage** is a pre-processing utility that has been developed within GRASS to generate the input information used by SWAT [Arnold et al., 1993]. As Arnold put it, "Rather than having manual user inputs into SWAT, raster-based map layer inputs for soil information, land use and land cover, and digital elevation models are interactively analysed and formatted by GRASS and SWAT model utility routines. GRASS also contains routines for basic hydrologic modelling and parameter calculations and this capability can be used to develop input to SWAT". Watershed boundary delineation, *Slope* and *Aspect* percent, and flow directions are examples of the important hydrologic parameter analyses that can be calculated by GRASS.

The SWAT-GRASS model has been applied for small scale hydrologic modelling as well as for continental scale. For example, Jacobson *et al.* (1995) evaluated the water quality impacts of the diverse crops and management practices in a 4.6 km^2 sub-watershed of the Herrings Marsh Run Watershed in the North Carolina Coastal Plains. Srinivasan and Arnold (1994) applied the SWAT–GRASS model to calculate several features (e.g., average annual rainfall, total water yield, actual and potential evapotranspiration, and annual grain yield and biomass production) for the entire USA. The input data such as the map of soil types (STATSGO), the map of land use (USGS LULC), and the Digital Elevation Model (DEM) were required to run the SWAT-GRASS model. The USA was divided into 78,863 STATSGO polygons for this analysis [Mizgalewicz and Maidment, 1996].

SWAT has also an ArcView extension developed by Diluzio et al., (2001). The linkage requires designation of land use, soil types, soil chemistry, weather, groundwater, water use, pond, and stream water quality data, as well as the simulation period, to ensure a successful simulation. Barnett and Fulcher (2001) developed another linkage with ARC/INFO using AML (ArcInfo Macro Language) as well as a user friendly, menu-oriented, graphic user interface for reformation of the modelling processes involved in SWAT model.

3.3.3 IDLAMS - The Work of Argonne National Laboratory

IDLAMS (Integrated Dynamic Landscape Analysis and Modelling System) is a decision support system that incorporates a number of ecological models and based on a GIS framework [Sydelko et al., 2000]. IDLAMS was developed in year 1994 by the U.S. Department of Energy at Argonne National Laboratory (ANL) and the U.S. Army Construction Engineering Research Laboratories (USACERL). IDLAMS aimed at predicting land conditions (i.e., vegetation, wildlife habitats, and erosion status) by simulating changes in military land ecosystems for given training intensities and land management practices. Therefore, the military land managers can use IDLAMS as a tool to compare different land management practices and to further determine a set of land management activities and prescriptions that best suit the needs of a specific military installation [Li, et al., 1998].

IDLAMS[21] includes four major components: the vegetation dynamics model, a set of wildlife habitat suitability models, an erosion model, and a scenario evaluation module [Li et al., 1998]. These components were integrated through a static GIS structure. Consequently, the flexibility and the dynamic interaction between these models were limited. To overcome these limitations, an object-oriented prototype of IDLAMS was developed based on an object-oriented architecture known as DIAS (Dynamic Information Architecture System) shown in Figure 3-4.

Figure 3-5 shows the conceptual design of OO-IDLAMS. OO-IDLAMS includes a number of key Objects such as: the domain object (e.g., grassland, watershed, stream, atmospheric layer, etc.); the Object Library; the Data Import/Export Utilities; the Discrete Event Simulation Manager; the GeoViewer module that provides the GIS functionalities; and the Course-of-Action (COA) object that is a flowchart of individual steps constituting a specific plan or action and is used to model procedural or sequential processes. The OO-IDLAMS prototype integrates a subset of the original IDLAMS components including the Vegetation Dynamics Model and the Habitat Model. For the OO-IDLAMS implementation, the Military Training and Land Management components of the original Vegetation Dynamics Model were broken into three COA objects (Training, Burning, and Planting). These COAs represent the land use and the land management plans for the study area. COAs are considered to be models within OO-IDLAMS. The natural succession processes remain part of the external Vegetation Dynamics Model. OO-IDLAMS also employs ***GeoViewer*** (an object-oriented GIS module) to navigate the study area to create, query, view, and manipulate objects.

[21] [21] IDLAMS is developed for military use and not available for public. Most publications describe the approach, but do not explain the integration method. We try to describe IDLAMS to the best of our knowledge from the available resources.

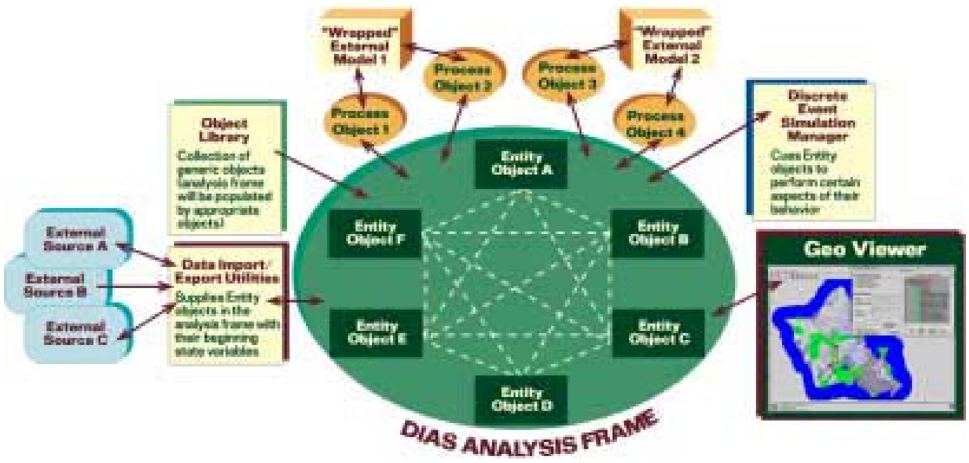

Figure 3-4: OO-IDLAMS Components (based upon DIAS)

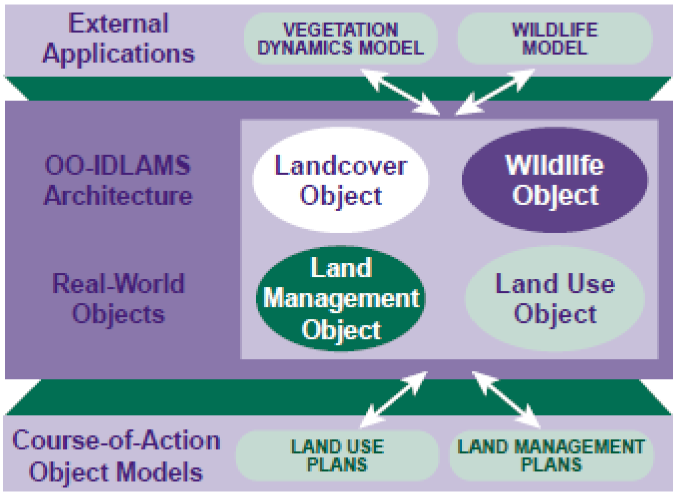

Figure 3-5: OO-IDLAMS Conceptual Design [Sydelko et al., 2000]

Noticeable, the models that appear in Figure 3-5, do not communicate directly together but are only integrated through their relationships with the domain objects. This makes it easier to replace a model or to integrate additional models without disrupting other models in the suite. This modular design makes OO-IDLAMS more flexible than the earlier IDLAMS version. However, Sydelko commented on DIAS by stating: “Although DIAS provides an excellent framework for the integration of multiple models, it does not solve the more basic ecological and environmental research issues related to model integration. These issues include, but are not limited to (1) the ecological implications of multiple-scale modelling and simulation and (2) the impacts of data aggregation and disaggregation. However, DIAS can be used as an excellent workbench from which to explore and investigate these issues.”

3.3.4 WaterWare -The work of Kurt Fedra

WaterWare is a river basin information and decision support system based on a set of related mathematical, water resources, simulation models. WaterWare has been initiated through the EUREKA project (EU487) and the related RTD projects[22]. WaterWare has evolved through a series of applications to: the river Thames in England, the Lerma-Chapala basin in Mexico, the West Bank and Gaza in Palestine, the Kelantan River in Malaysia; and a series of other case studies around the Mediterranean (e.g. in Cyprus, Turkey, Lebanon, Jordan, Palestine, Egypt, Tunisia and Morocco) within the framework of the INCO projects SMART and OPTIMA.

WaterWare is implemented within an object oriented framework. It facilitates the integration of several components. These components may include: (1) geographical data (e.g., administrative/land use/land cover maps, digital elevation models DEM, etc.); (2) A number of water resources simulation models (e.g., rainfall-runoff model (RRM); water resources model (WRM); water quality models (STREAM, BLTM); irrigation water demand model (IWD); and groundwater flow and transport model (XGW)); (3) River Basin Objects (e.g., water supply/demand nodes, sources of pollutants, etc.); (4) River Networks (shared between WRM and STREAM models and linked to the River Basin Objects); and (5) analytical and decision support tools (ranging from simple screening-level to sophisticated Optimization models) for water allocation. These components are integrated through a consistent architecture that includes a multimedia user interface with Internet access, a hybrid GIS, and an embedded expert system for environmental impact and assessment [Fedra, 1994, 1995, 1996a, 1996b, 2002, 2005]. Fedra stated: "WaterWare is designed to be a highly detailed operation analysis tool at short time intervals (hourly to daily); Strongly linked to water quality modelling of in-stream flows to determine optimal wastewater loading strategies as well as related engineering, environmental, and economic aspects".

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[22] The related projects can be found at http://www.ess.co.at/docs/gallery.html

Fedra described the basic data framework of the WaterWare as a combination of a hybrid GIS that provides the overall structure, and classes of objects that include: *river basin elements*, *model scenarios*, and *tasks*. The river basin elements include: sub-catchments, reservoirs, treatment plants, and river reaches. These elements are represented as polygons, lines, points, or regular cell grids. Their state is determined by a set of methods (model scenarios or sets of rules for the embedded expert system). Tasks are specific problem oriented views of river basin objects (or combinations of objects). They present their state, usually over time and based on a number of decision variables or scenarios, to the user to support planning and management decisions.

The various objects are linked in an explicit way. For example, the reservoir might be linked to: the sub-catchment that provides its inflow, the observation station that monitors the hydro-meteorological data, and the associated irrigation district. Models such as the rainfall-runoff model or the irrigation water demand model are used to update the state of these respective objects, and thus provide inputs to the water resource model. The water resource model, in turn, provides input to the water quality model that, again, operates in the context of other objects such as discharge nodes or water extraction and monitoring points.

For the purpose of this research we briefly describe the relevant parts from WaterWare system that are the Embedded GIS Tools and the irrigation water demand model (IWD).

WaterWare has its own GIS tools and functions that are specifically designed for WaterWare. These tools and functions are written in C and C++ programming languages and organized in a number of libraries. The GIS tools are associated with vector and raster layers as well as digital elevation data (DEMs). The important functions of the GIS tools include: arbitrary overlay stacking and zooming of map layers, display outputs from simulation and optimization models including the spatial interpretation of data as topical maps.

The map layers used in WaterWare either provide background for spatial reference and orientation, or direct data input for the simulation models. Examples for the latter are the digital elevation model (DEM), land use maps, and the river network. The embedded GIS functions and tools are represented in the WaterWare interface as a toolbar menu, as shown in Figure 3-6, that includes shortcuts for layer selection and stacking, zooming, colour editing, a four window mode for map comparison, 3D display of the DEM with any map draped over the elevation data, and read-back functions for locations, distances, or areas.

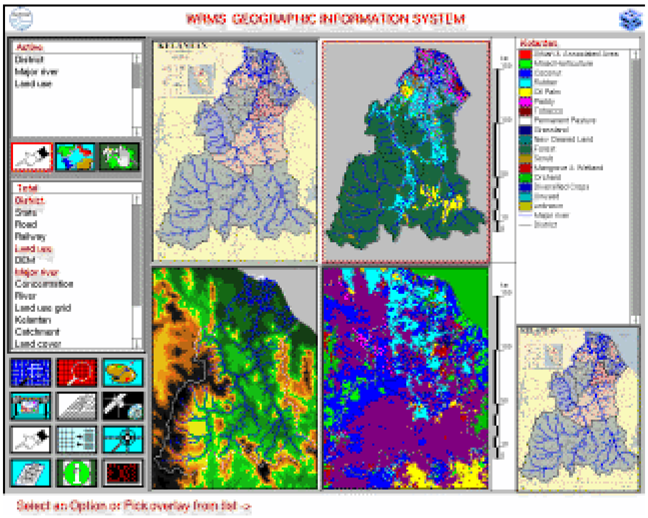

Figure 3-6: WaterWare Embedded GIS Tools. [Fedra, 2002]

The Irrigation Water Demand Model (IWD)

The IWD, as described by Fedra, is a *simulation model* aimed at predicting the water demand for any of the irrigation districts in the river basin. The IWD model describes the irrigation districts or units that can range in size and complexity from a single field to an entire regional irrigation scheme. The model *input* includes the size and the crop pattern of the irrigation object, irrigation technology and transmission, and the local climate as well as groundwater information. The model *output* is the daily or monthly irrigation water demand in terms of river diversion or water extraction/pumping requirements. In parallel to the water requirement, the model can generate a simple cost-benefit analysis for the irrigation operation [Fedra, 2002]. The model uses either the CROPWAT approach developed by FAO to determine crop water requirements in the growing season and computes supplementary irrigation water requirements, or an alternative model (**IRRWD**) based on a dynamic concept of crop specific physiological water demand.

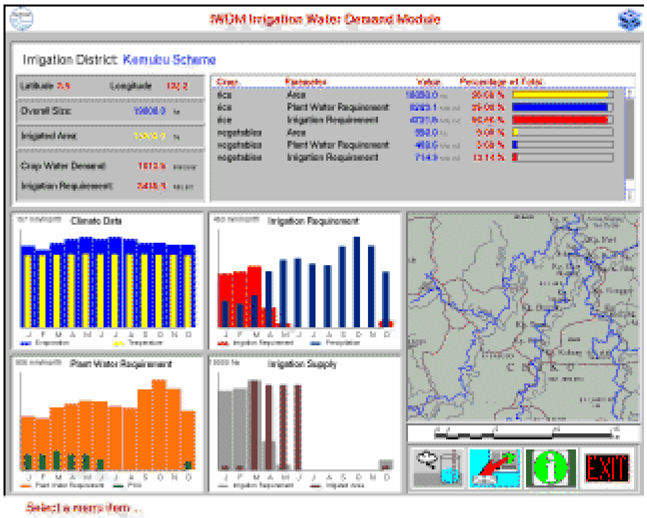

Figure 3-7: Irrigation Water Demand Model. [Fedra, 2002]

The model output is presented in a graphical format as time series of the various components of the water budget, which supports the calculation of multiple and overlapping growing seasons for multiple crops.

The model can be structured for hierarchies of irrigation operations, so that it can aggregate the output from numerous individual fields and plots into large irrigation districts. This possibility of a hierarchical representation makes it possible to configure complex irrigation schemes at a high level of detail and realism.

The output, the dynamic supplementary irrigation water demand, can be exported to the overall water resources model (WRM) where the respective irrigation district is represented as a demand node.

3.4 Hydrology and water resources applications

Several applications in water resources have been reported in literature where GIS has been linked with hydrologic/hydrodynamic models [Batty and Xie 1994; Zhang 1994; Shamsi 1996; Yao and Terakawa 1999]. Sasowsky and Gardner (1991) linked the Simulation of the Production and Utilization of Rangelands (SPUR) model to the GIS to develop input parameters for the model. Rewerts and Engel (1991) linked the ANSWERS model to the GIS for the development of input structures. As mentioned earlier, Srinivasan (1992) developed a link with the AGNPS model to the GIS not only for development of effective input opportunities, but also to visualize raster maps generated by the GIS based on the AGNPS output. Arnold (1992) developed a linkage for the SWAT hydrologic model similar to the AGNPS interface developed by Srinivasan. The SWAT linkage also incorporates advanced visualization tools capable of statistical analysis of output data. The methodology for linking the GIS to a hydrologic model is conceptually simple. A GIS-based front-end processor will analyse the input map layer(s) and extract the distributed parameter information based on the data in each map layer. The data are then formatted into an input file structure that the model can read, import, and then utilize as a basis for simulation. Depending on the capabilities of the GIS and the simulation model, the GIS can also be used to spatially display output information. This can be accomplished by either using GIS tools to build output map layers or by viewing text or graph outputs.

In the context of GIS applications in hydrology, Olivera and Maidment (1999) have used the GIS to identify flow path, to determine flow direction, and to delineate a watershed. However, this approach is limited in its application for diffusion processes (e.g., overland flooding), which does not follow a unique path or multiple paths. Olivera et al. (2000) have reported the development of a global-scale flow routing model using a source-to-sink algorithm that has been completely developed within GIS using *Visual C++*. One limitation of this approach is its rigidity, for example for water resources applications operating rules cannot be modified during the simulation. Davis (2000) and Whiteaker (2001) have developed Olivera's application to a new GIS data model, called ArcHydro, to represent natural basins, watersheds, and network of streams and riches. ArcHydro was intended to provide a structure for pre-processing GIS data for use in hydrologic simulation models. However, ArcHydro aimed at representing the process of surface water runoff that collects water from riches to channels to the mainstream to the sink point (e.g. to the sea). The irrigation network, however, works in the opposite direction. It distributes water from the mainstream to channels to the riches that provides water to agricultural areas. This implies a water distribution instead of water collection, or branching versus assembling. Therefore, modules of such as watershed, catchment, and basin in ArcHydro would not work in the modelling of an irrigation system and the governing rules for water distribution would have to be reformulated (reversed).

In the following paragraphs, we describe two simulators that have been developed for the Nile River Basin. The Nile River Basin is one of the largest river basins worldwide. There is a fascination about the Nile River that has captured human imagination throughout history (see for example [Terje Tvedt, 2002]). Some five thousand years ago a great civilisation emerged depending on the river and its annual flooding cycle. At the beginning of this new millennium, some academic institutions such as NOAA and University of Maryland undertake major scientific, investigatory projects on the Nile River Basin such as *Nile Forecasting System (NFS)* and *Nilesim* hydrologic simulator. Some of these projects are described in the following paragraphs to understand what has already been studied in the region.

3.4.1 MFS - The work of NOAA

In year 1990, The National Oceanic and Atmospheric Administration (NOAA) initiated a river forecast system for the Nile River called "Monitoring, Forecasting and Simulation" project *MFS* [Bellerby, 2003]. The MFS project was funded by the USAID and implemented by the FAO. The primary objective of the MFS project is to predict the inflow into Aswan High Dam with as much lead time as possible. An additional goal is to regionalise forecast capability so that many of the ten countries that share the Nile basin could benefit from the use of the Nile River forecasts.

Phase one of the project (1990-1993) involved initial development of the Nile Forecasting System (NFS) for the Blue Nile River in Sudan. In the further phases, a significant improvement of the accuracy of NFS and in the simulation of the NFS for the Blue Nile and the White Nile has been achieved. Version 2.1 of the NFS was installed in Cairo in June 1994 and contains enhanced satellite calibration coefficients, a hydrologic calibration system, an enhanced reservoir operation system for the Blue Nile, an improved data assimilator, and graphics outputs [Elshamy, 2006]. Because of the lack of adequate hydro-meteorological data, the European METEOSAT satellite data was used to obtain more detailed spatial resolution of the distribution of precipitation over the basin. A distributed hydrologic system was designed to take advantage of the satellite derived precipitation as well as known physical characteristics of the river basin from GIS.

3.4.2 NFS - The Nile Forecasting System

The Nile Forecasting System (NFS) is an operational satellite-driven distributed hydrological modelling system installed at the Nile Forecasting Centre (NFC) at the Ministry of Water Resources and Irrigation (MWRI), Cairo, Egypt. The system was developed under the auspices of the “Monitoring, Forecasting, and Simulation of the River Nile (MFS)” project managed under the auspices of United Nations Food and Agriculture Organisation (UN/FAO) with the primary development work undertaken by the United States National Weather Service (NWS).

Imagery data from the European METEOSAT satellite are received using a Primary Data User System (PDUS). This imagery is used to generate daily estimates of precipitation using a Cold Cloud Duration (CCD) technique with pixel-by-pixel rain-rate calibrations. The gridded rainfall data are then inserted into a distributed hydrological model operating on the 5km METEOSAT grid. Each cell of the model contains three components, a two layer non-linear water balance model,, a hill slope model that accounts for average travel times from hillsides to river channels, and a kinematic routing model which account for in-channel flow from grid-square to grid-square. The model is used for the operational simulation and forecasting of inflow to Lake Nasser, impounded by Aswan High Dam. Three-month forecasts are produced using the Extended Stream-flow Prediction (ESP) technique, which employs historical data to provide multiple plausible scenarios of future precipitation.

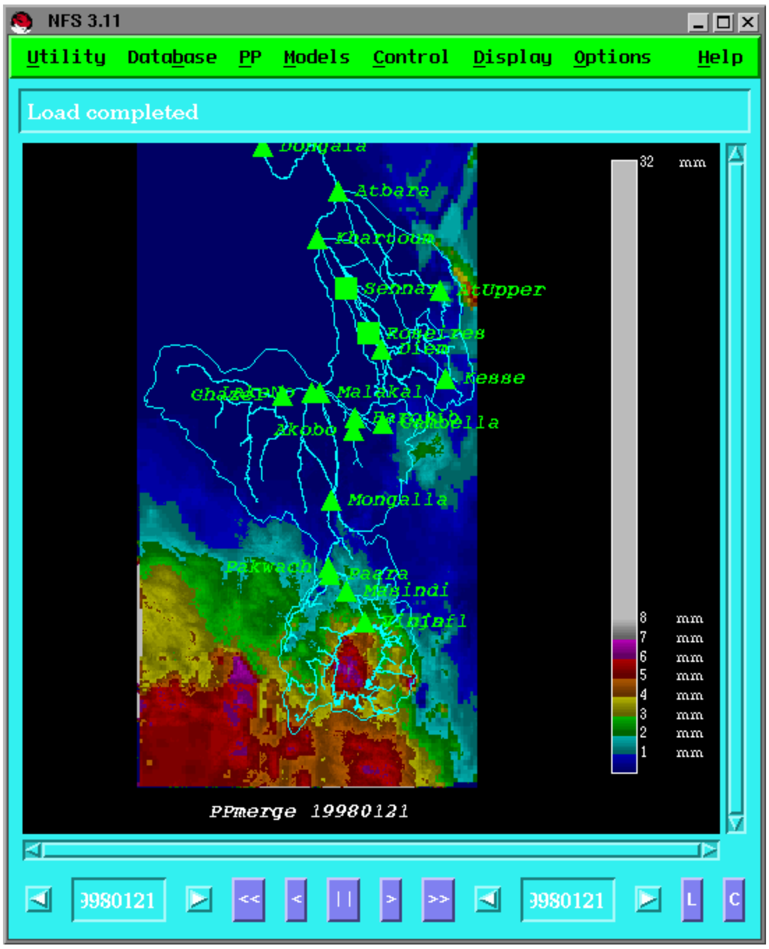

Figure 3-8: The GUI for the Nile Forecasting System NFS. [Bellerby, 2003]

3.4.3 NileSim - The work of Maryland University

NileSim is a hydrologic simulator for the Nile River basin developed at University of Maryland as a simulation-based learning environment. It is a free software[23] that is used at the University for the undergraduate course “The Nile: Technology, Politics, and the Environment”.

NileSim is a Windows-based graphical simulator for the entire Nile River Basin, which has been developed principally for the pedagogical purpose of explaining complex river behaviour and management to non-technical individuals. NileSim also allows for applications to study agriculture, economics, history, and sustainability of the region, thus addressing social as well as engineering issues. The simulator has been developed in a cost-effective manner, making use of modern software development tools from electronic design automation. This has provided a rigorously accurate tool, which is fast, graphically intuitive, and simple for people to use. The tool supports interactive experimentation with a simulated Nile River Basin for users to learn by observation how that basin system works.

The GUI of Nilesim shows a full-screen image of the Nile River basin from the Equatorial Lakes and Ethiopia to the Delta. This image is colour-coded, so that lakes, rivers, and reservoirs appear in dark blue, seas are light blue, political boundaries are yellow, and man-made features are red (Figure 3-9). Yet, the image is used as a background (not an interactive map) with invisible icons that divert the user to the underlying simulation model. While the NileSim program is a complicated set of algorithms, the user cannot see them and interacts only with the GUI.

The simulator is based on a detailed description of the physical hydrology of the river system and is calibrated to empirical records of the basin. Its output reproduces the descriptive statistics of observed hydrographs, reservoir levels, and travel times of flood waves along river reaches. The NileSim model incorporates

[23] The software can be downloaded from (http://www.isr.umd.edu/SimPLE/) Accessed 2007.

monthly river flow variability from analyses described in the literature [Said, 1993; Shahin, 1985]. The monthly flow and volume estimates include a stochastic component. The filling and draining of reservoirs obey mass balance, and the travel times of flood waves downstream are described by Manning's equation and geographically distributed reach geometries.

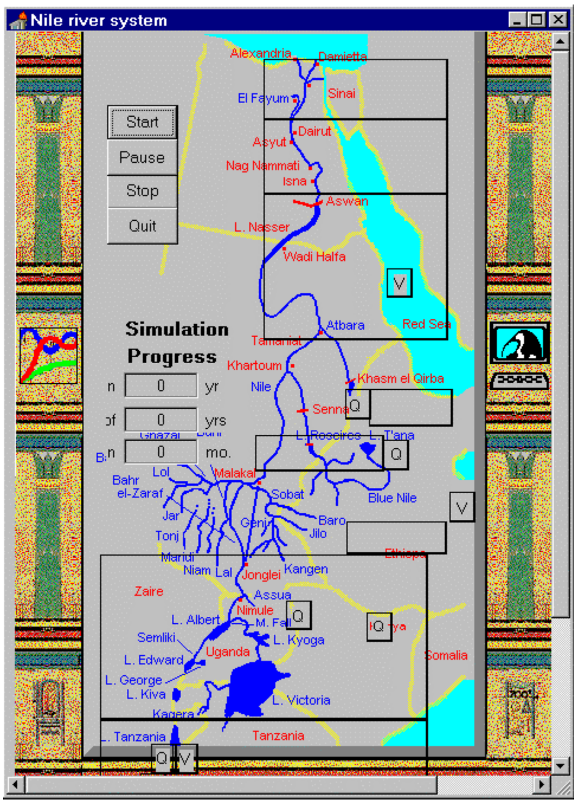

Figure 3-9: The GUI of the NileSim. [Levy, 1999]

The underlying network simulation of the river basin was developed using VisSim, a network simulation toolkit from the electrical engineering industry. VisSim combines a graphical development environment for rapidly building network diagrams with a set of mathematical and logical tools for describing analytical relationships within such networks. The NileSim GUI was built using Delphi 3.0. The final code constructed, using these tools, was compiled into a C-based executable code for users to download from the Internet. This strategy of using CASE tools rather than writing original code allowed NileSim to be developed within a few months and to have both the functionality and look-and-feel of standard Windows software; this consistency with industry standards is important in simplifying training and encouraging use.

Concluding Remarks

Most of the research discussed in this chapter emphasizes the importance of linking the dynamic modelling methodologies with the GIS. The capabilities of the GIS to analyse relational and spatial data makes this type of technology ideal for linking with environmental simulation models, in particular, the hydrologic models. The GIS, then, is used as a visual spatial analytical tool and to develop input parameters for the simulation model. Such linkage greatly reduces the time needed to develop input data for simulation models and to simplify the input process.

Attempts have been made to add the spatial dimension to the SD models. These attempts can be divided in two categories: (1) introducing spatial dimension into the system dynamics model (implicit approach) or (2) translating the SD model equations to run in the GIS. The first approach does not represent spatial dimension in an explicit manner, e.g., the Mono Lake model [Ford 1999]. In this model, spatially important features of the system are represented with aggregate relationships such as surface area–volume curve; and elevation–volume curve. The second approach involve translating SD model equations into a programming language and interfacing with GIS, for instance, Costanza et al. (1990), Theobald and Gross (1994), and Westervelt and Hopkins (1999). In these studies, the work is focused on spatial modelling (emphasis on GIS) and SD is used to bring the dynamic modelling (temporal aspect) capability into the GIS environment. Since SD model equations are translated to run within the GIS, a drawback of this approach is a loss of the interactive power of SD (changes cannot be introduced during the simulation). The main limitation in all the attempts that have been made thus far, for spatio-temporal dynamic modelling, is that the relationship between time and space is not made explicit, - they typically either span time or space, not both.

Noteworthy, the examples mentioned in section 3-3 and 3-4 (e.g., SME, CELSS, ELM, GRASS, WaterWare, etc.,) were developed by the effort of a sizable team of experts and large budgets. For example, WaterWare was developed through a European collaborative effort involving universities, research institutes, and commercial companies [Fedra and Jamieson, 1996a; 1996b; 1996c]. We believe that, in order to make an impact, we should consider reducing the time involved for both the development of and the simulation based on this type of models, and that we should move towards smaller, more transparent models and less expensive computational resources (e.g. personal computers). We should notice too that the integration of the simulation models and the GIS although successfully completed, has been extensive and has been completed using an extremely sophisticated systems design.

In section 3-3, three simulation models associated with GRASS have been described (i.e., AGNPS, TOPMODEL, and SWAT). In literature, such models are known as *catchment models*. In general, catchment models are distinguished by: a) the precision of the spatial units used in analysis as being lumped or distributed and b) the precision of the events modelled over time as being a single event or continuous time steps [Maidment, 1993].

Lumped or distributed describes the way in which the model spatially handles the data. Lumped models use spatially averaged parameters and perform computations over the whole catchment region. As the within variation for a catchment increases, the model predictions may become less informative and accurate. Distributed models are based upon the discretisation of the landscape into smaller functional land units. Usually a uniform grid is used for computational convenience. Calculations are performed on discrete cells and then accumulated to make predictions over the whole catchment. With advances in computer technology distributed models are gaining popularity. However they require large amounts of data. The advantage of distributed systems is that they are able to better account for local variability in land conditions. This is important for land management decisions which require a better understanding of land processes within a catchment and for applying farm scale management options.

Single event and continuous time step refer to the time frame over which the model runs. Single event models calculate a single rainstorm event and run over a short period of time that covers the rainfall duration and time for runoff to drain from the watershed. Continuous time step models run over longer periods like a year or over the period of a seasonal crop rotation. Both model types are useful and provide different types of information. Continuous time step models do not produce accurate calculations for single storms. Similarly, single event models may not necessarily provide accurate long term predictions. An example of a catchment model that implements a single event distributed parameter is the AGNPS model [Young et al., 1989]. An example of a catchment model that implements a continuous time step lumped model is the SWAT model [Arnold et al., 1993a]. Both models were developed in North America and have been significantly tested. Application outside North America is limited and mainly focused around research applications rather than part of decision support processes.

The disadvantage of lumped models is that they do not make predictions for specific sites, and therefore may potentially overlook significant environmental problems. Distributed models, on the other hand, are good at detecting local affects and anomalies. However they are very complex in their operation and require large volumes of input data to describe the variation in the landscape. For instance, AGNPS requires at least twenty-two parameters for each cell [Young et al., 1989]. Formatting and input of data is a time consuming task using manual methods. Integration with GIS has streamlined this process and resulted in improved data management and analysis ability [Fedra, 1996a]. But there still exists problems to develop data sets with respect to the parameter assumptions built-in environmental models, and to adequately validate models for local situations. Without proper validation users are not sure of the model outputs and are unlikely to use them for decision-making. Therefore, a tighter integration between GIS and modelling applications is needed to provide improved data validity of input and output data.

3.5 Conclusion

The efforts reported in this chapter leave no doubt that the integration of the simulation models with the GIS is highly demanded. The reviewed attempts are listed in Table 3-1. Theses efforts may be classified in many ways.

First, in terms of the simulation approach that has been used, we can distinguish between attempts used the System Dynamics models (appear in red *italics* in table 3-4) and the attempts used process based mathematical models. Second, in terms of the GIS data abstraction, the majority of attempts make use of Raster based GIS while Vector based GIS was limited although most of the network structures (like river streams and channels, transportation, utilities, and irrigation networks) are best represented in vector GIS. Third, in terms of the integration methods (i.e., loose coupling or tight coupling), the tightly coupling has been used once (WaterWare). Efforts may be also classified according to the types of simulation (i.e., continuous or discrete-event simulation); the knowledge domain (e.g., environmental, ecological, economical or social); or the method of implementation (using the available technology or build specific applications) and the cost and the efforts excreted. However, a close inspection for these efforts suggested that there is, to large extent, a room for more efforts.

This research addresses a certain gap found in the literature. That is integrating the system dynamics simulation models with Vector based GIS in a tightly coupled method, using the available technology, to analyse and study an environmental problem such as water scarcity problem that has large impacts on social, economic, and human lives. Therefore, the emphasis in this research is on the SD simulation models to be integrated with vector-based GIS for analysing the irrigation system within the context of policy design and strategy development for a highly significant problem that is the water scarcity problem.

Table 3-1: List of Reviewed Literature (attempts of integration)

Author	Software Name	Simulation Approach	Spatial Tools	Theme	Study Area	Integration method
Kasperidus 1988		*SD Model* Stella 5	R.GIS N/A	Agriculture	Germany	N/A
Singhasaneh & Eiumnoh 1991		*SD Model* N/A	N/A N/A	Urban Planning Landuse change	Thailand	N/A
Grossmann & Eberhardt 1993				Tourism, economy, & Agr. strategies		Conceptual Level
Dmitri et al., 2000	ECONET simulator	*SD Model* N/A	GIS N/A	Ecological nets of natural protected areas	Moscow State University	Loose coupling using Excel, Visual Basic, and Delphi
Zewdie, A., 1998		*SD Model* Powersim	*Vector GIS* Arc Info	forest depletion problem	Ethiopia	Loose coupling using Excel
Ling Shi 1999		*SD Model* Powersim	N/A	urbanization Landuse planning	China	Loose coupling using Excel
Anthony, H., 1998		*SD Model* Powersim	R.GIS Arc Info	Environment	Mono Lake	Loose coupling using Excel
Despotakis et al., 1993	Dynamic GIS	*STELLA*	SPANS	Environment	Greek Sorades Islands	N/A Using especial translators
Betz et al., 1998	VAFS/ LANDSIM	LANDSIM	Raster GIS ARC/INFO	Forest fires	Bryce Canyon Utah, USA	N/A
Sui, Dianzhi 1993		N/A	N/A	Urban	Hong Kong	N/A
Gilruth et al., 1990		Dynamic simulation	RS & R.GIS	Deforestation	West of Africa	N/A
Maxwell, T., Costanza, R., 1997	SME	*STELLA* Sim. code FORTRAN / C	Grid based	Ecosystem Landscape	University of Maryland	Using especial code generators, MML Objects
Sklar et al. 1985 - 1990	CELSS	SME Application	Grid Based	landscape	Louisiana USA	Code generators, & MML
Fitz C., et al., 1995	ELM	SME Application	Grid Based	water and nutrients	Everglades Florida, USA	Code generators, & MML
USA-CERL 1982-1995	GRASS	FORTRAN Hydro. models	R.GIS GRASS	Land Managt. & Env. Plan.	USA	Internal language & custom libraries
USDARS 1987	AGNPS	Single event sim. code	GRASS	Agricultural erosion	USA	Loose coupling link AGNPS/GRASS
Beven & Kirby, 1979	TOPMODEL	Several Prog. languages	GRASS	Rainfall-runoff	Leeds, UK	Loose coupling
Arnold, 1994	SWAT	FORTRAN	GRASS	River Basin	USA	Loose coupling
ANL & USA-CERL 1994 - 2000	IDLAMS OOIDLAMS	Dynamics ecological models	Grid Based	Landscape		N/A
Fedra 1995	WaterWare	Mathematical Hydrology models	Grid Based Emb. GIS Tools	Hydrology	AUSTRIA	*Tight Coupling*
NOAA 1993	NFS	Mathematical Hydrology models	Raster GIS	Hydrology and water resource management	Nile River basin	Conceptual Level
University of Maryland 2003	NileSim	Mathematical Hydrologic Simulator	Windows Based	Hydrology	Nile River basin	Conceptual Level
Gharib, S., 2008	SDGIS	*SD Model* Vensim	*Vector GIS* ArcGIS	Irrigation System	Nile Delta	*Tight coupling* using Object Orientation

Chapter 4

The Conceptual Framework

The Conceptual Framework for the SDGIS Application

4.1 Introduction

This chapter includes three main sections. In the first section we provide a brief description about Object Oriented GIS (OOGIS) and explain the differences from the traditional GIS. This is followed by an overview of the dominant software in GIS domain that is “ArcGIS”. We briefly explain the basic terminology, the main features, and capabilities.

In section two, we highlight the relationship between the Object Oriented paradigm and the System Dynamics. We analyse the basic SD language and explain how object oriented methods have been applied to the simulation software. We point to the OO extensions that can be added to SD. In this research we employ Vensim DSS, one of the available simulation software. Therefore, we assume that the user has some basic concepts regarding the Vensim software and its DLL functions. More information about the Vensim DLL functions can be found in the Vensim Manual.

Section three is the point of departure to develop the new application SDGIS from which we explain our new method of integration. First we describe the conceptual design, the various integration strategies, and the selection of the “tightly coupling” strategy to be implemented. Second we discuss a number of technical issues related to the development of the SDGIS application. These issues include: (i) using external or internal simulation models (models designed to run independently of from within the GIS), we explain the difference between using the external models verses internal models, and the relative strengths and weaknesses for each approach. (ii) The different ways to design and implement the user interface of the SDGIS application (i.e., as an ActiveX DLL that can be added to the ArcMap as a customised tool, or as a standalone UI that employ the ArcObjects to provide the required functionalities). (iii) Having decided to build a standalone application, we can implement this with either VB or VC++. Thus, we highlight the advantages and disadvantages of using the two developing environments. The conclusion of this chapter comes at the end of this section.

I should remind the reader that developing the SDGIS application and the integration work in this research has been done several times due to the rapid evolution of the technology. The first application was developed using ArcView 3.3 software to prepare(develop the maps and the attribute data associated with it) data the maps, Powersim Constructor to develop the simulation model, and the Microsoft Visual Basic 5.0 to build our new application and the GUI. MapObjects 2.1 has been utilised to provide the GIS tools embedded within the application and Powersim DLL to connect the application with Powersim Engine to simulate the model and obtain the results. Due to the fast progress in the technology, however, it was necessary to migrate to the more recently released packages. The second application is built using ArcGIS 8.3, Vensim® DSS version 5.2a, and Visual Basic 6. ArcGIS software package is fully object-oriented software that employs Visual Basic for Applications (VBA) as a modelling language[24]. Vensim DLL provides more functions and facilities to control the simulation model, and Visual Basic 6.0 has some improvements from the prior version (i.e., VB 5.0). Despite the release of Visual Basic *dot Net* that was intended mainly to facilitate the web applications, Visual Basic 6.0 is more suitable for our application and has all the functionality required. We also used ArcObjects shipped with ArcGIS instead of MapObjects 2.1 that has been used earlier.

The focus in this research is to integrate the simulation models with the GIS models. SD models may be built using Powersim, Vensim, Stella or any other visual SD software. The challenge comes in creating the link between the SD and GIS. This link can be established thought using the DDLs. Both software, Powersim and Vensim, have been successfully incorporated into our new application. Although Powersim Studio provides the opportunity to build more hierarchally structured models as opposite to the flat models in Vensim, Vensim DLL offers better capabilities for controlling the model from external applications such as VB. For this reason, we decided to use Vensim DLL in the final application SDGIS. Since the hierarchal structure is not provided in Vensim, the only option was to build a flat model.

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[24] ArcView 3.3 is Object based but not object-oriented and uses Avenue as a customisation anguage.

4.2 Object Oriented GIS

4.2.1 The Basic Concepts of OOGIS

Geographical features (also referred to as spatial entities or spatial objects) are natural, manmade, or abstract objects of interest. These features are usually defined in the form of two main data categories: spatial data and attributes (non-spatial data). The spatial data describes the geographical features by geometrical information (shape of the feature and position) and topological information (relations to other features). Attributes (or non-spatial data that are usually numerical and textual) are the characteristics related to the geographical features. Attributes have no specific location; only their association with spatial data defines them. For example, a river is a spatial entity that has a name such as “The Nile”; this is the non-spatial data.

The spatial data and its representation and management have always been the primary concern for GIS technology developers. Spatial data is a key feature and can, in GISs, be considered more important than non-spatial data, since this differentiates GIS from other types of information systems [Maguire and Dangermond, 1991]. The main distinction between the traditional GIS and OOGIS is the way the spatial data is handled and managed.

At the time when first GIS appeared, the task of displaying graphical information was very demanding due to limited hardware resources. Therefore, early GISs were usually based on systems that supported visualization of spatial data, such as computer aided design (CAD) systems. Low-level data structures used in CAD systems (like arrays, linked lists implemented as arrays, and dynamic linked lists) were used to store data, and traditional file handling techniques were employed in systems for managing data. This approach provided facilities for displaying and editing geographic information. However, because of the massive volume of spatial data that describes the geographical features and the significance of the topological links, CAD systems did not suffice [Mitrovic *et al.*, 1996]. The need to store, retrieve, and represent the spatial data adequately resulted in the development of a new data structures for GIS, such as various types of trees (R, Quad or KD trees) for fast spatial retrieval on large datasets [Samet, 1990]. These structures encompass both geometrical and topological data (which contain data about neighbouring objects such as farms and parcels on both sides of a river), sometimes accompanied by attribute data as well.

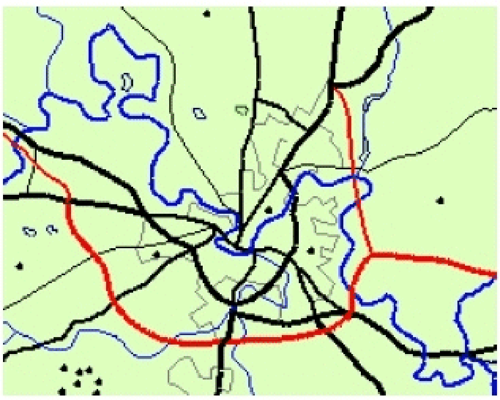
The commercial success of database management systems (DBMS) and their widespread use was also reflected in the development of GIS. Several commercial DBMSs emerged. Generally, they were based on one of the classical data models: hierarchical, network, relations or their derivatives [Codd, 1982]. Commercial relational database management systems (RDBMS) have gained much popularity, and products such as Oracle and Ingres were widely spread. They are built on the relational model that organizes data as tables and relations. The columns of the table are called attributes and all values in an attribute are elements of a common domain that describes the set of all possible values. Rows are referred to as records or relation elements [Ullman, 1982].

The first GIS package based on relational database systems (such as Arc/Info [ESRI, 1991] stored only attributes (non-spatial data) in the database, mostly because of limited performances of contemporary computer systems, while the spatial data were still kept in property data models; these two parts were linked to each other, but were supported by separate data managers. Such hybrid architectures were commercially successful and dominant at the market for a decade. Yet, the separation of the underlying data into two parts had undesirable consequences, particularly concerning the lack of support for ensuring data security, integrity control, multiple user access, and concurrency management for spatial component of the database [Mitrovic *et al.*, 1996].

The solution was to integrate spatial and non-spatial components under the control of a RDBMS. Initial efforts to implement a spatial database by way of pure relational model [Van Roessel, 1987] demonstrated that such an approach, although theoretically feasible, is unsatisfactory due to its low performance and the information concerning one object must be spread across many relations due to the normalization performed upon the relations, and many join operations must be performed in order to recreate complex spatial objects. The relational data model alone cannot provide appropriate indexing and retrieval operations for spatial data [Mitrovic *et al.*, 1996].

There were two subsequent research directions in using databases for storing both attribute and spatial data. The first approach is the extension of the relational data model and modification of RDBMS so that spatial data could be stored while retaining the advantages of the relational data model. This approach is based on abstract data types and relaxing the constraints of the relational data model (normal forms). Research in this area started in the 1980s [Abel 1989; Guptill and Stonebraker 1992; Mitrovic D., 1993], and commercial GIS tools based on the extended relational model are available (Smallworld, ESRI SDE, Oracle Multidimensional). The second approach is the application of OODBMS, resulting from the general acceptance of C++ as the major implementation tool for GIS.

Egenhofer and Frank (1992) proposed that the DBMS, as a subsystem of a GIS, can be replaced by another product of the same modelling power such as an OODBMS. Object-orientation possesses rich modelling structures, enabling a more intuitive representation that more closely parallels the natural structure seen in the maps. For example, Figure 4-1 shows a simple map and some data that represents two segments of a single "Road":



1LINE	226		5
	350460.000000	312880.000000	.000000
	350406.375000	313047.125000	.000000
	350393.937500	313185.937500	.000000
	350406.375000	313325.562500	.000000
	350480.000000	313680.000000	.000000
2LINE	226		2
	350060.000000	314320.000000	.000000
	350480.000000	313680.000000	.000000

Figure 4-1: A sample map and data[25]

[25] Source: Garvey *et al.*, 2000

In a relational database, each segment would have to be treated as a number of rows rather than a single object. A segment number would be needed to link the related records:

Line No.	Segment No.	Type No.	X	Y	Z
1	1	226	350460	312880	0
2	1	226	350406.375	313047.125	0
3	1	226	350393.9375	313185.9375	0
4	1	226	350406.375	313325.5625	0
5	1	226	350480	313680	0
6	2	226	350060	314320	0
7	2	226	350480	313680	0

In contrast, in an object-oriented database, a user-defined type could be created to hold the point coordinates and each segment could be represented as one object. In this approach, the segment numbers are unnecessary and the object orientation provides an improved way of representing the information that can be easily manipulated as a whole rather than in bits:

Line No.	Type No.	POINT
1	226	{ (350460, 312880,0) (350406.375, 313047.125,0) (350393.9375, 13185.9375,0) (350406.375, 313325.5625,0) (350480, 313680, 0) }
2	226	{ (350060, 314320, 0) (350480, 313680, 0) }

An object-oriented GIS allows for encapsulation of the spatial entities so that all of its geometry, data, and behaviours are contained in a single object. Hierarchies or networks of objects can be constructed to represent complex objects (e.g. hydrological network) and the interrelations between objects. The objects can also be related via a layer hierarchy based on any relationship.

An additional claim made for object-oriented database systems is that they make the task of constructing GIS software considerably easier. This is particularly relevant when manipulating complex data structures and for creating visualisations of the data. A successful GIS will invariably embody this type of data structure and will almost certainly require a visual representation of map data. A further motivation for the use of an object-oriented approach to the production of such a system is therefore the expectation that the approach will result in a system that has a clean interface and is easier to maintain than an equivalent system built using conventional programming techniques. ESRI sponsored this approach and the first fully Object-Oriented GIS package (ArcGIS 8.0) was released in 2001. ESRI's OOGIS data model is called *geodatabase*. In the following paragraphs, we briefly describe the structure of the geodatabase and the main characteristics of ArcGIS. More information concerning ArcGIS modules and functions can be found on ESRI URL [http://www.esri.com/software/arcgis/]

Geodatabase Structure

The object oriented data model that is used in ArcGIS is called geodatabase. It supports an object oriented vector data model. In this model, entities are represented as objects with properties, behaviour, and relationships. Support for a variety of different geographic object types is built into the model. These object types include: simple objects, geographic features (objects with location), network features (objects with geometric integration with other features), annotation features, and other more specialized feature types. The model allows for defining relationships between objects, together with rules for maintaining the referential integrity between objects. The Geodatabase organizes geographic data into a hierarchy of data objects. These data objects are stored in ***object classes***, ***feature classes***, and ***feature datasets***.

An ***object class*** is a table in the geodatabase that stores non-spatial data. All tables (and feature classes) have a set of required fields that are necessary to record the state of any particular object in the table (or feature class). These required fields are automatically created when the user creates a new table (or feature class), and cannot be deleted. Required fields may also have required properties such as their domain property. The user cannot modify the required property of a required field. For example, in a simple feature class, "OBJECTID" and "Shape" are required fields.

They do have properties such as their aliases and geometry type that user can modify, but these fields cannot be deleted.

A ***feature class*** is the conceptual representation of a geographic feature. When referring to geographic features, feature classes include point, line, area, and annotation. A feature class is a collection of features with the same type of *geometry* and the same *attributes*. Simply it is an object class that stores features and has a field of type geometry.

A ***feature dataset*** is a collection of feature classes that share the same spatial reference. The spatial reference for a feature class describes its coordinate system. Feature classes that store simple features can be organized either inside or outside a feature dataset. Simple feature classes that are outside a feature dataset are called standalone feature classes. Feature datasets are a way to group feature classes with the same spatial reference so that they can participate in topological relationships with each other. To most users, feature datasets also have a natural organizational quality, much like a folder on a file system. Since for many GIS applications the majority of the data for a particular database has the same spatial reference, the temptation to group large numbers of feature classes into feature datasets is irresistible.

ArcGIS supports two main categories of Features: Simple Features and Network Features. Simple Features include points, lines, and polygons. Network Features include Simple Edges, Complex Edges, Simple Junctions, and Complex Junctions. All Edges are connected throughout Junctions. A Simple Edge is a linear Network Feature with no internal junctions. A Complex Edge is a linear Network Feature that may contain one or more internal junctions, which are vertices that lie on the edge but do not split the edge. Thus a Complex Edge may join another Complex Edge anywhere along its length, while Simple Edges can only join other Simple Edges at their endpoints. Simple Junctions can be thought of as the nodes that connect Edge Features, although Junctions do not have to be attached to any Edges.

Complex Junctions are Junctions with special internal connectivity, analogous to a switchboard.

A collection of Features of the same type is stored as a ***Feature Class***. Each row in the Feature Class table represents an individual Feature. Feature Classes that share a common use can be grouped into ***Feature Datasets***. A Feature Dataset is a container that defines a reference frame for the Feature Classes that it contains. The reference frame includes information about the spatial projection, coordinate range and coordinate precision for the data. Feature Datasets can also store relationships between Feature Classes, as well as geometric networks. Relationships in ArcGIS are comparable to relationships in any RDBMS, with related rows in different tables being linked by a common identifier in key fields in each table. ***Geometric networks*** are used for defining network topology between Features. Geometric networks support tracing and connectivity tasks. Only Network Features (line and point features) may participate in a geometric network.

Feature Datasets, Feature Classes, relationships, geometric networks, and non-spatial tables are all stored in a Geodatabase. A Geodatabase is a relational database that serves as a container for spatial data in ArcGIS. Other RDBMS software, such as Oracle or Access, can open a Geodatabase. Using such software to view a Geodatabase reveals Feature Class tables, as well as other tables used to maintain the Geodatabase.

Custom Features

ArcGIS has extended the power and functionality of a Feature by incorporating object-oriented technology into its software design. In addition to their spatial and attribute information, Features can also possess special behaviours through the use of interfaces. For example, in addition to being a simple blue line on a map, the GIS representation of a river may also know how to route a flood wave from its upstream to its downstream end, how to draw itself at different scales, and which Features to notify if its' spatial or attribute information changes. By adding custom behaviour to Features, the GIS representation of real-world objects becomes a more accurate depiction of the reality that the GIS intended to represent.

Custom Features can also take advantage of ArcGIS's COM-compliant design. Because ArcGIS is COM-compliant, Features can access the capabilities of software such as Microsoft Excel to plot graphs, or Word to prepare reports. The code behind a Feature's behaviour can be written with a COM-compliant programming language, such as C++, meaning that users no longer must learn a proprietary programming language to customize the software.

COM-Compliant

ArcGIS is the first GIS software released by ESRI with a COM-compliant design. Through COM, ArcGIS can now communicate with other COM-compliant software, such as Word, Excel, and Internet Explorer, by utilizing public components (those that can be accessed by other applications) from the softwares' object library. ArcGIS also uses Visual Basic for Applications (VBA) as its customisation language, no longer requiring users to learn a proprietary language (such as Avenue or AML) for customisation purposes. Note that VBA is different from VB, in that Visual Basic is used to create standalone applications or DLLs, while VBA is used from within a software application to customize that application.

Through VBA, the graphical user interface of ArcMap and ArcCatalog can be tailored to fit the needs of the user. Custom buttons and toolbars can be created, and macros can be written to automate complex tasks. VBA is also the means by which the object libraries of other COM-compliant software are accessed. This means that ArcGIS can now link spatial data to spreadsheet applications, reports, and even web utilities. The customisation potential provided by COM-compliance and VBA has extended the functionality of ArcGIS far beyond that of any GIS software in the past.

ArcObjects

In addition to the customisation capabilities within ArcGIS, ESRI has provided a collection of objects (known as ArcObjects developer kit) from which users can create standalone programs that utilize one or more components from ArcGIS. These streamlined applications incorporate only the ArcGIS components they need, resulting in a much smaller and faster software product than the full version of ArcGIS software. This collection of reusable components is referred to as ArcObjects.

ArcObjects encompasses a Map Control (as an ActiveX control), Map Layout Control, and more than a hundred other objects that can be used in Visual Basic, Delphi, Java, and other industry standard programming environments [ESRI, 2001]. These controls possess much of the same functionality found in ArcGIS. Applications built with ArcObjects can support the display of spatial information, with functionality such as panning and zooming. ArcObjects also supports basic querying of features (either spatially or by attribute data), location of addresses, feature selection, and statistical calculations. While ArcObjects is not intended to act as a substitute for complete ArcGIS functionality, it can add GIS capabilities to an application that would otherwise be lacking a mapping component.

In this research we use ArcGIS to develop the spatial model that will be connected to the simulation model through our new application SDGIS. Because SDGIS is intended to be a standalone application, we utilise ArcObjects to provide the GIS capabilities and tools within the application. In the following section, we develop the spatial model that represents a surface flood irrigation system. This model will be used in the next chapter to test the performance of the SDGIS application.

4.2.2 Modelling the Irrigation System with GIS

To describe our method, we consider an example of a surface-flood irrigation system that includes: (1) a main stream delivering water to a number of secondary canals that deliver water to tertiary ditches which in turn supply water to farms; (2) a number of control-gates or regulators that usually located at the head of each canal and/or ditch to control the flow of water; (3) the agriculture lands that utilize the water for cultivation practices and planting crops and, (4) the supplementary data and information concerning the efficiency of the canal system for water delivery, the cropping pattern (i.e. succession of crops) and water needs for each crop during the growing period, the agriculture calendar, and the annual schedule of water releases from the reservoir.

The GIS model for such a system would include, and be organized in, four feature classes: (1) the irrigation network as a line feature class; (2) the control-gates and regulators as a point feature class; (3) the agriculture lands and farms as a polygon feature class; and (4) the topology feature class that is a geometric network links the three feature classes together.

Networks in GIS are conceptually simple. They are comprised of two fundamental components, edges and junctions. Streams, transmission lines, and pipes are examples of edges, while control-gates, switches, and the confluence of stream reaches are examples of junctions. Edges are connected together at junctions, and the flow from one edge can be transferred to another edge throughout junctions. Since features have a geometry shape and can easily be mapped, such a network is called a geometric network. Remarkably, for every geometric network, there is a corresponding logical network, which is a "behind-the-scenes" data structure that stores edges and junctions IDs and positions and the connectivity rules between them. The logical network consists of tables with unique identifiers. When the geometric network is created within the geodatabase, the logical network is automatically built and maintained. In fact, to analyse the flow through a network we simply deal almost exclusively with the logical network.

The attribute data related to the streams and canals; the control-gates and regulators; and to the various agriculture lands are stored into the attribute tables associated with each feature class. For example, the Canal Name, Canal Average Cross Section, Minimum Water Content, and Maximum Carrying Capacity are stored in the “Canals” feature class. While the Farm ID, Farm Area, Crop Type, and the Canal ID that delivers water to the farm are stored in the “Farms” feature class.

The maps are shown in Figures 4-2, 4-4, 4-6, and 4-7. These maps cover the Nile Delta region. During the fieldwork, we collected these maps from various sources. The maps were mainly in digital format; however, they were created from hardcopy maps that have different scales. Fortunately, the majority of these maps had the scale of 1:50,000. Therefore most of the necessary details do appear clearly.

We started with converting the digital maps from the shape-file format to the geodatabase format, correcting their projection, and unifying the coordinate system. Some editing work was necessary to verify and assure the consistency of data. Next, we extracted the intended features (e.g., canals, control-gates, and farms) and organized them in feature classes, and added the attribute data associated with each feature in the related attribute tables as shown in Figures 4-3 and 4-5. A geometric network has been built using the three feature classes and the water flow direction has been set for each canal. It was necessary to create a relationship between each canal and the farms irrigated from it. This is a one-to-many relationship. We implemented this by adding a new field in the “Farm” attribute table and inserting the Canal ID that delivers water to each farm in this field. During this process, we found that some of the farms have more than one source for irrigation. Therefore we inspected these sources and considered the closest, higher ranked, of these canals to be the primary source of irrigation. This work lasted over six months.

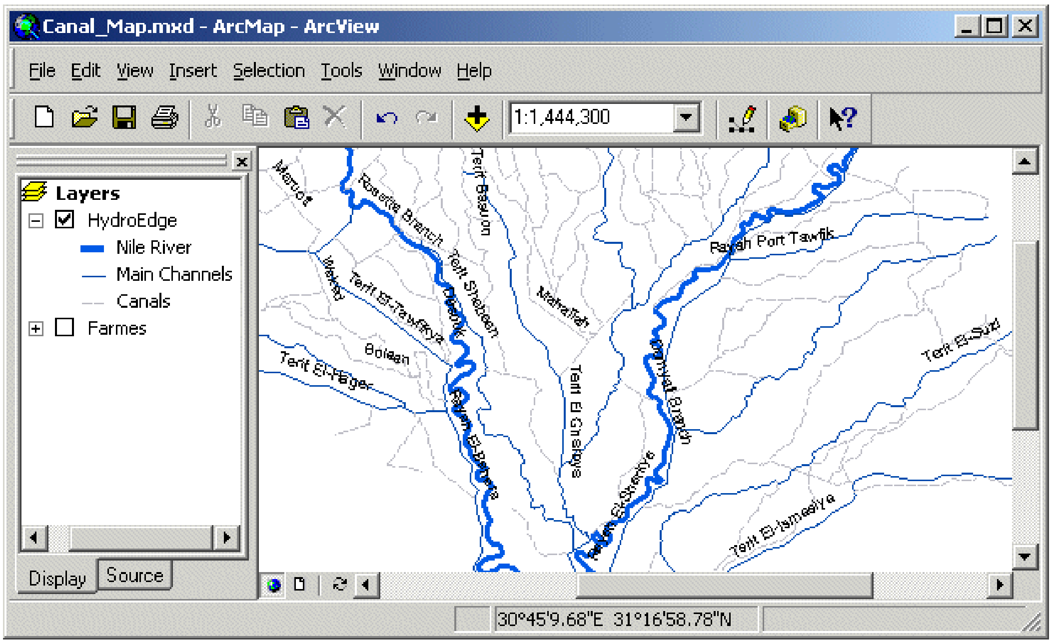
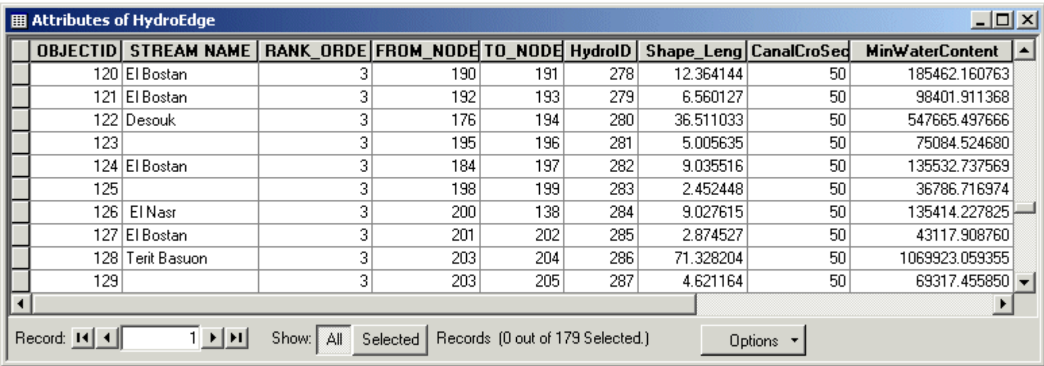


Figure 4-2: The irrigation network in the Nile Delta.


Attributes of HydroEdge

OBJECTID	STREAM NAME	RANK_ORDE	FROM_NODE	TO_NODE	HydroID	Shape_Leng	CanalCroSec	MinWaterContent
120	El Bostan	3	190	191	278	12.364144	50	185462.160763
121	El Bostan	3	192	193	279	6.560127	50	98401.911368
122	Desouk	3	176	194	280	36.511033	50	547665.497666
123		3	195	196	281	5.005635	50	75084.524680
124	El Bostan	3	184	197	282	9.035516	50	135532.737569
125		3	198	199	283	2.452448	50	36786.716974
126	El Nasr	3	200	138	284	9.027615	50	135414.227825
127	El Bostan	3	201	202	285	2.874527	50	43117.908760
128	Terit Basuon	3	203	204	286	71.328204	50	1069923.059355
129		3	203	205	287	4.621164	50	69317.455850

Record: 1 Show: All Selected Records (0 out of 179 Selected.) Options

Figure 4-3: The attribute table of the Canals feature class.

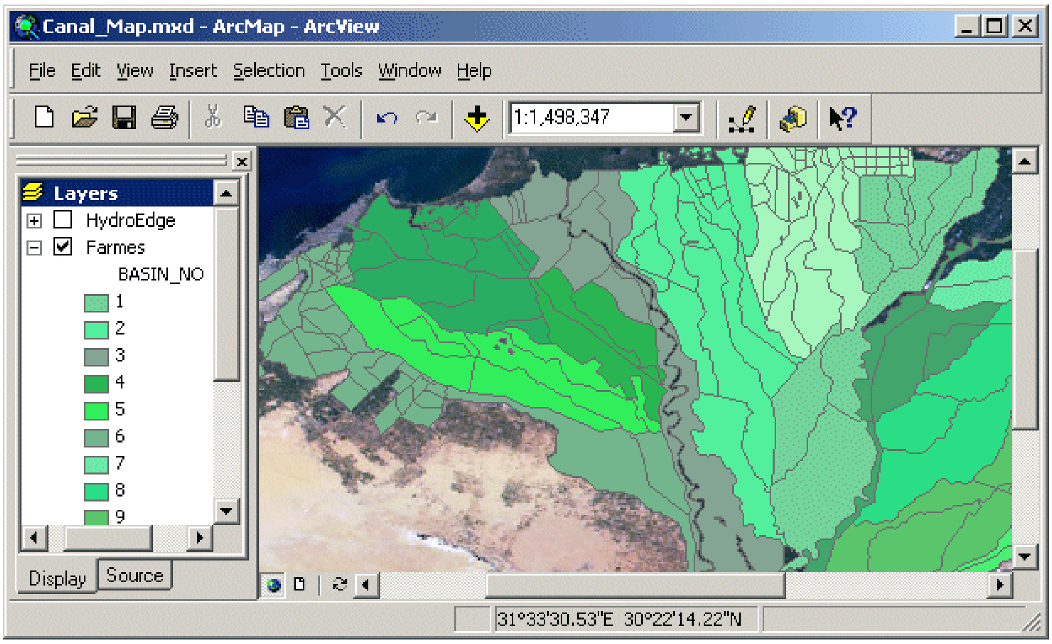
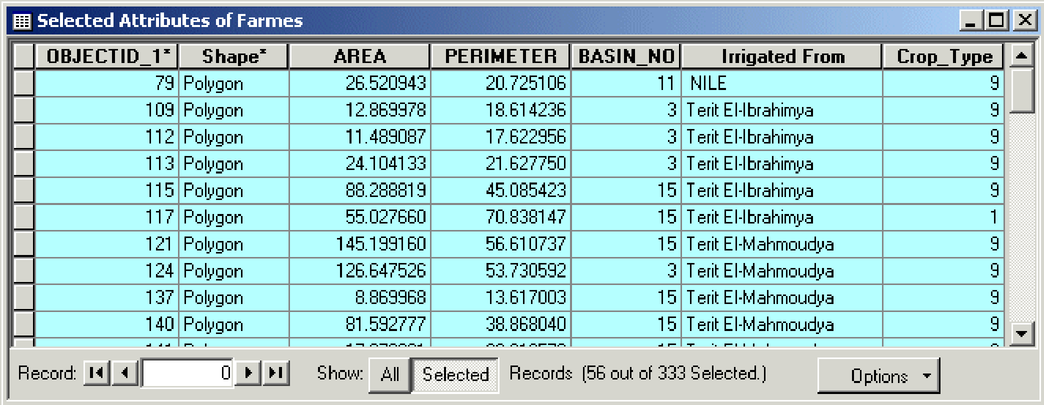


Figure 4-4: The irrigated farms feature class.


Selected Attributes of Farmes

OBJECTID_1*	Shape*	AREA	PERIMETER	BASIN_NO	Irrigated From	Crop_Type
79	Polygon	26.520943	20.725106	11	NILE	9
109	Polygon	12.869978	18.614236	3	Terit El-Ibrahimya	9
112	Polygon	11.489087	17.622956	3	Terit El-Ibrahimya	9
113	Polygon	24.104133	21.627750	3	Terit El-Ibrahimya	9
115	Polygon	88.288819	45.085423	15	Terit El-Ibrahimya	9
117	Polygon	55.027660	70.838147	15	Terit El-Ibrahimya	1
121	Polygon	145.199160	56.610737	15	Terit El-Mahmoudya	9
124	Polygon	126.647526	53.730592	3	Terit El-Mahmoudya	9
137	Polygon	8.869968	13.617003	15	Terit El-Mahmoudya	9
140	Polygon	81.592777	38.868040	15	Terit El-Mahmoudya	9

Record: 0 Show: All Selected Records (56 out of 333 Selected.) Options

Figure 4-5: The attribute table of Farms feature class.

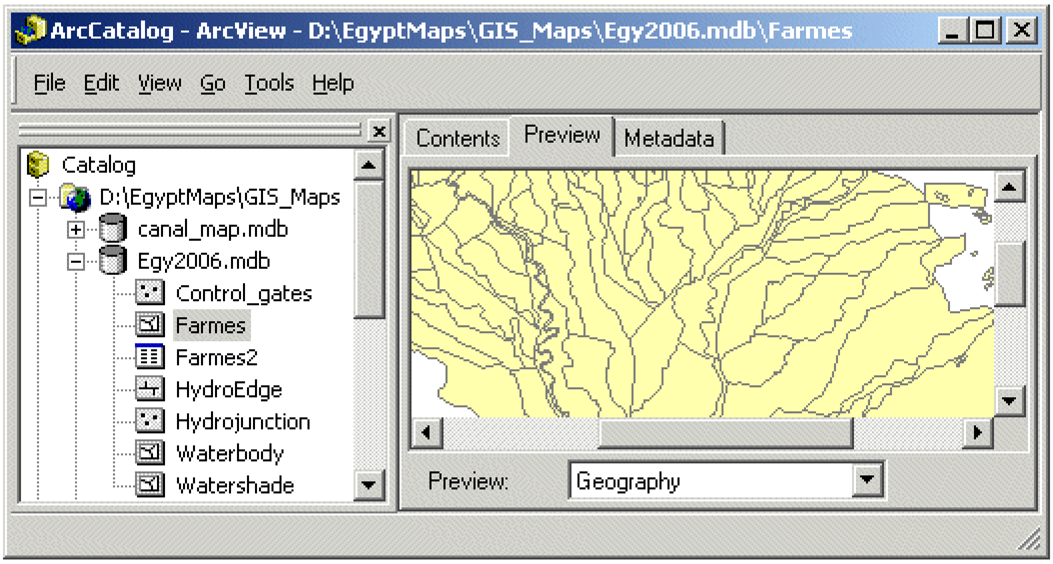


Figure 4-6: Creating the geodatabase in ArcCatalog from the main layers.

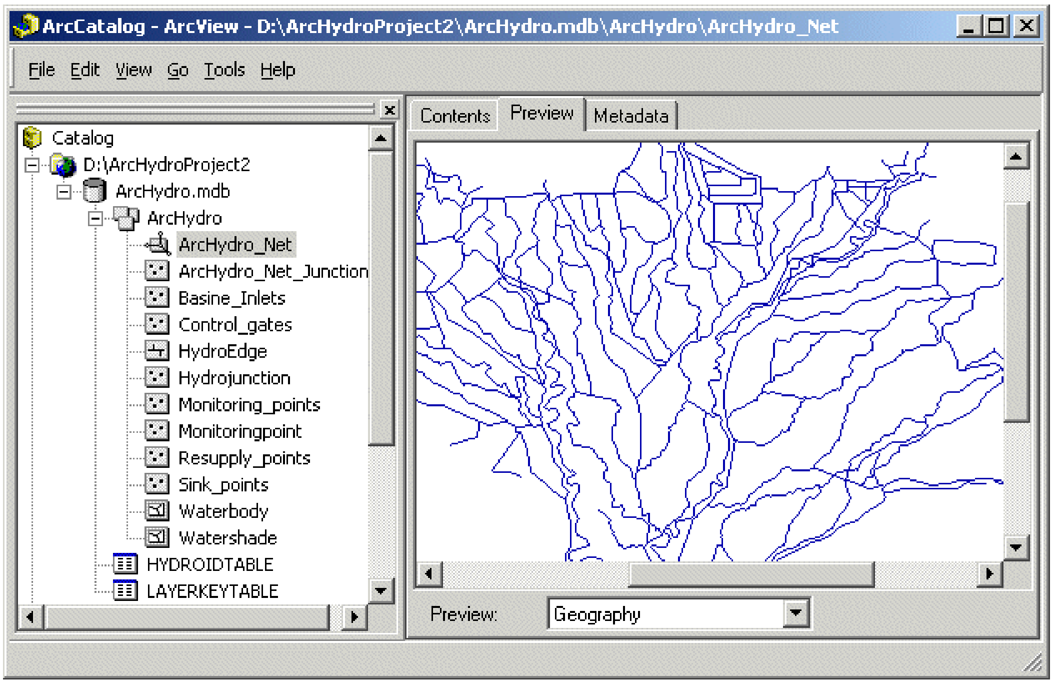


Figure 4-7: Creating the geometric network using ArcInfo.

Using the “identify” tool, the user can select any feature from the map and examine its attribute data in a dialog-box as shown in Figure 4-8. The user can also query the map using either “query by attribute” or “query by location” tool. For example, the user can select all canals that have width between 10-15 meters or the canals fall in certain geographical area. ArcMap will then redraw the results on the map using a different colour. The power of such software lays in its capability to find the spatial relations and answer the user’s questions such as *where, which, and how* (e.g., where is a certain feature, which canal supply water to a certain farm, or how many farms are irrigated from a certain canal). The user can also perform sophisticated calculations and statistics such as calculating the total length of the first-level canals, the total area of the farms irrigated from a certain canal, and so fourth.

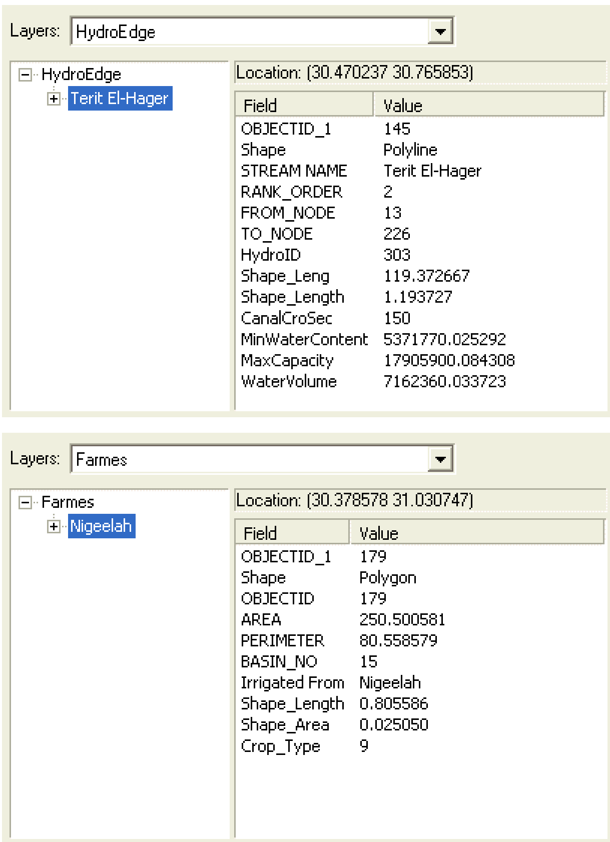


Figure 4-8: The identify dialog box in ArcMap.

The GIS model presented in this section is used in the next chapter alongside with the SD model described later in this chapter to explain our new method of integration and to assess in the development of the SDGIS application.

4.3 Object Oriented Paradigm and SD

4.3.1 The Basic Concepts of OOSD

The efforts of Dahl and Nygaard to create and implement new concepts for programming discrete simulation applications resulted in establishing the object-oriented paradigm [Dahl *et al.*, 1966, 1968]. Simula is considered the first object-oriented programming language and the predecessor to Smalltalk, C++, Java, and all modern class-based object-oriented languages. As its name implies, Simula was designed to perform simulations, in particular, discrete simulation. However, the Object-oriented languages and tools for continuous simulation took longer to arrive. Object orientation has been added to continuous simulation in two different ways: (i) As a library of classes usable from a general purpose OO language (usually C++) [Copstein *et al.*, 1997] and (ii) As a continuous simulation language with built-in OO constructs (e.g. the Object Oriented Continuous System Modelling Program OOCSMP) [Elmqvist *et al.*, 1997].

The Object-Oriented paradigm views any program as a collection of discrete objects that are self-contained data structures and methods that interact with other objects. It provides a way of dividing the program into modules by using objects as building block. The concept of *reuse* is central to object-oriented programming and it is achieved through inheritance. Whilst there are pure object-oriented languages such as Eiffel and Smalltalk, there are also hybrid-languages such as C++ which provides all the crucial elements for applying the object-oriented paradigm, and there are other languages, such as Ada 95, which are categorised as object-based because they contain some aspect of encapsulation inside objects that can be created from a set of existing classes, but does not provide the mechanism for creating new classes. The simulation software developed using object-based languages are considered to be an object-based software rather than object-oriented.

The simulation software designed for the developments of SD simulation models offer some common approaches to model building. In general, these tools enable model development through graphical specification of required relationships among variables (STELLA/iThink, Vensim, Powersim), or by the implicit writing of equations in text editors (COSMOS & COSMIC, Dysmap2, Dynamo) [Richardson and Pugh, 1981]. They also provide built-in functions that cover a wide range of simulation, mathematical and logical, statistical and analytical tools in the form of tables, graphs, animation, flow charts, or reports that explains simulation results. Some offer additional functionality for model sensitivity testing and optimisation [Coyle, 1996].

Despite the variety of simulation software currently available in the market, the basic SD language, in principle, has only two building blocks: the stock and the flow [Myrtveit, 2000]. Remarkably, this basic SD language is very powerful and facilitates building and expressing almost any dynamic system. This is due to the general nature of stocks and flows. The magnitude (value) of the stocks (i.e. the stock level) altogether represent the system state at any moment in time, and the magnitude (value) of flows (i.e. the flow rate) altogether represent the changes to the system state that take place as time advances. Stock levels and flow rates are represented as variables. Models can be built from only flow rates and stock levels, but, in practice, it may be useful to introduce auxiliary variables for expressing some of the logic behind the computation of flows.

Modelling and simulation software, especially those with visual programming style, can utilise well the benefits of Object-Oriented Programming, particularly the concept of *reuse*. There are a number of well-recognized SD models that have been developed over the years. Such models, or part of them, can be used as building blocks in other models. It is not necessary that modellers start from scratch every time they build a new model. Instead, the modeller can use some parts of these standard SD models. For example, the first order delay [Forrester, 1961] or coflows [Hines, 1983; Homer, 1983] are substructures (or model units, or components) that have been documented and are well understood. They may be employed as standard building blocks during the development of other models. In the SD literature, these independent substructures or prefabricated units are known as "*molecules*" [Hines, 1996] or *"components"* [Myrtveit, 2000]. These substructures are objects that encapsulate data, methods, and events ready for use in other SD models.

Creating substructures for reuse has been a major concern for SD modellers. Some claim that SD model components for visual simulation illustrates how a visual simulation model can be used to develop SD model with no programming experience, and in a short development time [Umar, 1997; Miller *et al.*, 1998; Balci *et al.*, 1998; Harrell and Hicks, 1998; and Mackulak *et al.*, 1998]. In the following paragraphs, we briefly describe and comment on three approaches to build substructures and implement the concept of "reuse" in various SD software. Theses approaches include *Molecules* developed in Vensim [Hines, 1996], *Components* developed in Powersim [Myrtveit, 2000], and Component-Based Programming CBP using C++ Builder [Ddembe *et al.*, 1999].

Molecules

As Hines described them, *Molecules* are structures, primitive compositions of stock and flow (or auxiliary) elements and are in turn the building blocks of complete models. A molecule is an element of substructure that serves a particular purpose. As a typical example, one of the simplest molecules and probably appears in most models is the decay process shown in Figure 4-9.

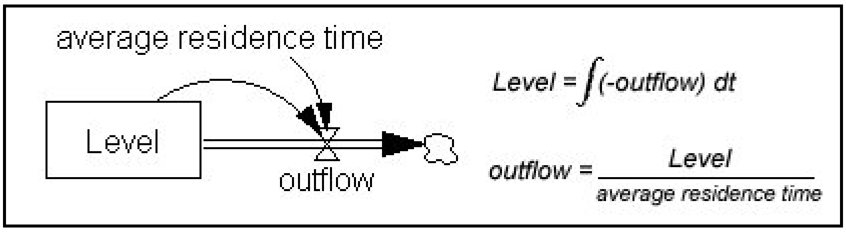


Figure 4-9: A sample of SD model substructure.

Molecules are closely related to what are called "classes" in object-oriented programming. For example, the material delay molecule is derived from the decay molecule and is used in the aging chain molecule. Similarly, the productivity coflow is derived from the standard coflow, which is derived from a smooth [Hines, 1983].

This object-oriented organization is very helpful because it provides a good way to learn about successively more complicated molecules. Once a molecule is thoroughly understood, it is a much easier task to understand the other molecules derived from it.

It is useful to distinguish between molecules and archetypes [Senge, 1990]. Archetypes present dynamic lessons that have been learned from systems having certain structural characteristics [Kim, 1989, 1994, 1995]. Molecules are building blocks from which more complex structures are created. Molecules may improve our ability to represent structure effectively and efficiently, but do not draw dynamic lessons from particular structures.

Currently, molecules are available as a stand-alone application that can be implemented as add-on to the Vensim® software. Figure 4-10 shows a preliminary selection of molecules and their relationships. Using molecules are easy. The diagram shown in Figure 4-10 is presented when the user selects “Molecules” item from “Windows” dropdown menu in the main toolbar of Vensim®. Double clicking on any of the names in the diagram brings up that molecule in a separate view. The user can then select the molecule, or a portion of it, copy it to the clipboard, and insert it into the model he/she is working on. Once this is done, the normal Vensim tools may be used to rename the model elements, change the units of measurement, and complete the construction of the model.

Molecules, and their organization, provide a framework for presenting important and commonly used elements of model structure to beginners and experienced model builders. By having access to theoretically consistent and well-tried formulations, modellers can review what has suggested in previous models and modify or directly incorporate these formulations into their own models [Hines, 1996]. Ultimately, the molecule framework will be available for use with system dynamics software supporting the model interchange format (MIF) protocol [Myrtveit *et al.*, 1995]. This will allow anyone with system dynamics software to use molecules.

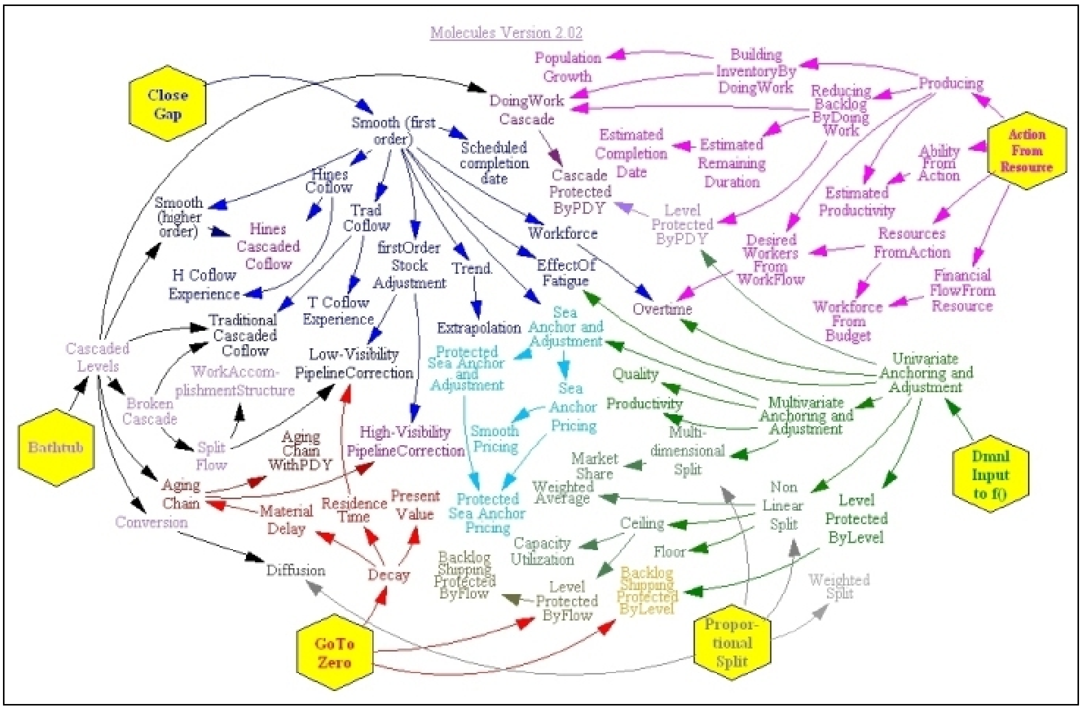


Figure 4-10: Molecules associated with Vensim software[26]

Comment:

This method (copy and insert/paste) maybe acceptable in small and medium size models, but with large size models it becomes more difficult to persist modelling without a hierarchical inheritance structure of the kind the object oriented paradigm suggests. The basic elements of any SD language support only flat models. In order to cope with complexity, it should be possible to introduce different levels of abstraction into the model. For example, at the highest level, the model represents some system and at the next level we have subsystems that can be further divided into smaller and smaller parts, all the way down to the basic building blocks (stocks and flows). Some simulation software use various kinds of visual filtering mechanisms (e.g., sectors, viewers, diagrams) in order to deal with complexity in large models, however, a new concepts to facilitate the hierarchal structure must be introduced. Component Extension, coming up next, proposed by Myrtveit might be the point of departure.

[26] Source: Vensim® website: http://www.vensim.com/molecule.html [Accessed Dec. 2007]

Component Extension

Magne Myrtveit[27] proposed a new design for an object-oriented extension called "*component*" [Myrtveit, 2000]. The concept of the component is similar, to some extent, to the concept of molecules. However, the new extension aimed at facilitating the hierarchal structure and supporting encapsulation and polymorphism. The components have been introduced in Powersim Studio software.

The component, as Myrtveit described it, can be seen as the counterpart of the *class* in object-oriented programming. It has a customisable *interface* for communicating with the rest of the model. Thus, the component encapsulates the entire elements (variables) of the sub-model, and can be used to create instances. The component has *methods* to import and export the values of its entire variables. Polymorphism could be achieved through the component interfaces, as components with equal interfaces are interchangeable.

A component would normally include basic variables (i.e., levels, auxiliaries or constants). Such variables are connected using basic links and flow symbols. When connecting components, there will be more than one basic variable involved. In this case we need a way to bundle variables together into a connector that can be plugged into a compatible connector of another component. Two new structured variable types were introduced for this purpose, the sockets and the plugs. Sockets and plugs can hold variables, and they also have an interface type. A plug can be connected to socket if the plug has the reverse interface of the plug. When a plug and a socket are connected, the variables on each side are connected. The same way is used when a sub-model variable is connected to a component. In both cases the connection can only be made if the interfaces match. Also, when a connection takes place, the implications for the underlying model equations are determined automatically. It is not necessary to edit any equations for the connection to take place.

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[27] The founder of Powersim

Comment:

This approach seems very promising. However, the DLL in Powersim does not support complete control over such structure from an external application. For this reason we would not be able to use it in developing our new application.

Component-Based Programming

Ddembe and Michael (1999) have used Borland C++ Builder to develop reusable components. C++ Builder is a visual programming environment where 32-bit Windows applications can be designed, developed and debugged. The style of programming supported by C++ Builder is widely known as Component Based Programming CBP. Telles (1997) describes C++ Builder as a true Rapid Application Development (RAD) tool. It offers programmers an Integrated Development Environment that allows programs to be written, edited, compiled and linked, all within a single application. It also offers CBP in which components are used in applications to ease the programming task and reduce the development time. However, in order to allow creation of components that may be used on other platforms, and facilitate the use and manipulation of components from other platforms in C++ Builder applications, additions have to be made to the C++ syntax.

The C++ Builder describes a component as an object in code. Visual Component Library (VCL) contains different types of objects, some of which are not components. Components in C++ Builder are identified as any class, which is directly descended from the TComponent class. Objects, which are not components, are derived directly from TObject, the ancestor class at the top of the VCL hierarchy. In object-oriented terms, VCL is a good example of the use of inheritance. TComponent, the ancestor of all components in the VCL provides the minimal properties and events necessary for a component to work in the C++ Builder environment. Other base classes that descend from it have specialised capabilities, which are present in all classes derived from them. One significant characteristic of all components is that they are visual and can be manipulated at design time.

However, developing simulation models with C++ Builder requires the direct writing of equations in code form. This is contrasting the physical assembly of building blocks when using simulation software package. However, it is possible to visually model both the equation and simulation interface given the availability of suitable components. C++ Builder currently has an extensive range of components, some of which are dedicated to specific types of application. An extensive collection of components is dedicated to use in database development and manipulation, and for Internet applications. However, *there are no components specifically developed for use in SD simulation modelling.*

As the model variables in SD (except for constants) are dependent on equations that make use of other variables to get their value, it is necessary to initialise the declared variables (placing them in the right order of execution) with the appropriate value or equation in the Forms constructor, to enable their use in subsequent calculations. The initialisation process involves assigning initial values to stocks and constants, and equations to flows and converters to set their values. Once initialisation is achieved, run time equation is written to set the cumulative value of stock variables. The next step is to establish a link to a graphics object that would display the result of calculations during model simulation and these forms a major aspect of the simulation interface building process.

In terms of displaying simulation results, C++ Builder offers two graph components on the ActiveX page of the component palette but initial explorations showed them to be unsuitable for use due to a lack of adequate documentation for their application, and the fact that their use within an application requires a major deployment of supporting files which must be installed and registered on the client's machine before application installation can take place. Nevertheless, it is possible to procure independent components from other source and install them into C++ Builder. To use the procured graph component for simulation purposes, it is important to override and re-write methods which set graph properties such as lines, tick marks, line points, axes values, grids, etc. Once the underlying implementation is complete, an interface that facilitates entering data for onward assignment to graph properties need to be created using a collection of components.

Comments:

Learning to use C++ Builder for CBP is somewhat tedious. It is necessary to become acquainted with the available components, their properties, methods and events, and also learn how to use them within an application. These components and the vast number of object classes available within the VCL are documented in volumes of manuals and in online help facility. For an experienced C++ programmer, learning and using C++ Builder maybe fairly simple task but for a user with little previous programming experience, the learning process may be time consuming.

Using current simulation software packages, presuming the modeller has knowledge of System Dynamics fundamentals; no special skill such as programming is required to successfully use the tool, other than to learn the specifics of features and functionality offered by the package. With CBP using C++ Builder, there is still the need to write some code even though the level of functionality, which has been built into the components, vastly reduces the level of effort and skill needed. However, programming a SD simulation model without components specifically provided for such use still require real technical skills and the benefits offered by the Component-Based approach in other situations therefore does not apply.

In terms of relevance of the CBP to simulation software architecture, the modelling framework provided by graphical SD software packages directly supports the dynamics of its elements (i.e., Levels, Rates and Auxiliaries), and enables the specification of the relationships between these elements through links created by connector object. C++ Builder, being a generic programming tool that is not geared towards any specific application development, does not offer features that directly support the fundamental principles of SD modelling.

A significant useful feature of the simulation software is that they provides underlying support in the specification of equations, arranging them in the necessary order of execution and creating part of the run time equation.

Programming a SD model with C++ Builder requires a greater level of technical skills, and in the absence of the suitable SD components, the benefits of component-based programming cannot be successfully applied to SD simulation modelling. The level of programming required in the use of components depends on the degree of functionality built into them. It is therefore possible to develop SD simulation components, which would require little or no programming skills.

Concluding Remarks

The power and beauty of the basic SD language lie in its simplicity and flexibility. A skilled modeller can capture the essential dynamics of a large system using only a few variables. For example, the Forrester's model of *World Dynamics* [Forrester, 1970, 1973] is a huge model that represents the world. Remarkably, it has five state variables. Therefore, it might be worthy to keep our models as simple as possible.

SD modellers can make use of the benefits of object-oriented paradigm, in particular, the concept of reuse. In this context, three approaches to create reusable substructure or model-units have been introduced: molecules, components, and component-based programming. However, molecules support only developing flat models. Components overcome the limitations of molecules by supporting the hierarchal structure, but they are limited to Powersim Studio and there are no MFI standards to use components in other SD software. Another limitation of the components use is that Powersim DLL (or ActiveX control) does not support a full control over the model from an external application. The third approach, that is to build simulation models using C++ Builder, requires sophisticated technical skills in programming and using components.

For the purpose of this research, we make use of a simple model to explain our new method. In fact, what we need is a simple and flexible modelling environment (e.g. Powersim, Vensim) that provides the basic SD language (stocks and flows), and a mechanism that facilitates a full control over the system. The focus in this research is to integrate the simulation models with the GIS. SD models may be built using Powersim, Vensim, Stella or any other visual SD software. The critical part is the link between the SD and GIS. This link can be established thought the DDL. Both software, Powersim and Vensim, have been used to develop our application. Although Powersim Studio provides the opportunity to build more hierarchally structured models as opposed to the flat models in Vensim, Vensim DLL offers better capabilities for controlling the model from external applications such as VB. For this reason we decided to develop the final application SDGIS using Vensim DLL that provides more flexibility and control over the simulation model. Since the hierarchal structure is not provided in Vensim, the only option was to build flat model.

4.3.2 Modelling the irrigation system with SD

A simple simulation model capturing the essential dynamic processes of water supply and utilization in agriculture is presented in this section. The irrigation scheme can be described in this way: the water inflow of the mother river is received and stored in the natural reservoir behind the dam (e.g., the High Dam Lake at the south of Egypt). Water is released from the reservoir, flows into the Nile mainstream that contains a number of barrages on certain locations to direct, slow down, or raise the level of the flow. Barrages are normally located at the head of the main distributor canals. The water flows from such main canals to secondary canals from which the water is delivered to the agriculture lands and farms passing through the tertiary canals or what is known as irrigation ditches [Holmen, 1991; Tiwari and Dinar, 2002]. Part of the water carried by the irrigation scheme is lost to seepage and percolation as a result of topography and other part of water evaporates during conveyance. After transmission, water is applied on the fields. Planting for crop-production consume part of it, another fraction ends up in the drainage network and a third fraction is lost to seepage. Thus taking into consideration the structure of the irrigation network, the irrigation system efficiency can be split into conveyance or delivering efficiency and application efficiency. Whereas the conveyance efficiency points to the ratio between “the quantity of water released from the storage facilities and the quantity of water received at farm level” [Martinez, 1994], the application efficiency refers to the water use at the farm level [Tiwari and Dinar, 2002]. The model is shown in Figure 4-11.

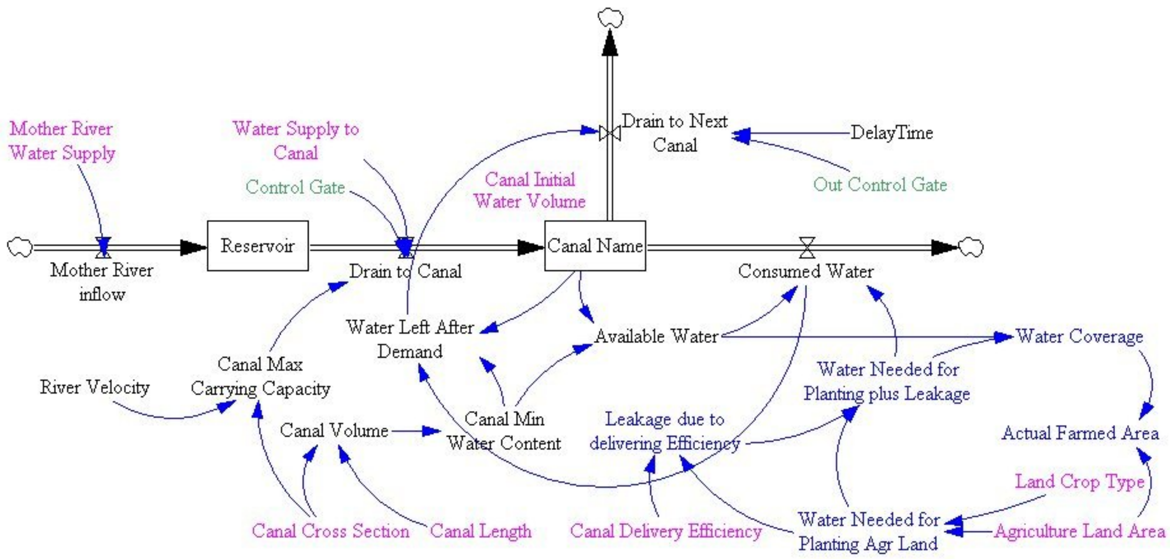


Figure 4-11: Simple Canal Model

The model contains two stocks: the reservoir stock (i.e. High Dam Lake) that stores the annual water inflow that comes from the mother river, and regulates the supply of water into the Nile mainstream during the year. The second stock is the Canal (anonymous canal) that carries and conveys the water to the agriculture land (consumed water). The water left after the demand has been met, drains to the next canal(s) or to the sea if the canal is located at the tail of the system.

The annual inflow of the mother river varies from year to year and therefore the water release from the Aswan High Dam depends on the received inflow. However, the water is released in a way that sustains the irrigated agriculture and the domestic needs. Figure 4-12 shows one of the patterns of water releases practiced by MWRI.

Naturally, every canal has a carrying capacity that cannot be exceeded. The carrying capacity is calculated according to the canal cross-section and the speed of the flow. For various reasons, a minimum quantity of water should always exist in the canal (for example, to retain fish and lilies or for navigation purposes). This quantity is calculated as a percentage (i.e. 25%) of the canal volume.

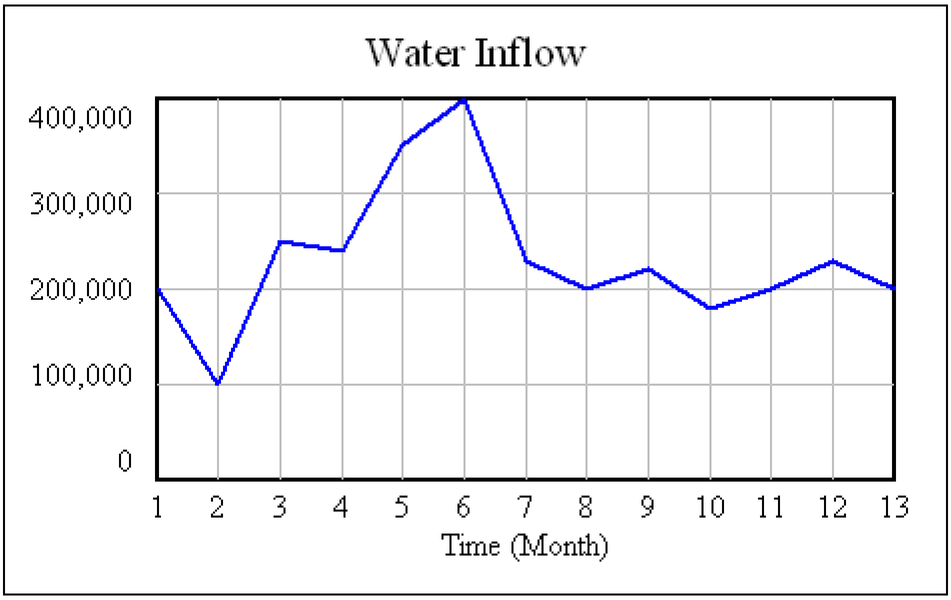


Figure 4-12: The annual inflow rate.

Different crops need different amounts of water. A list of the most popular crops being planted in Egypt and their water requirements per growing period are shown in tables 4-1 and 4-2. Thus, the water demand is simply equal to the area of the agriculture land multiplied by the quantity of water needed to plant the proposed crops. For many years, farmers have used to plant certain crops in succession order. This is known as the cropping pattern. The obvious reason for this is their suitability to the climatic seasons and the flood season, and the growing period for each crop. By careful planning, the farmers can utilize the agriculture land in an optimum manner during the whole year. Dates of planting are well identified and collectively known as the agriculture calendar. The cropping patterns commonly applied in Egypt are listed in Table 4-3.

Table 4-1: Crop Water Need

Crop	Crop water need (mm/total growing period)	Sensitivity to drought
Alfalfa	800-1600	low-medium
Banana	1200-2200	high
Barley/Oats/Wheat	450-650	low-medium
Bean	300-500	medium-high
Cabbage	350-500	medium-high
Citrus	900-1200	low-medium
Cotton	700-1300	low
Maize	500-800	medium-high
Melon	400-600	medium-high
Onion	350-550	medium-high
Peanut	500-700	low-medium
Pea	350-500	medium-high
Pepper	600-900	medium-high
Potato	500-700	high
Rice (paddy)	450-700	high
Sorghum/Millet	450-650	low
Soybean	450-700	low-medium
Sugarbeet	550-750	low-medium
Sugarcane	1500-2500	high
Sunflower	600-1000	low-medium
Tomato	400-800	medium-high

Table 4-2: The growing period for popular crops

Crop	Total growing period (days)	Crop	Total growing period (days)
Alfalfa	100-365	Millet	105-140
Banana	300-365	Onion green	70-95
Barley/Oats/Wheat	120-150	Onion dry	150-210
Bean green	75-90	Peanut/Groundnut	130-140
Bean dry	95-110	Pea	90-100
Cabbage	120-140	Pepper	120-210
Carrot	100-150	Potato	105-145
Citrus	240-365	Radish	35-45
Cotton	180-195	Rice	90-150
Cucumber	105-130	Sorghum	120-130
Eggplant	130-140	Soybean	135-150
Flax	150-220	Spinach	60-100
Grain/small	150-165	Squash	95-120
Lentil	150-170	Sugarbeet	160-230
Lettuce	75-140	Sugarcane	270-365
Maize sweet	80-110	Sunflower	125-130
Maize grain	125-180	Tobacco	130-160
Melon	120-160	Tomato	135-180

Table 4-3: The cropping patterns commonly used in Egypt

		Cropping Patterns		
		Group1	Group2	Group3
1	January	Clover	Wheat	Beans
2	February			
3	March			
4	April			Corn
5	May	Cotton		
6	June		Rice	
7	July			
8	August			Potato
9	September		Corn	
10	October	Rice		Tomato
11	November			
12	December	Clover	Wheat	Beans

The annual water demand for the three cropping patterns listed above is presented in the model as table functions. Figure 4-13 shows the water demand for each crop pattern assuming that the area of the agriculture land (i.e. equals 8.6 million faddan[28]) is planted with one crop pattern once at a time.

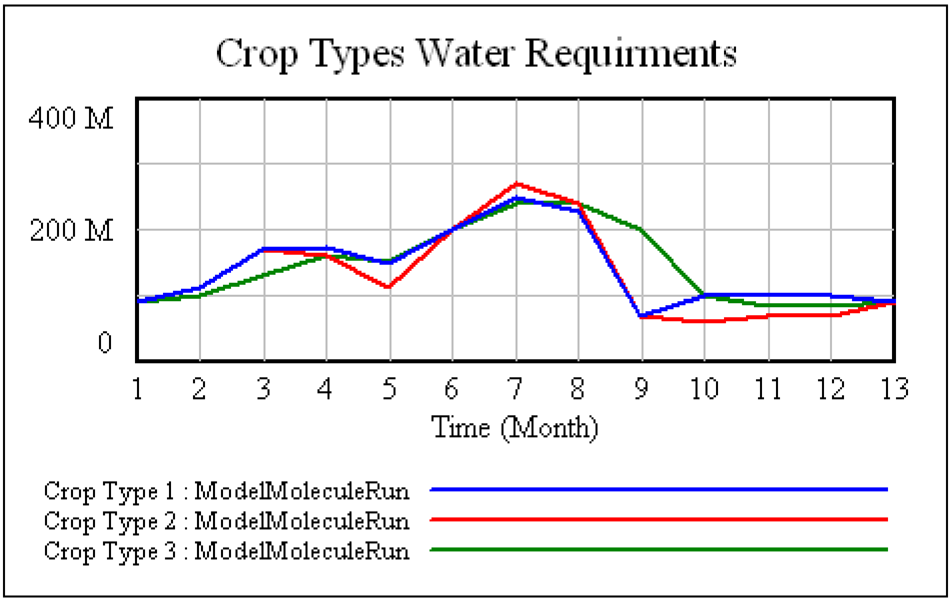


Figure 4-13: The crop types water requirements.

The delivering efficiency in this model is assumed to be 95 percent, meaning that, only five percent of the amount of water delivered is lost. Application efficiency,

[28] Faddan equals to 4200 square meters.

being largely depended on different farmer's behaviour and their awareness, is not included in this model. The quantity of water lost due to delivering efficiency is added to the water demand (water needed for planting) and this becomes the "total water demand" which is compared to the "available water" to identify the "water coverage". If the water coverage is below one, this means there is a shortage in water supply and vice versa. "Available water" simply calculated by subtracting the "minimum water content" that should remain in the canal from the water volume in the canal. If the available water is larger than the total water demand it is simply delivered to the farms (consumed water) and the water left is drained into the subsequent canals. If not, the farms will receive only the available water and the minimum water content in the canal will drain to the next canals with some time delay. From the water coverage, we can calculate precisely the "Actual Farmed Area" from the agriculture land. The model shown in Figure 4-14 has been modified by removing the "Reservoir" stock and the "Mother River Water Supply" rate to work as a *molecule* that can be reused to build a larger model that encompasses the complete irrigation system in the Nile Delta region. This will be explained in chapter five.

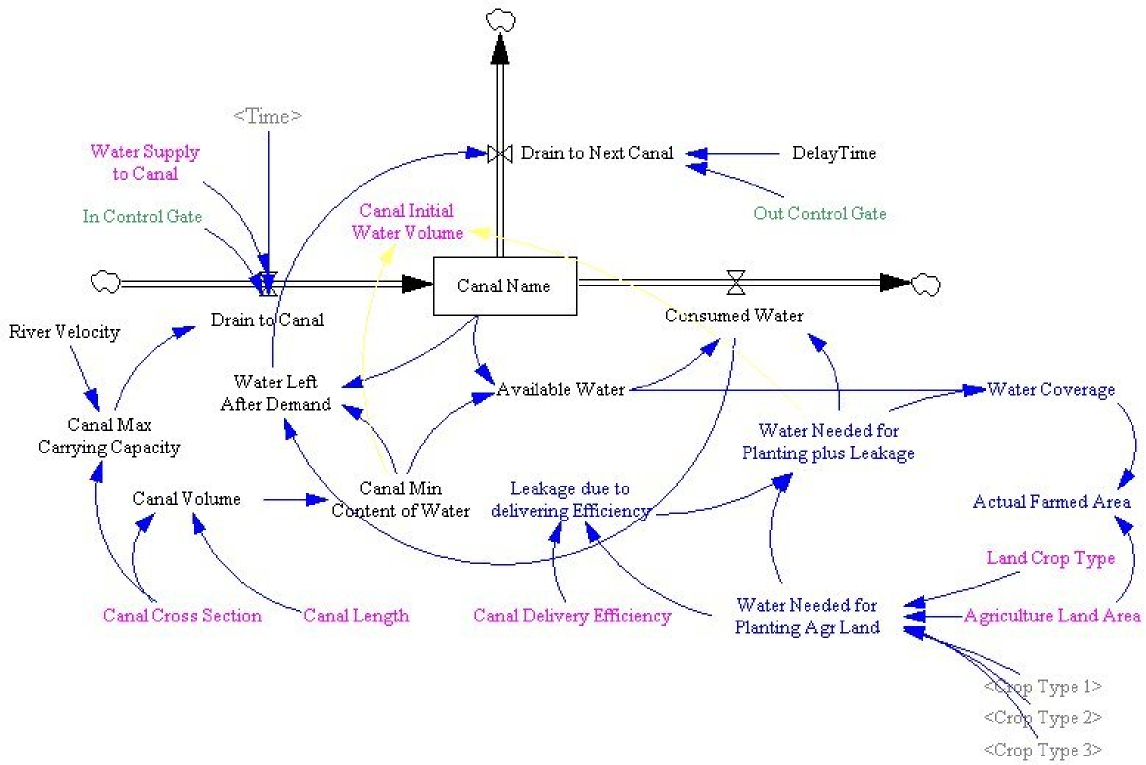
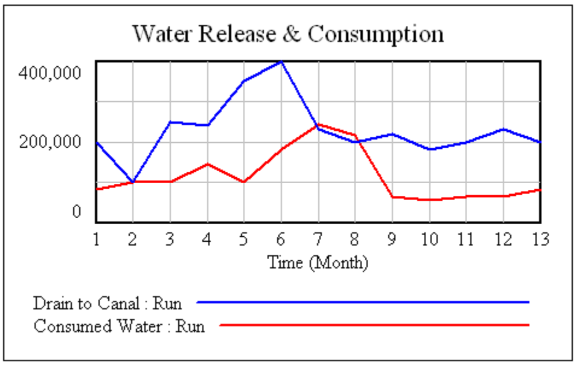


Figure 4-14: The Irrigation model molecule.

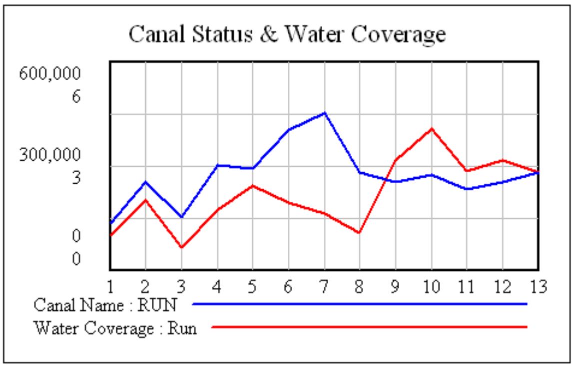
The Model Results

The model is calibrated by introducing the real data obtained from the Ministry of Water Resources and Irrigation (MWRI) and the Ministry of Agriculture and Land Reclamation (MALR) in Egypt during the fieldwork. The data obtained from MWRI illustrates the annual schedule for water release from the High Dam at Aswan. The schedule indicates the quantity of water released every day over the year. For example, the average quantity of water released is 220 million cubic meters and the maximum is 270 million cubic meters at the highest demand in month June. The data obtained from MALR, however, is at "agriculture seasons" basis (i.e., three seasons per year). It illustrates the anticipated water demand according to the cropping pattern plan. The data has been processed, filtered, and introduced to the model to reflect the real situation in an average canal in the second level of the irrigation system that includes three levels in all. It is clear from the Figure 4-15 (a) that the water supply exceeds the demand most of the year with the exception for the month of June where a number of factors combine to mark the month as the water-shortage period. As the hot season peaks, the last irrigation is desperately needed before the harvest season begins, this comes at the time of the lowest level of water in the reservoir, after three long months of flow support from the dammed up water and before the flood arrives in August. Therefore, it is normal to see the canal volume falls and with that the water coverage during this month as shown in Figure 4-15 (b).

The set of graphs on the right hand side in Figure 4-16 represents the model's first run with the real data obtained from MWRI and MALR. The DT considered in this run was one month. Notably, the actual farmed area suffers some losses during the third month of the year. This is obviously related to the descending water coverage during the same period, likely to be below 100%. A close inspection for the model to identify the reasons for such behaviour reveals that there is no real causes stand behind such behaviour. Therefore, it was necessary to change the DT to simulate the model on daily basis rather than monthly basis. The new behaviour shows: no losses in land farmed, the water coverage is above 100%, and the behaviour of the canal looks smoother (more naturally).



(a) The water demand and supply



(b) the Canal state and water coverage

Figure 4-15: The model results.

DT = one month DT = one day

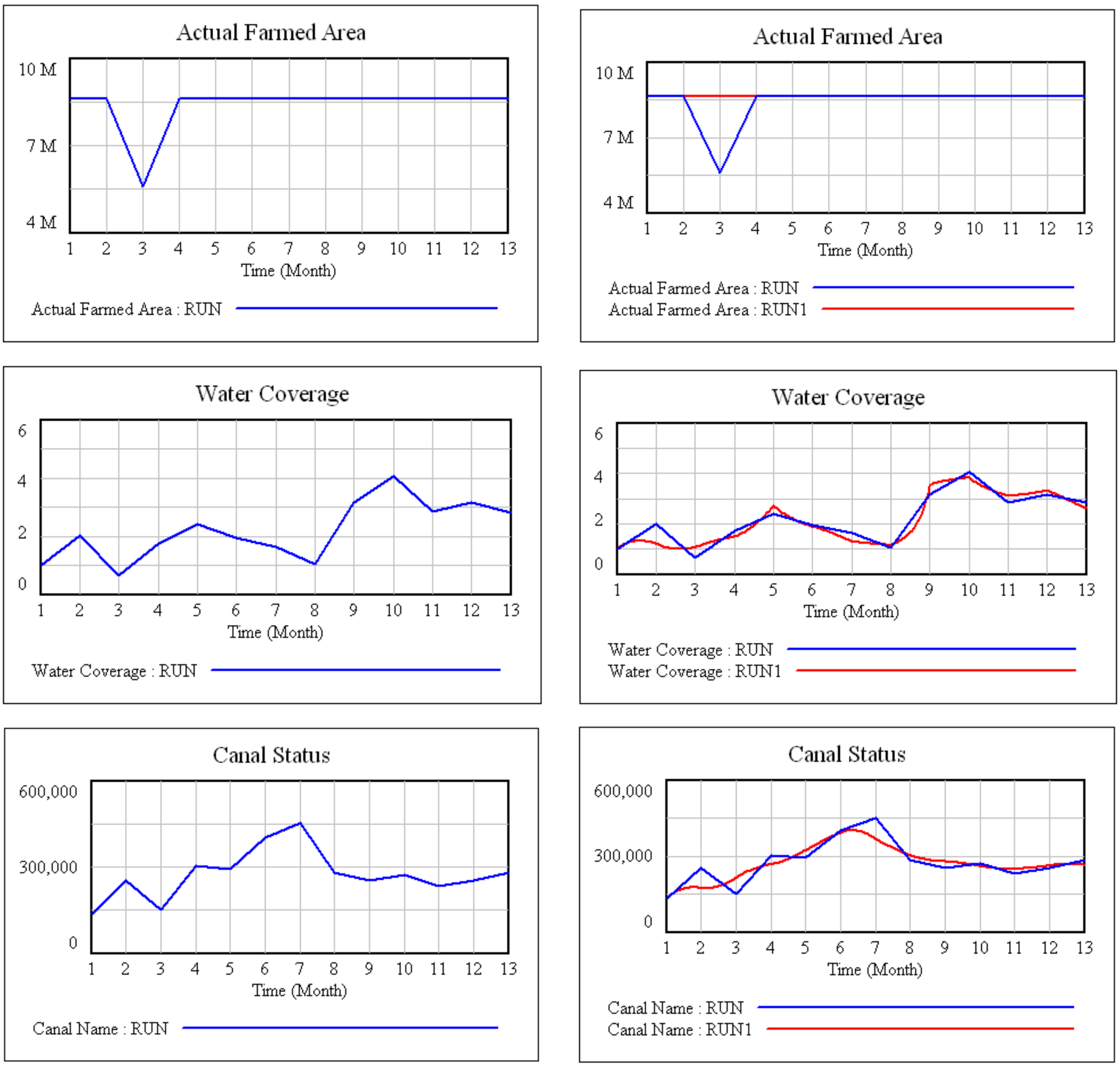


Figure 4-16: The model results from two runs based on various DT.

4.4 Development Strategy

In this section, we describe the outline procedures to develop the SDGIS application. First we explain the conceptual design, the various integration strategies, and select the strategy to be implemented, that is, the "tightly coupling". Second we discuss a number of technical issues related to the development of the SDGIS application. These issues include: (i) using external or internal simulation models (models designed to run independently of from within the GIS), we explain the difference between using the external models verses internal models, and the relative strengths and weaknesses for each approach. (ii) The different ways to design and implement the user interface of the SDGIS application (either from within the ArcGIS by creating the UI as an ActiveX DLL and adding it to the ArcMap as a customised tool, or by using VB to create a standalone UI and employ the ArcObjects to provide the required functionalities. (iii) Having decided to build a standalone application, we can implement this with either VB or VC++. Thus, we highlight the advantages and disadvantages of using the two developing environments.

4.4.1 The Conceptual Design

Up to this point, we have developed two models for the irrigation system. The first model is the GIS model (spatial model) and the second one is the SD model (simulation model). Each of these models provides different insights into the irrigation system. Both models are intended to support the water allocation decision making process, and to help decision makers to take the appropriate actions. In this section, we explain the abstract method to connect both models and the conceptual design of the SDGIS. The implementation of this design will be explained in the next chapter.

Starting with the simulation model, we can see that the stock acts as a container that hosts the value of a variable (e.g., the quantity of water in the canal). The value of the stock changes only through its flows (the control-gates). In GIS, the model is consisting of spatial features assembled in feature classes (layers) that are classified according to the features type (geometry shape such as points, lines, and polygons). The line is simply defined as a connection between two points and represents a linear feature (e.g., river, stream, canal) that acts as a conveyer (or a container) carrying water, which moves from the start point (source) to the end point (sink). Within an irrigation network, such points (source and sink points) normally have control-gates (regulators) to control the flow passing through them. The water volume in the stream is changing through these points (control-gates). Consequently, it can be easily assumed that the linear features (streams) in GIS are the counterparts of the stocks in SD model and the point features (control-gates) are the counterpart of the flow-rates. Lines and points are connected to another neighbouring lines and points forming the irrigation network, the same way the stocks and flows are connected together to form a complete model (the outflow of one stock would be the inflow of the next stock). Therefore, an equivalent simulation model for the GIS model of the irrigation system would include a stock for each canal (this maybe modelled as array stock), and the network of relationships between stocks would follow the same sequence of water flow directions. The inflow-rate of this stock is the control-gate located at the head of this canal. The outflow-rate can be presented either with an end point (sink) or a control-gate if the canal is connected to a neighbouring canal. Because the farm’s area does not change, farms would be represented as auxiliaries rather than stocks. Non-spatial data (attributes) such as conveyance efficiency, crop water needs, crop growing period, and cropping pattern, are represented as constants, tables, or graph functions. In this way, we can connect the simulation model components with the associated GIS features. Simply, for every canal there would be a corresponding stock and for every flow-rate there would be a control-gate.

Since the results of the simulation model are numerical, we can easily store the values of the stocks, flows, and auxiliaries over time in the attribute table of the associated feature class. Then, using symbol palettes provided by ArcGIS (e.g. single symbol, unique values, graduated colours, etc.), we draw/redraw the results as a new map with time advances. Thus, for every time step, with every change in the state of the system we store the new values of the variables and redraw a new map to create a series of snapshots. At the end of the simulation we can retrieve all the snapshots and re-display them sequentially.

Figure 4-17 describes the sequence of operations' execution and the flow of data and information through the SDGIS application. As shown in the top-right side of the figure, first we need to prepare the GIS model by organizing the digital maps into feature classes (e.g., *Canals*, *Control-gates*, and *Farms* feature class). In the attribute table associated with *Canals* feature class, we calculate the length for each canal (this is an automated process within ArcMap), add the canal's average cross section, and calculate the volume of the canal (i.e., the canal length times cross section). The *Control-gate* feature class is connected to the *Canals* feature class to confirm that each canal has a control-gate. In the attribute table of the *Farms* feature class, we calculate the farm area (again, it is an automated process). Then, we build the topological layer (the geometric network) that describes the relationship between the features in the three feature classes. Second, the SD model is developed based on our knowledge regarding the number of canals, their connectivity, and the flow direction. Once completed, the model can be run and tested. These two steps are executed outside the SDGIS application.

Several functions have been created to facilitate the connection between the features in the three feature classes and their counterparts in the simulation model. These functions are organized in modules alongside with the GUI of the application. Therefore, the SDGIS application can be seen as consisting of three modules (the GIS module, the SD module, and the application functions module). The first step to run the SDGIS application starts with loading both models (the SD model and the GIS model) into the application. In the GIS module, the user selects the canals he/she desires to observe its behaviour. The application functions-module, that contains routines to retrieve information from the GIS maps, obtains the values of the selected canals (e.g., canal length, cross section, etc.,) and communicates them to the SD module to initialise the SD model. In the same time, the user can assign values for the decision variables within the SD model (e.g., the initial water volume, the delivering efficiency of each canal, etc.) using the control objects provided in the application interface. The user can set the simulation setup values (i.e., the start time, stop time, and the DT). These steps are represented in the Figure 4-17 with blue arrows. The simulation model would run for one time step. The new values of the stocks (canals) are then communicated back to the GIS module through the functions-module. Using a predefined colour set, the application redraws the selected features according to their new values obtained form the simulation model. The user has the option to save the output map as a new map every time step until the end of simulation where he/she can display the output maps as series of snapshots.

Based on the observed behaviour and the aim of the simulation, the user may take a number of decisions to test policies' performance under a variety of scenarios. For example, for water preservation purposes, the user can adjust a control-gate to regulate the flow of the water through a certain canal (as a short-term action), change the cropping pattern (as a mid-term action), or upgrade the efficiency of a certain canal (as a long-term action). The decision taken by the user alters the values of the model variables. As the simulation continues for one more time step, the model calculates the new values and communicates them back to the GIS module for display. This loop continues until the end of simulation. This loop is represented in the Figure 4-17 with red arrows.

Thus, the GIS model provides the spatial information to the SD model. Then, SD model, through simulation, identifies changes in spatial features over time and communicates them back to the GIS model. These changes in space in turn affect decisions taken by the user. In this way, the operations within the irrigation system can be modelled in time and space in an integrated way while capturing underlying accumulation process, the feedback, and nonlinearities.

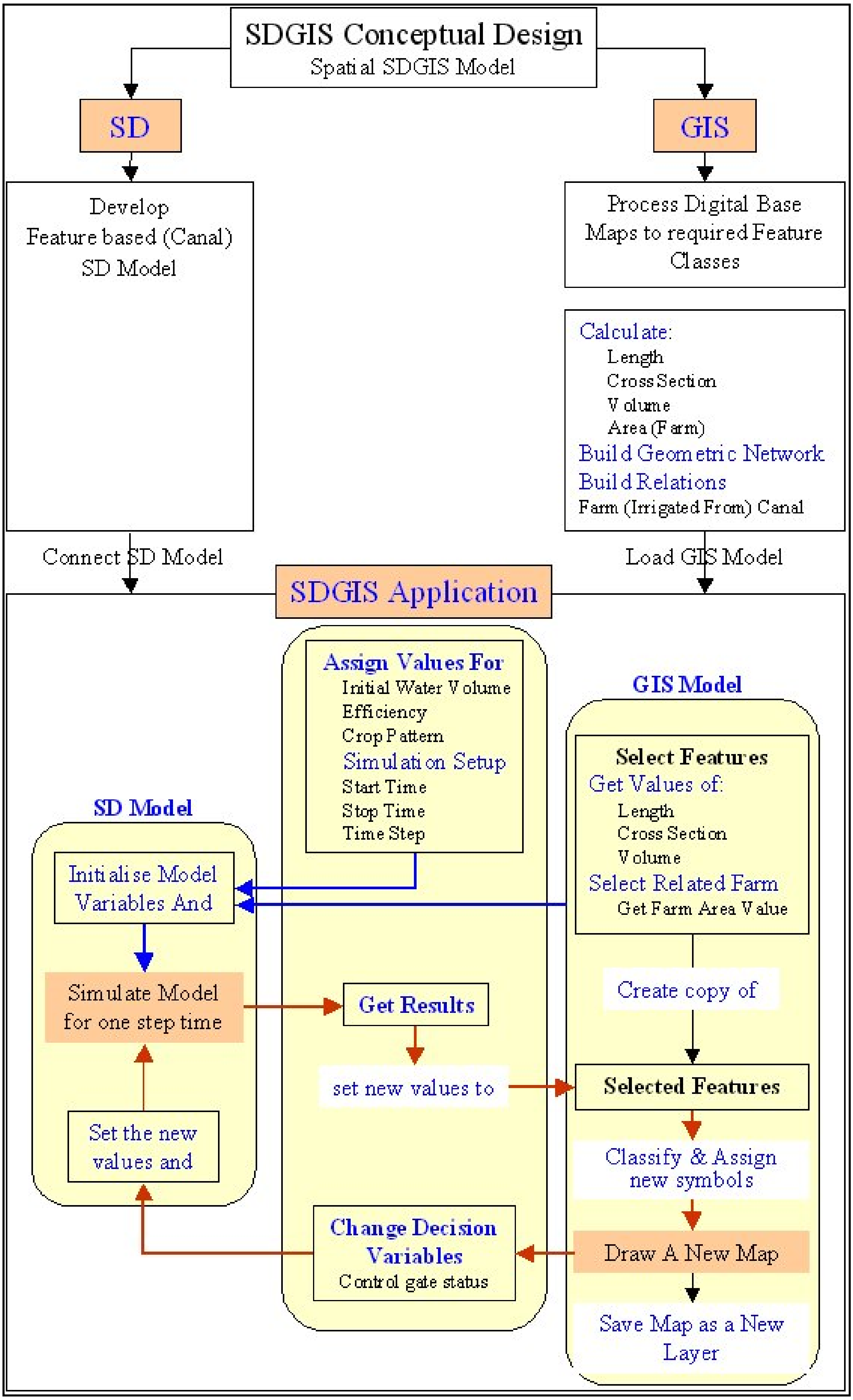


Figure 4-17: The conceptual framework for SDGIS Architecture.

4.4.2 Development Approaches

Conceptually, the integration strategies range from loosely coupled to fully integrated system as Nyerges and Goodchild identified them. In a loosely coupled system, GIS software is used to construct input files that a simulation program can read. The result of the simulation is then read back into the GIS software for display and analysis. The loosely coupled system may be developed using existing technologies, but this type of integration lacks in providing: (1) A consistent user interface; (2) A consistent data structure; (3) the support for development and modification of models and; (4) the user interaction during the simulation runtime.

In tightly coupled system, the GIS user has access to the simulation model through software hooks and/or built-in macro languages. This type of integration can provide access to a consistent user interface and data structure, but currently available software does not support model development/modification and user interaction during the simulated event.

Ideally, in a fully integrated system, the simulation model and the GIS capabilities would be part of the same geo-processing software. Such software should support the construction, execution and manipulation of a geographical simulation model in seamless, user-friendly environment. Unfortunately, such a software package does not exist; the user has to tailor it for applications of his interest as we discussed in the cases of GRASS and SME.

Despite the various integration strategies, the methodology for linking a simulation model (or any computational model) to a GIS is conceptually simple. A GIS-based front-end processor will analyse the input map layer(s) and extract the distributed parameter information based on the data in each map layer. The data are then formatted into an input file structure that the model can use and the model is then run. Depending on the capabilities of the GIS and the model, the GIS can also be used to spatially display output information. This can be accomplished by either using GIS tools to build output map layers or by viewing text or graphical (line) outputs. In fact, the majority of computational applications on water resources utilize information prepared by the GIS. The data is pre-processed in the GIS and then exported to a separate program where the bulk of the computations are carried out. In some cases, the computational model is built within the GIS (e.g., using Map Algebra to simulate the wildfire spread or the oil spill[29]). This approach tends to avoid some of the errors or difficulties that may arise when attempting to establish a communication between two different software packages. In this scenario, the computational model could directly access features in the ArcGIS data model. Some basic concepts behind developing an internal or external computational model are discussed below.

External Model

Creating a simulation model (whether a computational model or SD model) for an irrigation system (or water resources management) that runs independently of ArcGIS provides the model-developer with much freedom of design. In fact, this is the route that most hydrologic simulation models have taken. The disadvantage of this approach is that the developer may have to “recreate” some of the core functionality provided by ArcGIS, such as a network model and editing routines[30]. While some of this functionality can be added using ArcObjects components (viewing, querying, etc.), the more powerful GIS operations can take place only within an ArcGIS application.

Since the simulation model is designed to run independently (externally) from the GIS, some routines would have to be developed within the linkage (e.g., the SDGIS application) to export data from the GIS to a format that the simulation model can understand. Note that import/export routines may not be required if the model (or precisely, the linkage) utilizes the ESRI Object Library (which is of a COM-compliant nature). However, an external model should be expected to run in the

[29] For more information see the illustrated models shipped with ArcGIS 8.3, Spatial Analyst Module Tutorial.

[30] This is exactly the situation that took place when we developed the complete SD model explained in chapter six.

absence of GIS data or even a GIS system, so the ESRI object library would most likely not be included in the model. This is the case implemented in this research, and it is also the case in HEC-RAS, which allows for the user to either create the components for the model simulation in RAS user interface, or import the information required to create the components from exported GIS data [HEC, 1999]. The simplest approach is to import from and export to a file format that is both compatible with and efficient to access from the GIS and the simulation model (in case of ArcGIS, the file types are database files and/or text files). In this research, however, we took the advantage of using object orientation that enabled us to create common objects and associate them with the GIS features and the simulation model components.

Internal Model

If the simulation model is built to operate from within the GIS, then the problem of creating export routines is avoided since the model components can communicate directly with ArcGIS components. An internal model can also incorporate the functionality provided by the GIS. In this case, the graphic simulation software (e.g., Vensim) can not be used and the model should be written as text then the model would be created as an ActiveX DLL that utilizes the ESRI Object Library. The DLL can then be added to an ArcMap document as a custom tool. The disadvantage of this approach is that the computational model's operation must follow the rules of the ArcMap application; otherwise, it may generate an error that causes ArcMap to halt.

Interface Design

There are two main alternatives to create the graphic user interface (GUI) for the integrated system. The first one involves utilising the ArcObjects. In this case, the developer would use for example Visual Basic or Visual C++, and has complete freedom in designing the interface. However, the developer should still follow guidelines of sound interface design, such as those outlined by Hartley (1998).

The second alternative is to create a custom graphical user interface within the ArcGIS (i.e., within the ArcMap module) utilising the internal VBA Editor. This is the approach that ArcFM has used with its special ArcFM Viewer. The Viewer is built from the basic ArcGIS GUI components, with additional tools and buttons designed to work with the ArcFM software [ESRI, 1998]. By developing the user interface within the GIS, many of the basic interface components (such as file menus, selection tools, etc.) from the ArcGIS may be used, resulting in a shortened development time for a given application.

Development Environment

In the following paragraphs, we highlight some of the considerations when choosing a development environment. In principal, developing with ArcObjects does not restrict the developer to a proprietary development environment, and any compiler capable of working with COM can be used. However, the choice of development environment is not a simple task, and is influenced by many factors. Many developers would select either: the Visual Basic for Applications, Visual Basic, or Visual C++, while others may use Delphi, C++ Builder, or similar languages. The primary driving force is the experience and skill level of the developer(s) that will write the code. Other issues worth considering are the requirements, performance, the development process, and security of code.

The performance issues of choosing the development language are not as significant as a developer might think. Since the majority of the work will be performed within the ArcObjects objects, which are all written in C++, the developer's customisation language is for the most part used to control the program flow and user interface interaction. Since Visual Basic uses the same optimised back-end compiler technology that Visual C++ uses, the generated machine code performs at a comparable level. Tests have shown that to perform typical actions on features contained within a database (drawing, querying, editing, and so on), Visual Basic is approximately 2% slower than optimised Visual C++ code, and Visual Basic for Applications is 2% slower than Visual Basic [Microsoft website; ESRI, 2001].

Visual Basic is a very productive tool, especially for user interface development, but there are limitations to what can be done in Visual Basic. In the majority of cases, these limitations will not affect developers customizing and extending ArcObjects, with the exception of Custom Features. Many of the limitations have to do with the development environment itself. Debugging Visual Basic code is not as flexible as Visual C++. Using Visual Basic in a large development environment with many developers is not as productive as Visual C++, since partial compilations of projects are not supported. If one file is changed in a Visual Basic project, all the files must be recompiled. Since Visual Basic hides much of the interaction with COM away inside the Visual Basic Virtual Machine, low-level COM plumbing code cannot be written in Visual Basic.

Since Visual Basic for Applications does not support the creation of DLLs, all the source code must be shipped inside a document. It is possible to lock the source code projects with a document to stop third parties from seeing the customisation code. However, this locking of the project also prevents third parties from using VBA to customize the application further. VBA is an ideal prototyping environment that provides the means for deploying lightweight customisations, but for other more elaborate customisations Visual Basic should be considered. VBA also suffers from having its own form designer, meaning the UI source cannot be shared between VBA and Visual Basic. In addition, the controls used by VBA do not expose their window handles, which further limits their use.

To use ArcObjects in a standalone Visual Basic application, the developer must first add a reference to the ESRI Object Library (esriCore.olb). Using ArcObjects inside ArcMap or ArcCatalog, a reference to the esriMx.olb and esriGx.olb libraries is automatically made when the user start the application. Thus, no external referencing to the ESRI Object Library (esriCore.olb) is required. These technical issues will be explained in more details in the next chapter.

Concluding Remarks

For the SDGIS application presented in this research, different architectures for coupling SD with GIS (embedded coupling, tight coupling, and loose coupling) were considered. Finally the integration under a common interface, also known as tight coupling, is used. The selection of the tight coupling is based largely on the functionality requirements depending on the purpose of the system. One requirement was a dynamic data exchange (DDE) between the SD model and the GIS to provide a feedback between time and space (DDE is not possible with loose coupling). Another important aspect was to keep the SD modelling tool as the main model development environment because of its ability to build models using graphical icons (not possible with embedded coupling). The link is provided through a common interface (that is the SDGIS application) that supports the integration of the spatial features (e.g., lines, and polygons) with the simulation model components (stocks and flows).

4.5 Conclusions

Object-oriented methods cover methods for design and methods for analysis. Sometimes there is an overlap, and it is really an idealization to say that they are completely separate activities. Design encompasses the process of decomposition and a notation for depicting logical and physical as well as static and dynamic models of the system under design. Analysis examines requirements from the perspective of the classes and objects found in the vocabulary of the problem domain. Within the object orientation paradigm, methods developed for design are frequently applicable to analysis, and vice versa.

Object-orientation does not just mean that there is a database with objects in it, but that the system is organised around the concept of objects that have properties and behaviour (methods). The main advantage of the Object Oriented paradigm is its’ easy of understanding; it enables natural representation of real world objects, their mutual relationships and behaviour is therefore close to end-users. Object oriented applications are easy to maintain because they are modular and objects are independent of each other; a change in one object should not affect other objects in the system. The paradigm supports reusability too; objects are self-contained and may be reused effectively in other similar applications. It also supports distributiveness and parallelism.

Within the Object Oriented framework, the entities of the phenomena of interest form the essential objects. These objects are linked through associations. The location (represented by geographical coordinates) and the time (represented by date or time step) are the properties of the objects. Methods are actions that objects execute when certain event occurs. Thus, with the time advance (event), object can easily change/update its location (method) that explicitly leads to state-change of an object. Issues such as incompatibility in data resolution, spatial-temporal handling, and dynamic (runtime) simulation can be adjusted due to the flexibility of this framework.

Object-oriented GIS allows for encapsulation of geospatial entities so that all of its geometry, data, and behaviours are contained in a single object. Hierarchies or networks of objects can be constructed to represent complex objects (e.g. hydrological network) and the interrelations between objects. The objects can also be related via a layer hierarchy based on any relationship.

The object-oriented paradigm originated in computer simulation domain. Simula has been considered as the first object-oriented programming language and the predecessor to Smalltalk, C++, Java, and all modern class-based object-oriented languages. Simula was designed to perform discrete simulation. Object orientation has been added to continuous simulation in two different ways: As a library of classes usable from a general purpose OO language (usually C++) and as a language with built-in OO constructs.

The essence of the object-oriented paradigm has been applied to a number of simulation software in different ways. Molecules and Components are two of them. Molecules are associated with Vensim while Components have been implemented in Powersim Studio. Molecule is a portion of a well-tested and documented model.

Molecules are made of primitive stock and flow (or auxiliary) elements and are, in turn, the building blocks of superior models. One of the simplest molecules, and one that probably appears in most models, is the decay process. Components are similar to molecules although they may have more complex structure. The component is the counterpart of the class in object-oriented world. It has a customisable interface for communicating with the rest of the model. Thus, the component encapsulates the entire elements (variables) of the submodel, and can be used to create instances. The component has methods to import and export the values of its entire variables. Polymorphism could be achieved through the component interfaces, as components with equal interfaces are interchangeable.

A number of commercial simulation software, commonly come with DDE or DLL, is available. However, there is a significant difference in the DLL's capabilities and not all of them can communicate with external applications. Vensim DSS provides enhance features and strong DLL with enhanced functions.

The focus in this research is to integrate the simulation models with the GIS. SD models may be built using Powersim, Vensim, Stella or any other visual SD software. The challenge lays in the link between the SD and GIS. Such a link can be established thought the use of DDLs. Although Powersim Studio provides the opportunity to build more hierarchally structured models compared to the flat ones in Vensim, Vensim DLL offers more capabilities to control the model from external applications such as Visual Basic. Both software have been used to develop a simulation model for the irrigation system and have been tested to work with our application SDGIS that has been built using Visual Basic. Based on our experience, we decided to proceed and develop the final application SDGIS using Vensim DLL as we then obtain more flexibility and control over the simulation model. Since the hierarchal structure is not provided in Vensim, building a flat model was the only option. However we make use of the concept of reuse and created a simple model to work as a molecule that would be use in developing the complete model in the coming chapters.

In this chapter, we introduced the conceptual framework to integrate a simulation model for an irrigation system with a GIS model encompasses various feature classes representing the spatial network of the irrigation system. The framework (or the conceptual design) will be implemented using Visual Basic in the next chapter. Vensim® software is used to develop the simulation model for the irrigation system, and ArcGIS software for the geographic data processing and visualization. The GIS provides irrigation network characteristics (e.g., connectivity rules, branching, flow direction, and sink points) and information on canals (e.g., name, location, length and cross-section) from which other variables can be calculated. Whereas, the SD model describes the flow process, the accumulation and/or discharge of water in/from the canal, and calculates: water volume; water availability; water demand according to the farm area, crop type, and crop water needs per growing period, water coverage, and actual farmed areas. There is a dynamic data exchange between the SD model and GIS to simulate the water flow process and to calculate any spatial and temporal variation in agriculture area and water coverage.

Chapter 5

The SDGIS Architecture

The Implementation of the SDGIS Application

5.1 Introduction

The primary goal of this chapter is to explain the integration method using simple examples. First, we document the creation of the SDGIS application that is the common interface that facilitates the integration of the simulation model with the GIS model by converting the conceptual framework to an application software[31] (i.e., SDGIS). This application is developed using Microsoft Visual Basic. We describe the application structure and its components through a comprehensive set of figures and diagrams. A number of functions that facilitate the connectivity between the simulation model and the GIS model are described in this section. The functions are described in the same sequence of their execution as the user runs the application and establishes the connections between the two models. The complete source code of the application is provided in Appendix A.

Second, we run the application and test its performance using: (1) the simulation model developed in chapter four (section 4.3.2) that represents the interaction between the water distribution process and the water utilization in agricultural processes; (2) an enhanced version of the GIS model that includes a number of feature classes that represent the components of the irrigation system and the corresponding pieces of agriculture land. The two models are tightly connected through the SDGIS application. It is very important to test the operability of the SDGIS application with a real data from the real world. To do so, we used a part of the data collected during the fieldwork.

Third, having tested the application and become confident of its operability, we took a step further and developed another larger simulation model using molecules as building blocks and the array structure to cover the entire irrigation

[31] **Application software** is a subclass of computer software that employs the capabilities of a computer directly and thoroughly to a task that the user wishes to perform. This should be contrasted with *system software* which is involved in integrating a computer's various capabilities, but typically does not directly apply them in the performance of tasks that benefit the user. In this context the term *application* refers to both the *application software* and its *implementation* [Wikipedia: the free encyclopaedia, Accessed 2007].

system. We also used a new version of the GIS model that covers the entire area of study (i.e., the Nile Delta region). The new models made it necessary to introduce some changes within the GUI of the SDGIS to comply with the array structure. Therefore, we developed a new version of the SDGIS application and described the changes that were introduced and the associated test results at the end of this chapter. The SDGIS Array Application source code, the associated SD array model and the Canal Classes Map are provided in Appendix B.

This development has proved that SDGIS, and consequently our method of integration, is not limited to a certain simulation model or to certain maps. The SDGIS application supports efficiently any SD simulation model and any number of maps associated with such a model. The key issue is the matching, and the concept behind this matching, between the SD model components and their counterparts (i.e., the spatial features) in the GIS model.

5.2 The Implementation of the SDGIS

In software engineering, the implementation (also known as programming or coding) is the process of writing, testing, debugging, and maintaining the source code of a computer program. This source code is written in a programming language. The purpose of the programming is to create a program that exhibits a certain desired behaviour. Implementation is regarded as one phase in the software development process, and it is the phase that follows the conceptual design [Wikipedia: the free encyclopaedia, Accessed 2007].

In this context, Microsoft Visual Basic 6.0 was employed to implement the SDGIS application and to create the GUI. The application is implemented as a stand-alone application that runs on the Windows platform. The aim of the SDGIS application is to facilitate the integration of the simulation model with the GIS model by establishing connectivity between the simulation model components (stocks and flows) and the features in the landscape (using their unique key attributes). The specific procedure followed in this case for creating the SDGIS is described below, followed by a description for the implementation of this application based on empirical data.

The main interface of the SDGIS application consists of one *Form* module contains a number of panels that are generally a *Tab* dialogue created with the SSTab *Control* component and they are designed to group related functions together. Components such as *Frame* and *Label* are used mainly to set the appearance of the dialogue box whilst *Edit-Boxes* serve as the major source of the user input. *Slider Controls* and *Check-Boxes* are used to indicate the user choices and *Combo-Boxes* present a list of items for the user to choose from. To accept input from a component such as an Edit-Box and assign the value to a property, it was necessary to write few lines of code in the component's procedure page. Some panels also include *Tool-Bars* made up of *Command Buttons* that are used mainly as shortcuts to execute various functions that organized in *Standard* and *Class Modules* within the application.

5.2.1 Creating the SDGIS Project

The SDGIS is created as a Standard EXE Project within the environment of the Visual Basic (VB) software. It is worthwhile to remember that VB is an independent software that should be installed on the computer, alongside with the Vensim and ArcGIS software, in order to create such integrated application as SDGIS. To create a new Standard EXE Project, simply start Visual Basic, when prompted for the type of project to create, select Standard EXE and click *Open*. Visual Basic prepares the project for the creation of an EXE application. In the Project Explorer window shown in Figure 5-1, a single empty *Form* with a default name *Form1* has been automatically created by the software. *Form1* is the default Start-up component for the EXE project, which serves as a link between various Objects. In the *Properties* window, several properties for *Form1* are listed. For the purpose of our application, *Form1* has been renamed into “FrmMain” by editing the *Name* field in the property page of the *Form*.

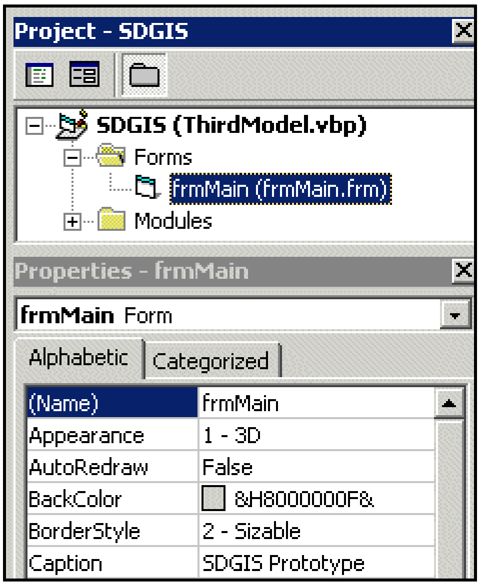


Figure 5-1: Properties of SDGIS application.

Setting References for the Application

In order to make Visual Basic recognize the various Object-Classes included in the ArcObjects Developer Kit, a reference to the ESRI Object Library must be added to the Project's *References* as shown in Figure 5-2. ESRI Object Library contains a standard set of *Object-Classes* and *Interfaces* used to perform various tasks associated with the ArcGIS. The *Interface* is simply a declaration of related properties and methods that may be used by a *Class*. No implementation code exists in the interface. The implementation details are left up to the class that implements the interface. For example, the properties and methods of the *MapControl* are used to define a map in the project. Before the *MapControl* interface can be implemented, the project must obtain a reference to the ESRI Object Library. In the Project's Menu, click *References* to open the references window, place a check mark by: ESRI Object Library, ESRI AF Commands (VB) Library, and ESRI AF Commands (VC) Library. The project can now access all the *Public* components of the ESRI Object Library.

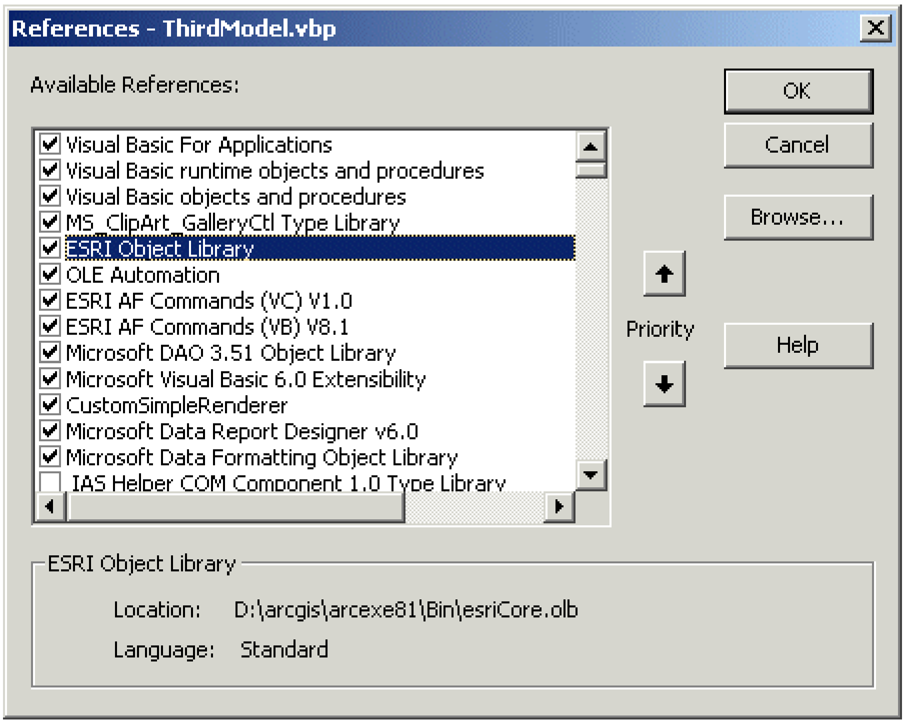


Figure 5-2: Adding a Reference to the ESRI Object Library.

A reference to the Vensim® software must be added too, however, Vensim can be run, and communicate directly with the application, through its Dynamic Link Library (i.e., the file called "vendll32.dll" installed on the computer and located in the directory C:\windows\system32). In this case, we only need to declare the functions that included in this DLL as shown in Figure 5-3. Note that Vensim DLL is an independent library that can be called from other applications such as Visual Basic, Visual C++, Delphi, etc. The details of the functions that included in the DLL are explained in the Vensim Manual. The declaration of the functions can take place on either the Form "FrmMain" procedure's page or in another Module. To have a well-organized project, we chose to declare the functions associated with each model (SD model, and GIS model) in an independent module.

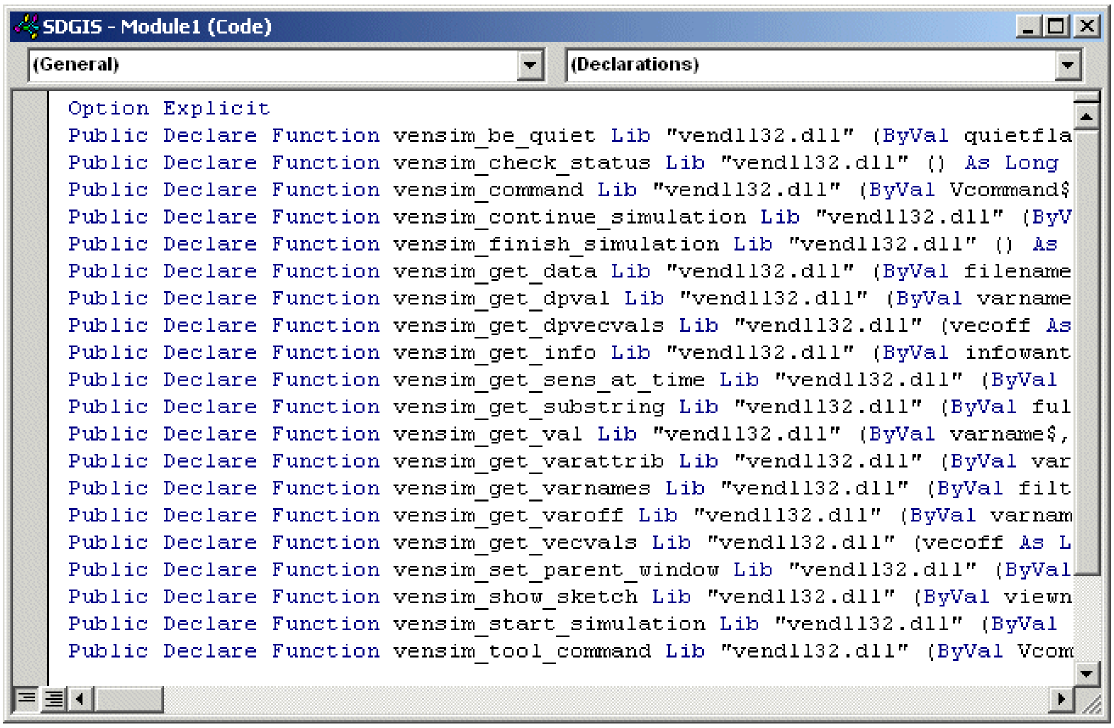


Figure 5-3: Adding Reference to the Vensim software.

The Project Layout

In Visual Basic, the source code is stored in modules. There are three kinds of modules: *Form* modules, *Standard* modules, and *Class* modules. Form modules are visible to the user while other modules contain code only and are invisible. Simple applications can consist of just a single *Form*, and all of the code in the application resides in that form module. As the application gets larger and more sophisticated, additional forms maybe added. Eventually we might find that there is a common code we want to execute in several forms. We do not want to duplicate the code in both forms, so we create a separate module containing a procedure that implements the common code. This separate module should be a *Standard* module. Over time, we can build up a library of modules containing shared procedures. Each standard, class, and form module can contain:

- Declarations: Where we can place constant, type, variable, and DLL procedure declarations, as we did with Vensim.

- Procedures: A Subroutine, Function, or Property procedure contains pieces of code that can be executed as a unit.

Form modules (.FRM file name extension) are the foundation of most Visual Basic applications. They can contain procedures that handle events, general procedures, and form-level declarations of variables, constants, types, and external procedures. If we were to look at a form module in a text editor, we would also see descriptions of the form and its controls, including their property settings. The code that we write in a form module is specific to the particular application to which the form belongs; it might also reference other forms or objects within that application.

Standard modules (.BAS file name extension) are containers for procedures and declarations commonly accessed by other modules within the application. They can contain global (available to the whole application) or module-level declarations of variables, constants, types, external procedures, and global procedures. The code that we write in a standard module is not necessarily tied to a particular application. It could be reused in many different applications if we were careful not to reference forms or controls by name.

Class modules (.CLS file name extension) are the foundation of object-oriented programming in Visual Basic. We can write code in class modules to create new objects. These new objects can include our own customized properties and methods. Actually, forms are just class modules that can have controls placed on them and can display form windows.

In this application, SDGIS, we chose to create one *Form* module (FrmMain.frm) and three *Standard* modules (SDModel_Functions.bas, GIS_Functions.bas, and ErrorHandling.bas) that contain source code associated with the functions related to each model (SD model and GIS model). the project layout is represented in Figure 5-4.

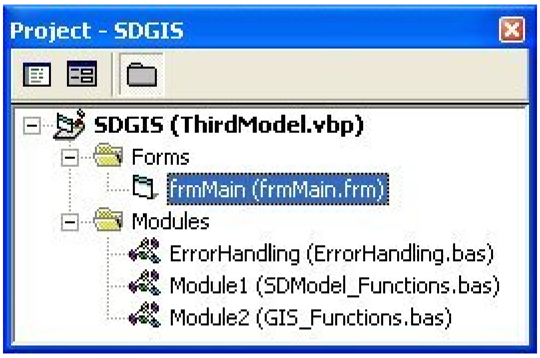


Figure 5-4: The SDGIS application Layout.

The Form Module (FrmMain.frm) includes five panels. Each panel has a number of control objects (e.g. Command Buttons, Picture-Box, List-Box, Text-Box, etc.) to facilitate the connectivity between the SDGIS application, the simulation model, and the GIS model, and to provide the user with a full control over the models, the simulation performance, the map display, and the creation of reports. The panels and the control objects included in the FrmMain are described in details in the GUI Architecture section.

The Standard Module (SDModel_Functions.bas) contains a number of functions and subroutines associated with the simulation model. The functions were declared as *Public* functions to make them accessible from any point in the application. For example, command buttons placed on the FrmMain can call the functions in this module to load the simulation model, to retrieve the variable's names and values, to trigger the simulation, to retrieve the results, and to display the graphs as they are produced by the simulation software.

The Standard Module (GIS_Functions.bas) contains a number of *Public* functions and subroutines associated with the GIS model. For example, the function *BuildCommandCollection* creates a toolset that contains 23 tools (e.g. add/remove layer, zoom in/out, select feature, query attribute, etc.) and places them on a Tool-Bar that works with the feature classes loaded into the project's MapControl.

The Standard Module (ErrorHandling.bas) contains a variety of functions to handle the errors that may arise as a result of the user's incorrect actions. Handling the errors properly is very important because : (i) If a tool, for example, produces an error and does not adequately handled, ArcMap considers the tool as a “broken” tool and will not allow further calls to it; (ii) If a tool is broken, then it will not function again until the tool’s DLL is reinstalled on the computer. In this application, errors were addressed in two ways: error prevention and error handling.

A useful method to prevent errors is to limit the range of inputs allowed by the user. For instance, if a tool adds values from a user-specified field to produce a total value, then the input form should limit the choice of fields to those that store numeric values. Similarly, functions that perform operations on lines (e.g. stream, canal) should only display *Polylines* layers as choices on the input form. Limiting user inputs to feasible values can save many hours of error handling work later on. Limiting user selections also benefits the user by removing many of the fields or layers that the user would not select anyway.

Another method for preventing errors is to check the nature of each value before processing that value. For instance, before an operation is performed on a value in a field, the tool should check to see if that value is valid. Otherwise, the tool may attempt to perform an operation on a null value, resulting in an error. While this method is a more secure way of preventing errors than the previous method, it can also add an enormous amount of code to the project. A combination of both methods was found to be the best approach to error prevention.

If errors do occur during a tool’s operation, a message box appears displaying a description and a number for the error. In some cases, the location of the error within the code is also specified. While this technique may not be the best strategy for handling errors, it is easy to implement and satisfies ArcMap so that the tool is not considered broken and the execution terminates.

The GUI Architecture

The main *Form* (FrmMain) in the application is shown in Figure 5-5. The *Form* includes five *Panels* named as following: “SD Model”, “GIS Tools”, “Graphics and Charts”, “Tables”, and “Reports” respectively. The panels were created by adding an SSTab Control Object to the *Form* and setting the number of *Tabs* equal to five in the properties’ window of the SSTab. We designed the Form in this way in order to organize the appearance of the application according to the functions associated with each model (the simulation model and the GIS model).

On the code page of the FrmMain, a number of global variables were declared. These variables are used to store the values of the intended features from the GIS model and their counterpart components from the SD model in order to couple them. For example, CanalLengthVal, CanCroSecVal, are variables declared to store the values extracted from the fields “Canal Length” and “Canal Cross Section” in the attribute table of the irrigation network layer and to push them to the simulation model to initialize the variables “Canal Length” and “Canal Cross Section” in the model. Similarly, CurCanWaterVol is a variable that stores the value of the “current canal water volume” extracted from the stock “Canal” in the simulation model and send it back to the map in order to draw/redraw the canal feature with a new symbol and colour suited for this value. CanIntWaterVolVal, CanMaxCapVal, are variables that hold values of the “initial water volume” (to initialize the canal stock) and the “maximum capacity” of the canal. The values of these variables can be assigned in two ways: (i) The user can edit the associated Text-Box on the FrmMain and set the value or; (ii) It can be automatically calculated by the application. For example, the “initial water volume” can be calculated as a percentage of the “maximum capacity” of the canal (e.g., 30%), the maximum capacity in turn can be calculated as: the “canal length” times the “canal cross section”. By default, the application calculates the values of these variables first (when the map is loaded) and displays these values in the associated Text-Boxes. Then, the user has the choice to modify these values. Finally, the application pushes these values to the simulation model.

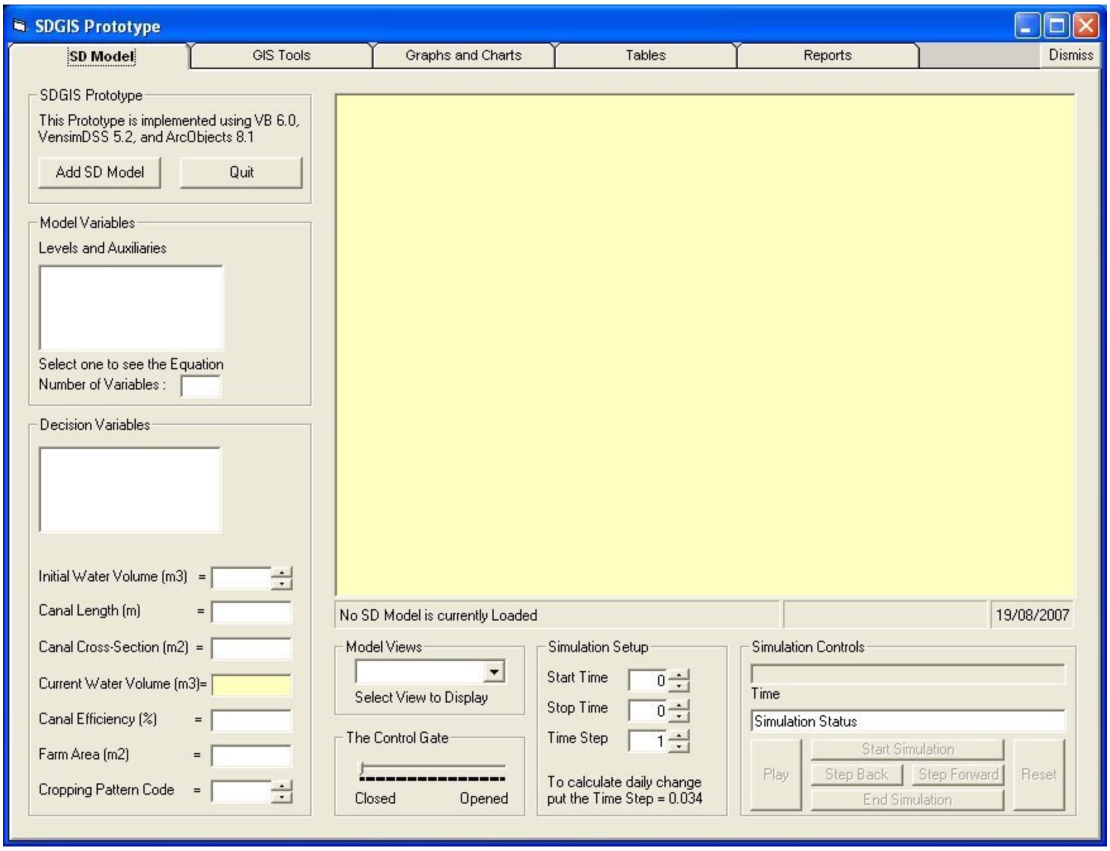


Figure 5-5: The GUI of the SDGIS application (SD Model Panel).

5.2.2 The "SD Model" Panel

The first panel in the SDGIS interface is called "SD Model". As its name implies, the panel contains a number of control objects such as: a PictureBox working as a viewer to display the model sketch/views and the output graphs during and after the simulation. Two List-Boxes are located on the left hand side of the panel: The upper one is used to display the model variables' names (i.e., the names of the stocks, flows, and auxiliaries). The total number of variables is shown in the Text-Box right below this List-Box. When the user selects a variable from this List-Box, the equation associated with this variable is displayed in the Status-Bar under the Picture-Box. This give the user access to the equation related to each variable. The lower List-Box is used to display the constants. We chose to put them in a separate List-Box because the user might want to change their numerical values by editing the content of the Text-Boxes placed below the list or by the way of any map related to the model.

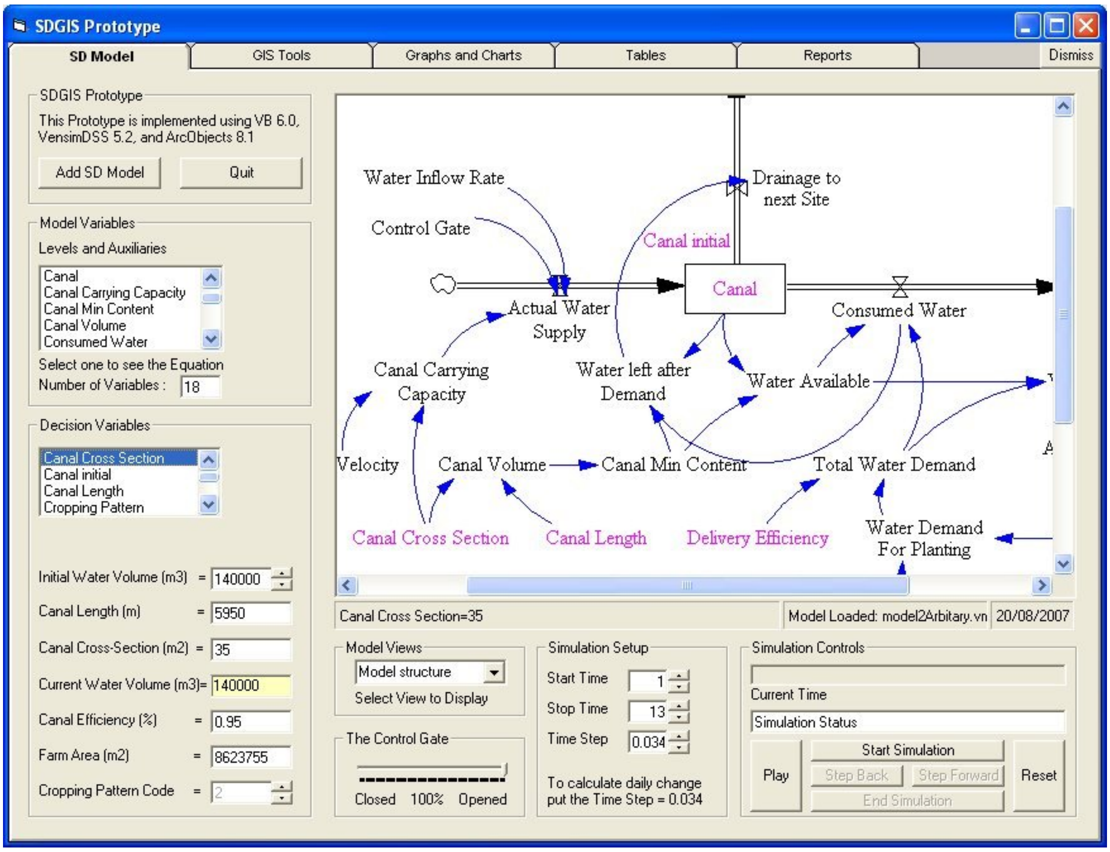


Figure 5-6: Loading the simulation model into the SDGIS application.

In this panel, the "SD Model" panel, there is a number of control objects (e.g., Command Buttons, Text-Boxes, Combo-Box, and Slider) organized in several Frames. The role and the functions associated with these control objects are described in the following paragraphs.

Command Button: Add SD Model

This command button launches a dialog box (popup window) and requires the user to select a simulation model to be imported into the application. The application then calls seven functions to extract information about the selected model. These functions are used in other procedures within the application. Therefore, we made them *Public* functions and kept them in the SDModel_Functions Module. The functions are described in their order of execution in the Add SD context:

GetModelName: This function retrieves the name of the selected model from the popup window appearing when the user clicks the button and sets the model's name and path into the application as the target model to work with.

GetModelVariableNames: This function retrieves a vector of the *levels'* and *auxiliaries'* names from the target model and puts them as single items into the upper List-Box. The property *Click* of the List-Box has a method to call the function *GetModelVariableValues* to retrieve the string value (the equation) of the selected item from the model and display it in the Status-Bar right below the Picture-Box.

GetModelVariableValues: This function retrieves the numeric values of the variables that will be connected to the associated features in the map. The function can retrieve the numeric values as well as the string values (the equations); therefore, the same function works with the upper List-Box described above.

GetModelConstantNames: This function retrieves a vector of the *decision variables*' names (gaming variables), the *constants*, *initials*, and *lookup* tables. The function then puts these names as separate items into the lower List-Box. The property *Click* of the List-Box has a method to call the function *GetModelVariableValues* to retrieve the *value* (numerical/string) of the selected item and display it in the Status-Bar.

GetModelConstantValues: This function deals with the simulation *Start* time, *Stop* time, and *Step* time. The function retrieves the value of the simulation times and put each of them into a separate Text-Box located in the Frame labelled "Simulation Setup" shown in Fig. 5-9. The Text-Box is also editable, meaning that the user can change the value of the *Start*, *Stop*, and *Step* time before the simulation is triggered.

GetModelViews: SD models may contain multiple diagrams, windows, or views. This function gets a vector of diagrams' names and put them as individual items into the List-Box located in the Frame labelled "Model Views" under the Status-Bar and to the left of the Frame labelled "Simulation Setup". The property *Click* of the List-Box has a method to call the function *WinnitHandel* that displays the selected view in the Picture-Box as shown in Figure 5-6.

Command Button: Quit

This command button checks the status of the simulation, terminates the running simulation if it is in an active mode, unloads the simulation model from the application, resets all the control objects to the default position (e.g., evacuates the Picture-Box, List-Boxes, Combo-Box, etc.). Sets the values of the global variables to *Null* and recovers the memory space. This command button is used if the user wants to change/remove the simulation model without terminating the application itself.

The Combo-Box: Model Views

Usually, a large and well-organized SD model contains a number of views (or diagrams). When the user loads the simulation model, the application retrieves the names of the views included in the simulation model and lists them in this Combo-Box. When the user selects a certain view from the Combo-Box, the application displays the selected view in the Picture-Box.

The Slider: Control Gate

One of the significant decisions that the user may take during the simulation is to regulate the flow of water into the canal. In the original model, the control gate is set completely open. During the simulation, the user may choose to reduce the quantity of water that passes through the control gate, or to close it completely to stop the flow of water. For this purpose, a *Slider* control object is provided to receive the user's decision as a percentage of the full opening valve capacity. For example, Figure 5-7 shows the behaviour of the system without any intervention from the user. In Figure 5-8, the simulation has been started with a complete open valve (100%), the water inflow (represented by the green line) followed the same course. At simulation Time = 4, the control gate has been closed completely (0.0%). Obviously, the water supply curve dropped to zero, and the course of the canal volume and water demand curves has changed. Then, at simulation Time = 6, the control gate has been opened half way (50%) until the end of the simulation. The effect of using the control gate slider on the behaviour of the system can be seen by comparing the two figures.

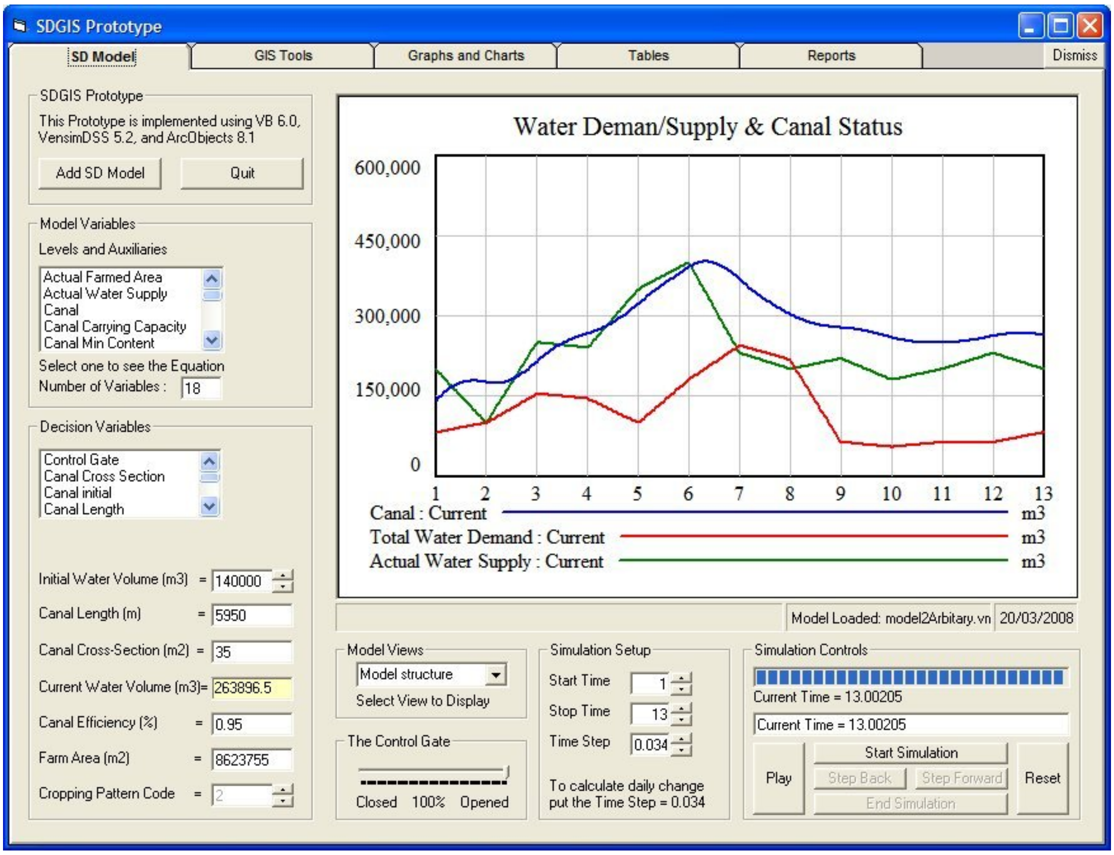


Figure 5-7: The behaviour of the system without intervention.

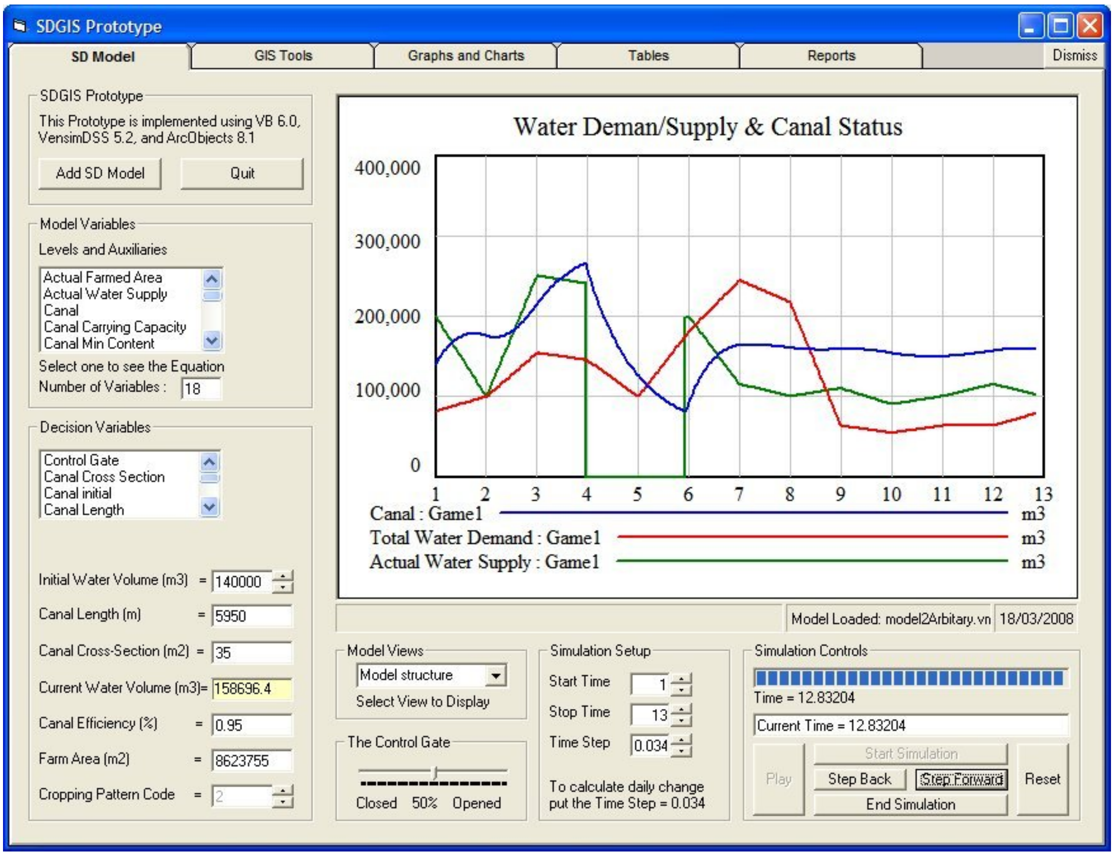


Figure 5-8: The effect of using the control gate slider during the simulation.

The Frame: Simulation Setup

This frame contains three Text-Boxes associated with the simulation time settings. The Text-Boxes are editable, meaning that the user can modify their values. Editing the values in these Text-Boxes triggers the call for a number of functions to *get*, *set*, and *check* the *Start*, *Stop*, and *Step* time.

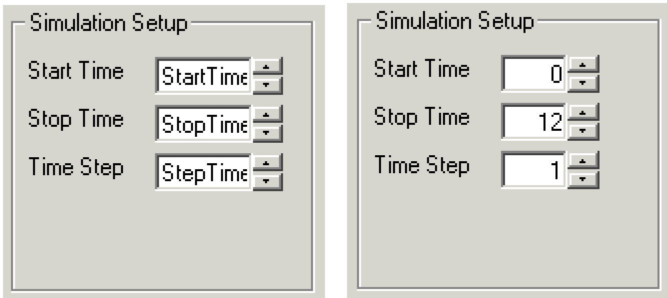


Figure 5-9: The simulation setup controls before and after loading the model.

When the user loads the simulation model into the application, the function *GetModelConstantValues* makes further calls for three other functions: *StartTime*, *StopTime*, and *TimeStep*. These functions perform the following tasks:

The ***StartTime*** function obtains the value of the "start simulation initial time" from the original model and puts it into the upper Text-Box. The user can then edit the Text-Box and change the *Start* time value. When the Text-Box value changes, the function *SetModelSimulationTime* is called to set the new value into the simulation engine that will run the model. The original value of the *Start* time in the original model remains unchanged (as a default value) so that the next time we load the model into the application we retrieve the same value.

The ***StopTime*** function obtains the value of the "stop simulation final time" from the original model and puts this value into the middle Text-Box. The user can change the *Stop* time value the same way s/he did in the StartTime. However, the function first checks the user's input to prevent conflict with the value of the start time. The user cannot set the value of the stop time less than the value of the start time. If the user's input passed the check, the function makes a call for the function *SetModelSimulationTime* to set the new value into the simulation engine.

The ***TimeStep*** function obtains the value of the “simulation time step” from the original model and puts it into the lower Text-Box. The user can edit the Text-Box to change the *Step* time value. When the Text-Box value changes, the function *SetModelSimulationTime* is called to set the new value into the simulation engine.

The Frame: Simulation Controls

This frame encompasses a collection of Command Buttons associated with the execution of the simulation. The buttons perform functions to run the simulation at once, step by step forward and backward, and to reset all initial values of the model variables if the simulation is interrupted for any reason.

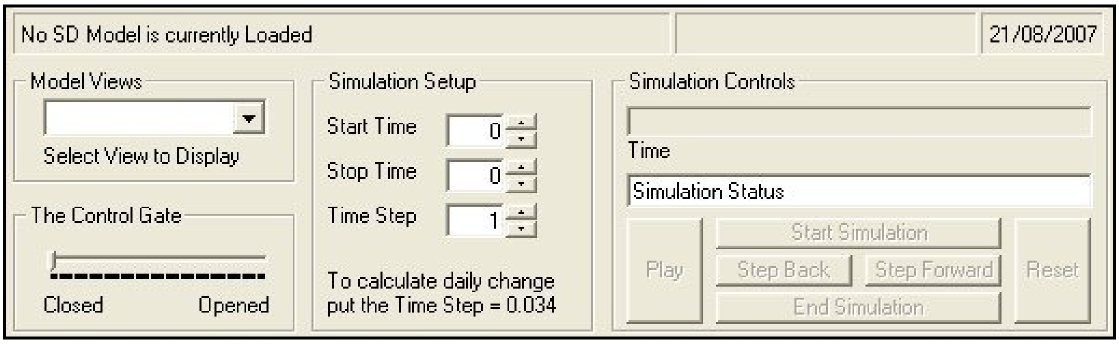


Figure 5-10: The simulation setup frame and simulation controls frame.

As shown in Figures 5-5, 5-6, and 5-10, before the model is loaded, all the command buttons in the “Simulation Controls” frame are initially deactivated. Only *Play*, *Start Simulation*, and *Reset* buttons become active immediately after the model is loaded (see Figure 5-11). The rest of the command buttons (*Step Back*, *Step Forward*, and *End Simulation*) become active only after the *Play* or *Start Simulation* button is triggered. In this case, the *Play* and *Start Simulation* buttons become inactive again until the simulation ends. Switching between *active* and *inactive* modes was for a mean to prevent errors.

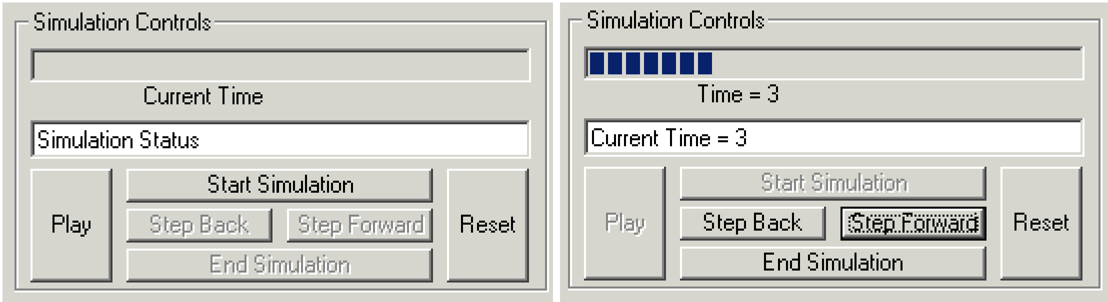


Figure 5-11: The simulation run controls before and during the model run.

Command Button: Play

The button *Play* triggers the simulation and runs the model. However, the user has no control over the model until the simulation ends and the cursor control is returned to the user. Pushing the button Play performs the following steps:

- Retrieve the name of the targeted model and push it into the simulation engine.
- Read the output custom graph (or creates a new one if necessary) and create a name for the RUN.
- Call the function *SetModelSimulationTime* that retrieves the values of the *Start*, *Stop*, and *Step* time, entered by the user into the associated Text-Boxes and pushes these values to the simulation engine.
- Call the function *SetModelValues*, which obtains the values of the *initials* and *constants* changed either by the user or by the application, and pushes them to the simulation engine. Note that if the user did not change these values in the associated Text-Boxes, then the function takes the default values from the original model. If the model is connected to the GIS model, the function takes these values from the map.
- Assign the Picture-Box control object to display the simulation results.
- Run the simulation, obtain the new values of the targeted variables, and put them into the associated control objects (e.g., Text-Box, Picture-Box, etc).

Running the simulation under the user's control

Apart from the command button *Play*, there are four command buttons provided to control the simulation progress. These buttons have given the names Start Simulation, Step Forward, Step Backward, and End Simulation respectively.

Start Simulation button performs the same steps from 1 to 5 described in the command button *Play* paragraph. The main task of this button is to launch the simulation. This is a mandatory step in Vensim. Then, the cursor is returned back to the user waiting for interaction.

Step Forward button performs the following steps:

- Check the current time value. By default, if the current time value equals to the *Stop* time value the simulation will terminate. Otherwise, the simulation will continue for one more step time.
- Call the function *WinnitHandle* to draw the simulation results in the Picture-Box.
- Call the function *GetModelValues* to retrieve the values of the intended variables and put them into the associated control objects.

Step Backward button checks the current time value. If the current time value equals to the *Start* time value, the function will do nothing, otherwise, the function decreases the current time value by one step time, retrieve the values of the intended variables at that time, and call the function *WinnitHandle* to redraw the simulation results on the Picture-Box.

End Simulation: Pushing this button, at any time, will end the simulation immediately and call the function *Reset*.

Reset button executes the function *Reset* that checks the status of the simulation engine. If there is an active simulation, the function ends the simulation, and then resets all values of the variables to default values extracted from the original model.

The Display Function (*WinnitHandel*): This function is a *Public* function that can be called by other functions to display the model sketch and the output graphs.

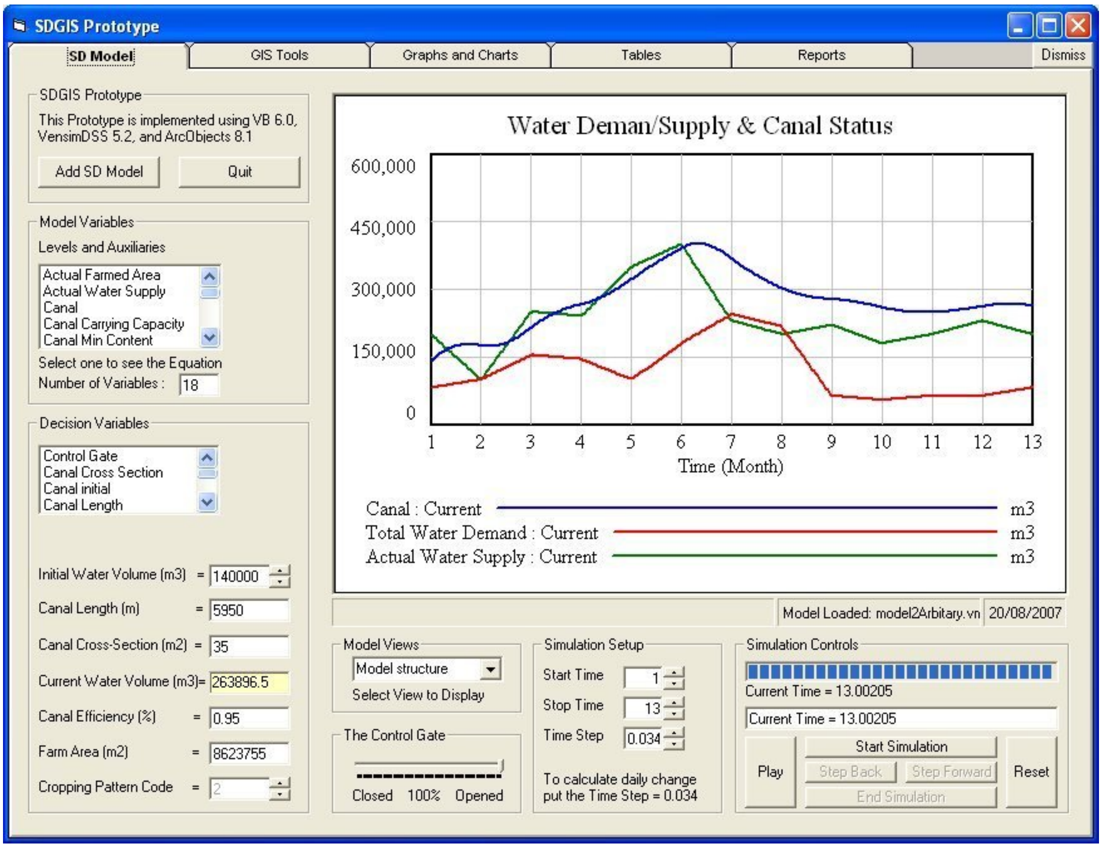


Figure 5-12: Display function that shows the model’s output graphs.

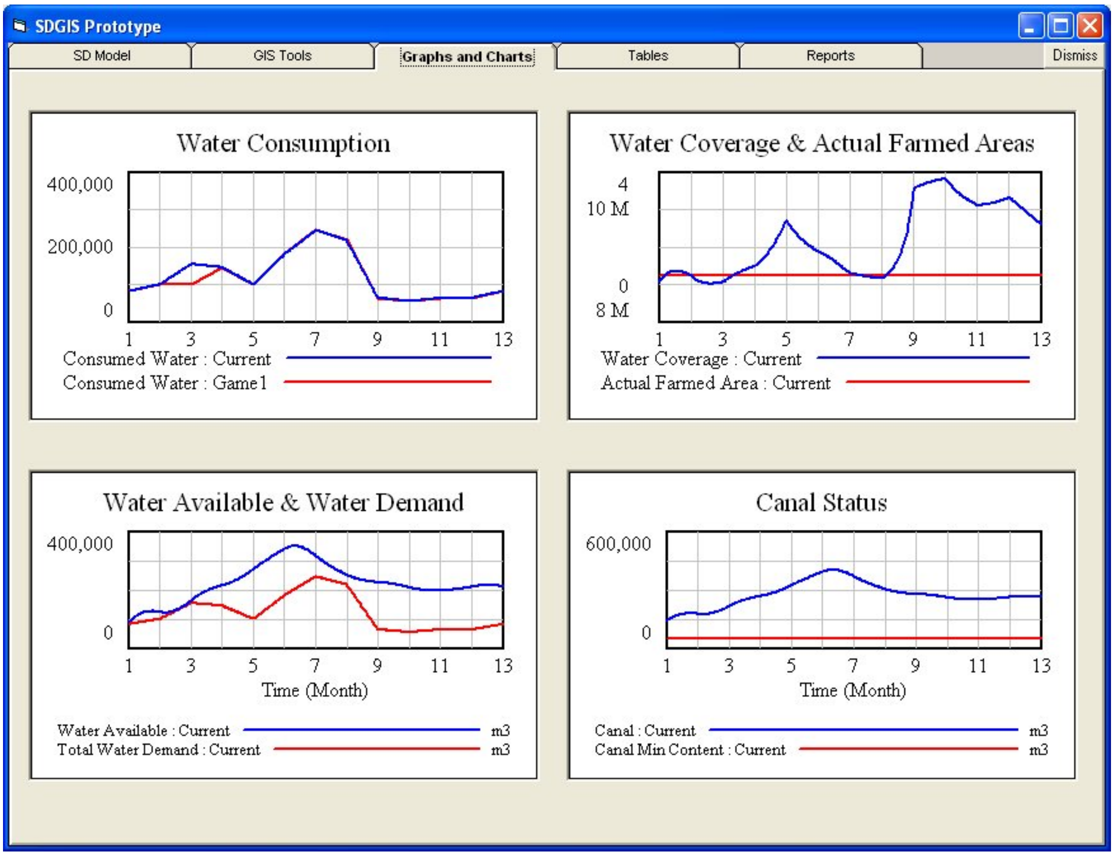


Figure 5-13: The model output graphs.

5.2.3 The "GIS Tools" Panel

The Second panel in the SDGIS interface is called the "GIS Tools". This panel contains several control objects (e.g. MapControl, Tool-Bar, Command Buttons, List-Boxes, and Text-Boxes) to facilitate operations with the GIS model. The primary control object is the "ESRI MapControl" that appears in the middle of the panel (Figure 5-14). The MapControl acts as the main viewer (i.e. the data view in ArcMap) where the map is displayed and the user can interact with the map. In fact, all processes associated with layers are executed using this control object.

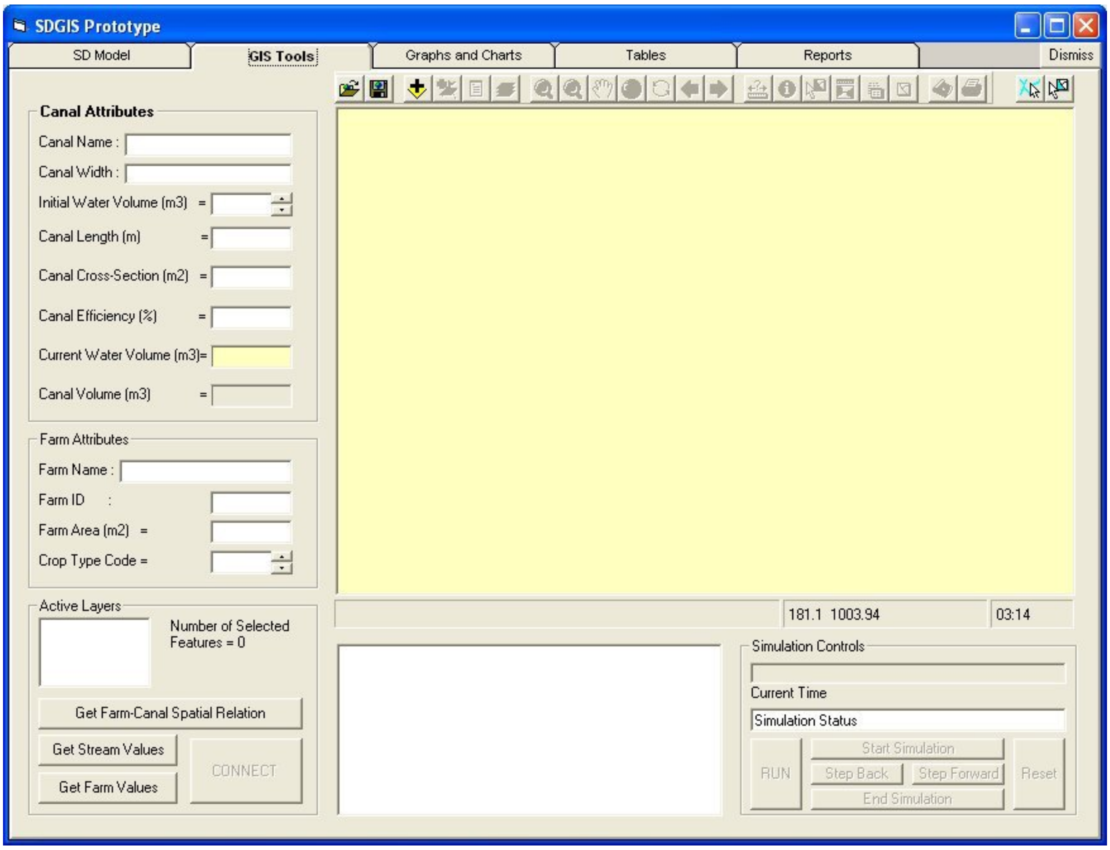


Figure 5-14: The GUI of the SDGIS application (GIS Tools Panel).

Creating Spatial Tools to use with SDGIS

A custom Tool-Bar menu contains 23 tools have been created using ESRI Object Library, AF Commands (VB) Library, and AF Commands (VC) Library. The toolbar, shown in Figure 5-15, is placed at the top of the MapControl. The tools are created during runtime by calling four functions: "Build Command Collection", "Add

Command", "Setup Button Characteristics", and "Refresh Tool Button Locations". The tools interact with MapControl to perform tasks specific to the user's needs such as: open/save map document, add/remove layer, configure layer, launch table of content (as a legend), zoom in/out, pan, measure, identify feature, select features by shape, query geodatabase, export and print maps. The general procedure used to create these tools and the details of the functions executed by these tools can be seen in the code page of the "GIS_Functions" module provided in Appendix A. For the purpose of this dissection, we focus on "Open/Add Map" tool and the "Selection tool"; these are the starting points to connect the two models.

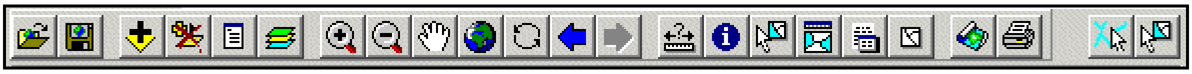


Figure 5-15: A collection of 23 tools is created as a custom Toolbar.

Open Map and Add Layer Tools

The command buttons Open Map and Add Layer, the first and third buttons from the left hand side on the toolbar, launch a dialog box and call for the user to select a map document or layer to load into the application. The application then calls the function RefreshList to extract information about the layer(s) contained in the selected map. The function iterates through the layers, retrieves their names and properties, and puts their names in the List-Box placed on the "Active Layers" Frame at the lower-left of the panel as shown in figure 5-16. We added a pull-down menu to the properties of the List-Box as shown in figure 5-17 to create a convenient and fast way for the user to interact with the layers. The menu appears when the user selects an item (i.e., a layer's name) from the List-Box and presses the right button of the mouse. The user can use this pull-down menu to re-arrange the layers, remove any layer from the application, or to retrieve the layer's properties (the properties dialog box). These functions, included in the pull-down menu, are common functions shipped with ArcGIS that we have composed for our specific purpose and established a link to the reference of their class ID (CLID) in the Windows Registry file.

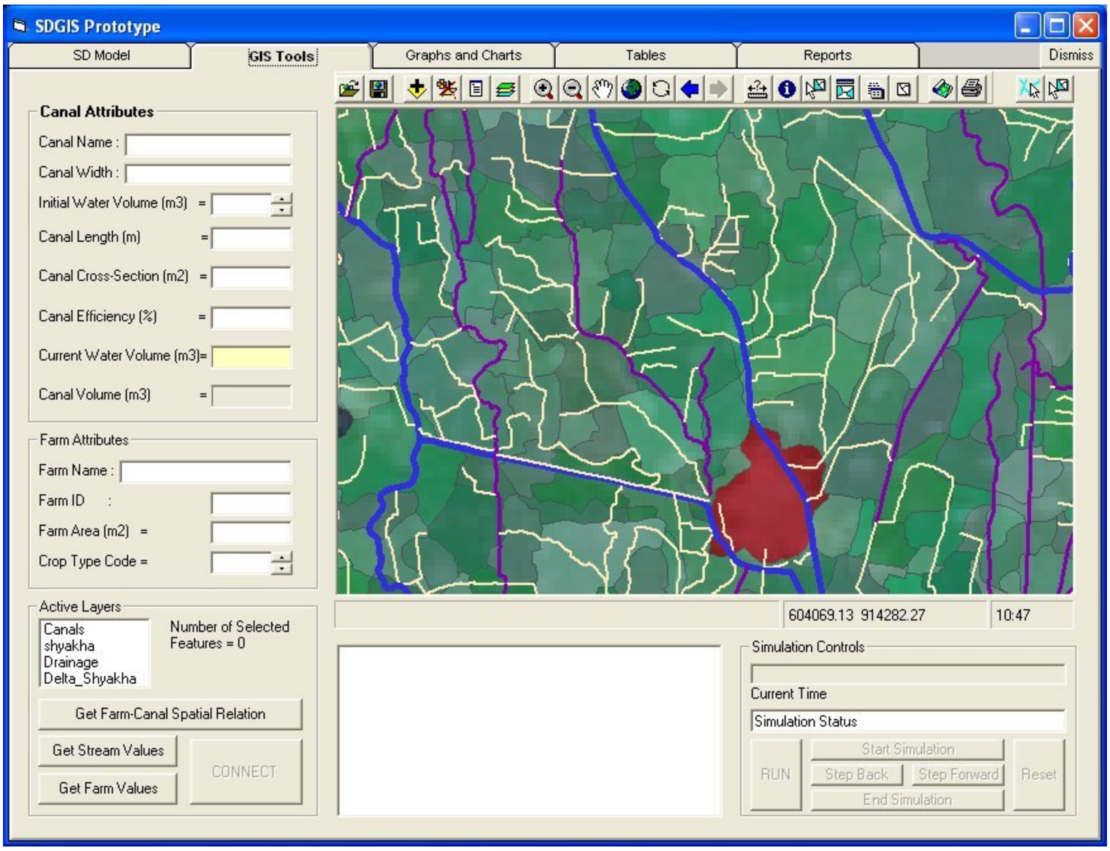


Figure 5-16: Loading the map document into the SDGIS application.

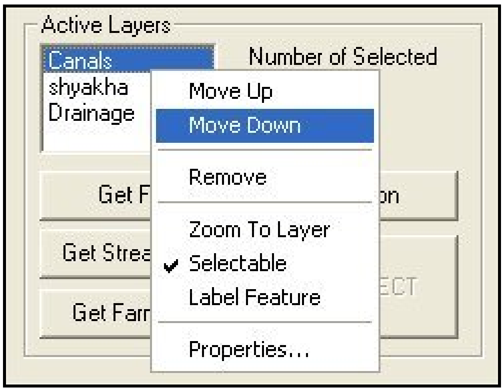


Figure 5-17: The pull-down menu associated with the Active Layers List-Box.

The Selection Tool

The selection tool, appears at the end of the toolbar (the second button from the right hand side), calls *SearchShape* function. The function provides the user with a “circle shape” cursor to select features from the layer(s) displayed on the screen so as to connect these features to their counterparts in the simulation model. The ArcGIS makes a copy from the selected features and store them in a new *container* created by the application known as *collection*. The collection is created “on the fly” specifically for the purpose of keeping the selected features on focus and ready to perform actions. It is a temporarily collection that normally collapse (or destroy by the application) when the purpose of creating this collection is met (usually when the lifetime of the selection tool ends by shifting the focus to another tool). The selected features are then redrawn with a different colour to distinguish them from the unselected features. The user may use the command buttons labelled “Get Stream Values”, “Get Farm Values”, or “Get Farm-Canal Spatial Relation” to retrieve the values of the selected features from the geodatabase (Figure 5-18). The functions associated with these command buttons are described in the following paragraphs.

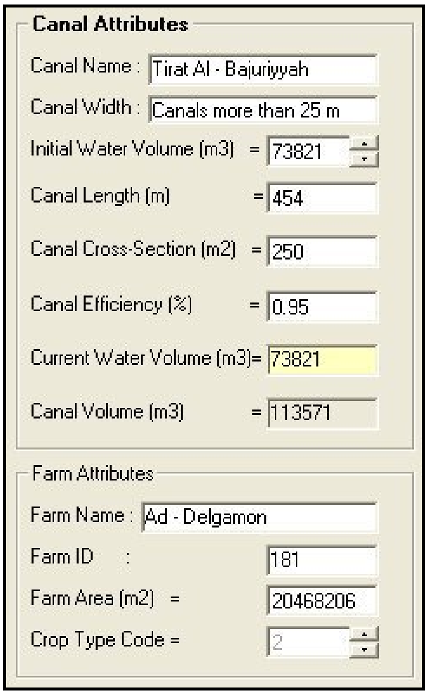


Figure 5-18: The attributes of the selected features.

Command Button: Get Stream Values

This command button calls the function *GetStreamValues*. The function obtains the *canals* only from the collection by examining the geometry type for every feature in the collection. In ArcGIS, as soon as any feature is selected, its record in the attribute table is highlighted. This makes the function retrieve easily the feature's ID by search only the highlighted records. Then, the function collects the record of values associated with the canal, instantiates a new object collection, copies the data record and pastes it into the new object collection. The extracted values (e.g., canal name, canal length, etc.) are then set to the global variables associated with them in the application. The function also displays these values in the associated Text-Boxes. Note that, for simplicity, we used unified names among the three parts of the application. For example, the term "canal length" is used in the attribute table of the layer as a field name, the same term is declared as a global variable in the application, and the same term is used as a variable in the simulation model.

Command Button: Get Farm Values

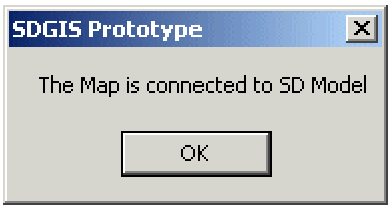
This command button calls the function *GetFarmValues*. The function obtains only the *farms* (which, by default, have *polygon* as a geometry type) from the collection. The function retrieves the selected Farm ID, obtains its record of values, instantiates a new object collection, copies the data record and pastes it into the new object collection. The extracted values (e.g., farm name, farm area, etc.) are then set to the global variables associated with them in the application. The function also displays these values in the associated Text-Boxes.

Command Button: Get Farm-Canal Relation

This command button executes the same functions *GetStreamValues* and *GetFarmValues*, as explained above with one more sophisticated step. To explain this step in a simple way, we consider the following situation: If the user selected only a canal, the function checks the spatial relationship between the layers and retrieves the value of the farm irrigated from this canal and vice versa. In this way, the user can easily recognise which canals deliver water to a certain farm and/or which farms are irrigated from a certain canal.

Command Button: CONNECT

This command button checks the selected features from the map. If there is no selected feature(s) stored in the collection, a message box appears to inform the user to select at least one feature to connect it with the simulation model. If the user did select a feature, but has skipped the *GetStreamValues* function, the command button executes the same steps that the function performs. In other words, it obtains the values of the selected features from the collection and assigns them to the global variables and displays them in the associated text-boxes. At the end of the process, the application gives a feedback informing the user that the two models are now connected and the application is ready to start the simulation. The feedback appears in a message box as shown below



Before starting the simulation, the user can see and check the following:

There are two frames on the panel, each of them containing a number of labels and text-boxes. The left frame shown in Figure 5-19, lists the attributes of the selected canal. These values will be used in the simulation model. If the user wants to change these values s/he can use the text-boxes in frame to the right.

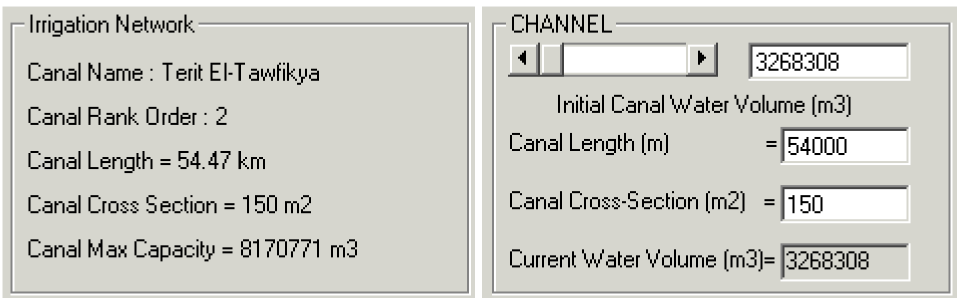


Figure 5-19: Two frames show the values of the selected Canal.

On the “SD Model” panel as shown in figure 5-20, the user can notice that the values have changed from the original values extracted from the simulation model to the new values extracted from the map. Now, the model is ready to simulate.

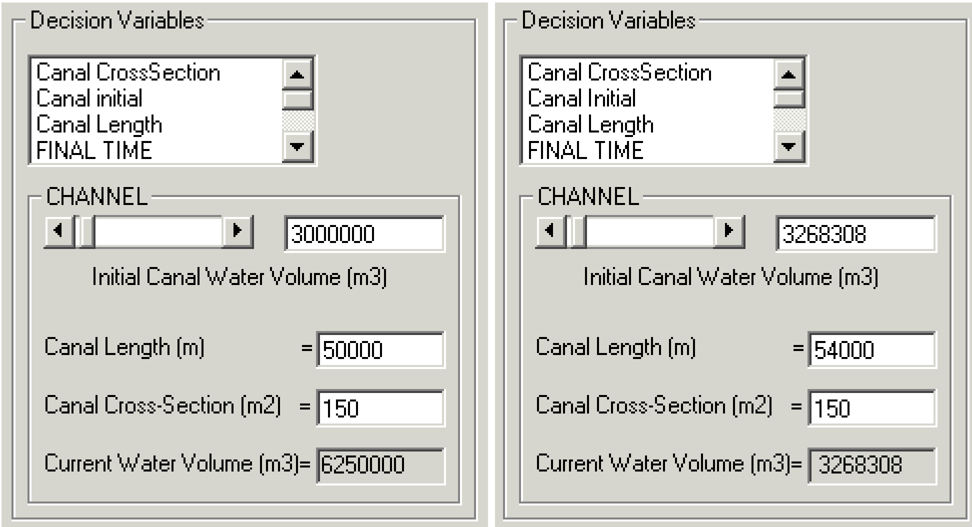


Figure 5-20: The SD model variable values have changed after connection.

The Simulation Run Controls

These controls are *enabled* only after the connection process takes place. Unlike the simulation controls in the “SD Model” Panel, they call extra functions to display the simulation results in the associated maps.

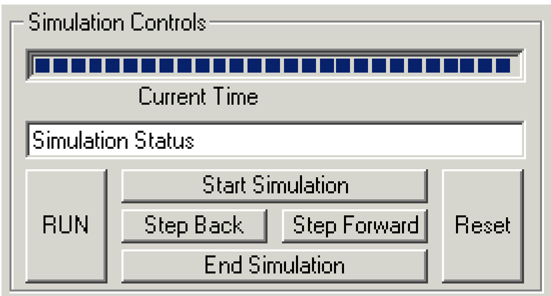


Figure 5-21: The simulation controls on “GIS Tools” Panel.

Command Button: RUN

This command button performs the following steps:

1. Check the connection with the simulation model.

2. Call the function *SetModelSimulationTime* to obtain the values of the *Start*, *Stop*, and *Step* time from the associated text-boxes (in case the user has changed them) and send the new values to the simulation engine.

3. Assign the Picture-Box control object to display the simulation results.

4. Send a command to the simulation software to start the simulation.

5. Check the current time value, by default the simulation will continue for one more step time if the current time value is less than the *Stop* time value, otherwise the simulation will terminate.

6. Retrieve the value of the “current water volume”, that is, the value of the stock “Canal”. The value is set into the global variable that is used to redraw the canal on the map with a new line width and colour using the function *DrawWithSymbol*.

7. Call the function *DrawWithSymbol*: This function performs the following steps:
    - Retrieve the new value of the *Canal* and transform it into suitable line width.
    - Using a predefined table of colours, the function picks the suitable colour.
    - Using a predefined set of symbols, the function picks the appropriate symbol (e.g. simple line for canals, filled area for farms)
    - Draw the selected feature(s) with the selected colour and symbol.

8. Call the function *Display* to draw the simulation results in the Picture-Box.

9. Check the current time value to decide either to continue the simulation for one more time step or to end the simulation.

Noticeably, pushing the command button RUN will execute the simulation very fast at once and the user would not be able to get the cursor before the simulation is terminated. This means that the user can *not* stop the simulation during runtime and study the changes. For this reason, we chose to create four command buttons to run the simulation step by step to give the user the chance to watch and study the changes in the status of the canal. The four command buttons are similar to those buttons in the SD Model panel. However, in their code page they include calls for the function *DrawWithSymbol* to redraw the canal on the map with suitable line-thickness and colour according to its value every time step.

5.2.4 The "Graphs and Charts" Panel

This panel includes four Picture-Boxes to display graphs that are being produced by the Vensim simulation software (see Figure 5-22). The user should build such graphs using Vensim and mark them as Work In Progress graphs (WIP). Within the SDGIS application, the user has the option to build up to six graphs and display them in the six Picture-Boxes provided in the application (one in the SD Model panel, the second in the GIS Tools panel, and four in the Graphs and Charts panel). The user can decide the location where a certain graph will be displayed by naming the graphs sequentially within the Vensim (as Graph1, Graph2, …and Graph6). Therefore, the first graph will appear in the first Picture-Box on the SD Model panel and the second will appear in the GIS Tools panel and the rest in the Graphs and Charts panel from upper left to lower right order. The Picture-Boxes are interactive, they are updated every time step. Thus, the progress of the simulation can be observed in the Picture-Boxes during runtime.

5.2.5 The "Tables" Panel

This panel provides the user with pilot tables containing: the common crop rotations and cropping patterns; the water needs for most popular crops and their growing period (see Figure 5-23). Using these tables, the user can choose and assign, for example, a certain cropping pattern to a certain farm, calculate the water demand and initialize the simulation model. It also assists in designing policies for cropping patterns and water allocation.

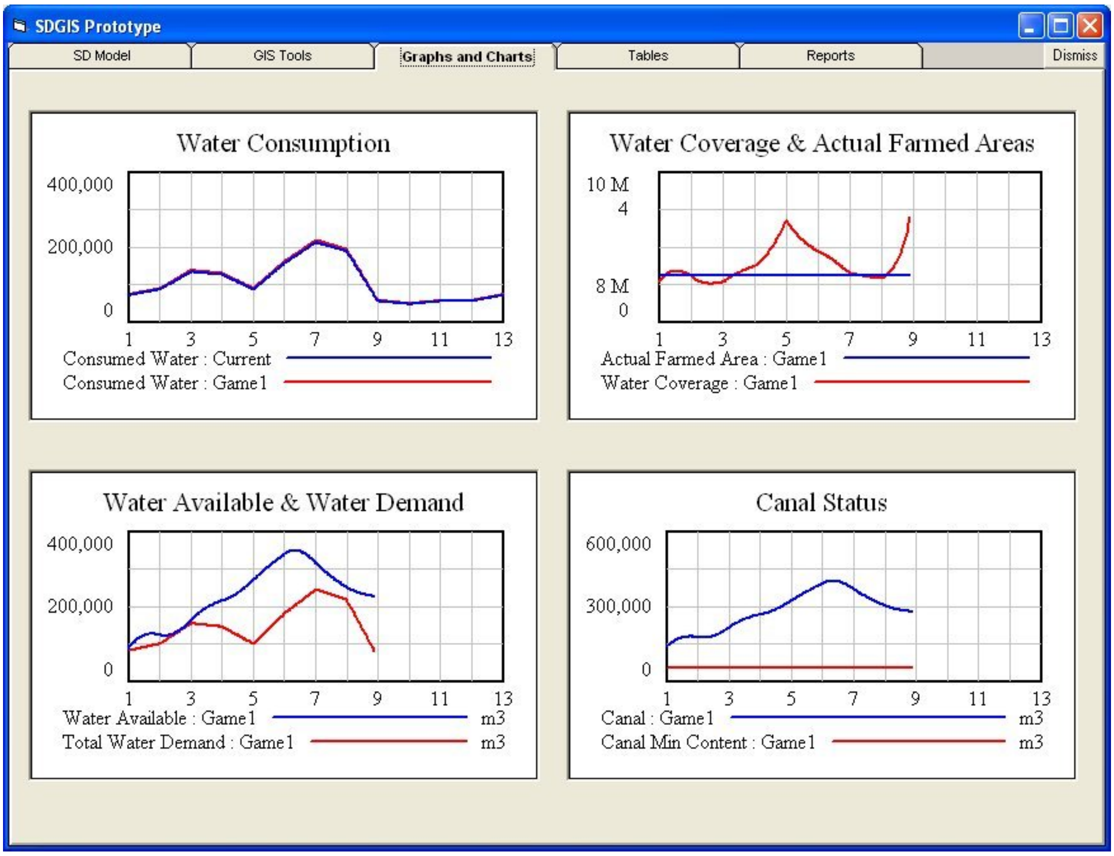


Figure 5-22: The Graphs and Charts Panel.

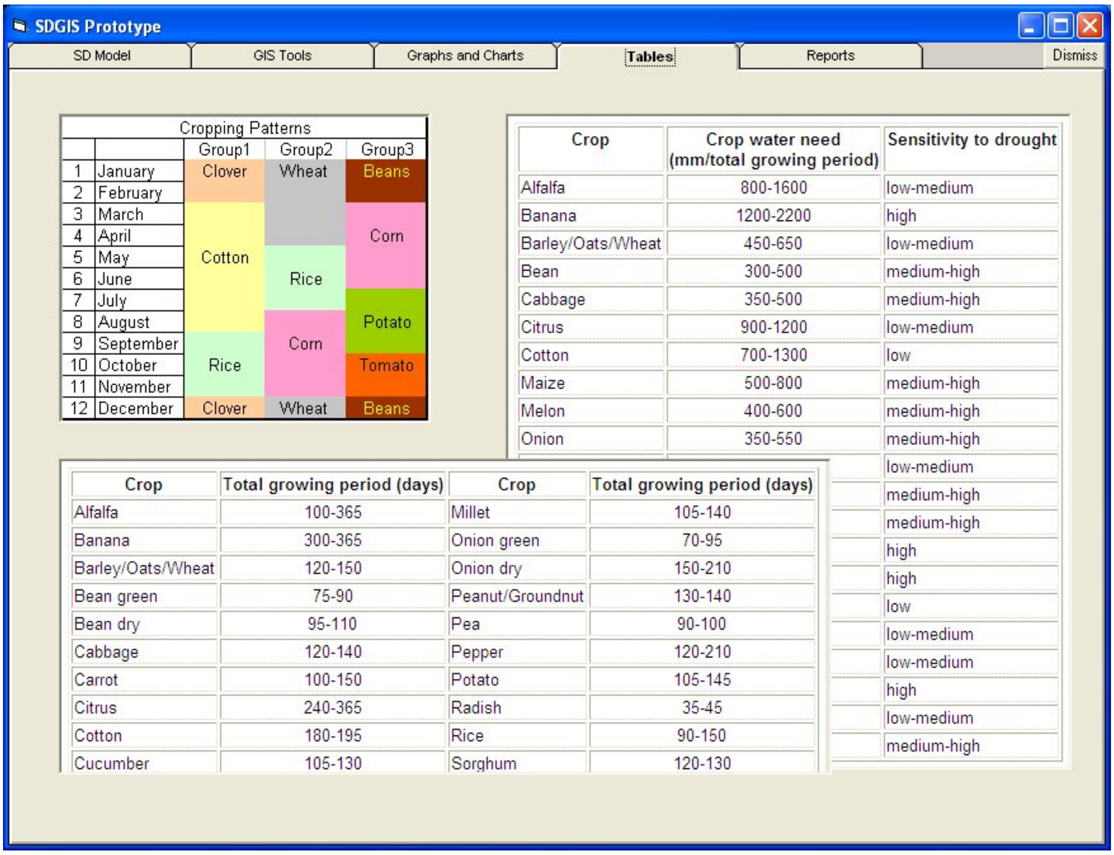


Figure 5-23: The Tables Panel.

5.3 Testing the SDGIS Application Performance

It is very important to test the performance of the application with a realistic data. During the fieldwork, a massive volume of data was collected including maps of various scales of the study area, technical and analytical reports, and statistical data. In this section, we describe how the SDGIS was put into operation based on the empirical data collected during the fieldwork.

The simulation model developed in chapter four, that is the irrigation molecule model, is employed in this test. No major modifications have been made to the model structure. However, the GIS model has been improved in several ways. First, we verified the water flow directions in the irrigation network according to the data gathered during the fieldwork. Second, we added important tabular data into the attribute tables associated with each feature class. For example, in the *Canal* feature class we have added the fields “Canal Cross Section”, “Initial water Volume”, “Efficiency” to the attribute table to store data associated with each canal. Similarly, in the *Farm* feature class, the fields “Irrigated From” and “Crop Type” have been added. These fields appear with asterisks in the association table illustrated in Figure 5-24. The table indicates the link between the fields from the attribute table of the map and their counterpart variables in the SD model.

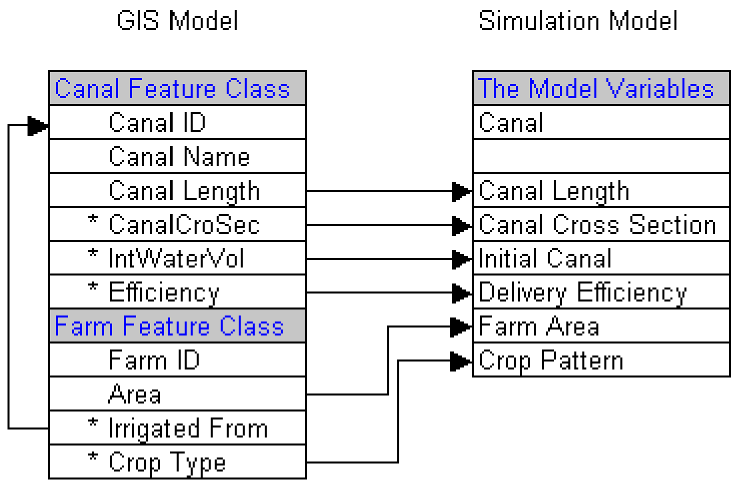


Figure 5-24: The Association Table.

This data processing, designed to ensure that the data fed to the simulation model is accurate, was particularly demanding. Most of the natural canals vary in their width and depth from site to site along the course of the canal. We calculated the average values of the width and depth to obtain the average cross section. The averaging process was repeated for the canal efficiency. The initial water volume was calculated as a percentage of the canal carrying capacity, modified by the monthly average water level in the canal. The crop type accounts for the majority of the crops planted within the boarders of the administrative area. For example, in some provinces the majority of farms plant cotton where fruits are rarely planted, this is not necessarily the case in other provinces. The simulation was based on the dominant cropping pattern in each province. The data processing leading up to this initialization was initially conducted for one province at the centre of the Delta region shown in Figure 5-25, and was subsequently repeated for all provinces in the Delta.

Figure 5-25: The central part of the Delta.

Given the SD model and the maps representing the irrigation network and the agriculture areas, we start the SDGIS application and perform the following steps:

In the first panel, we load the simulation model into the application by pushing the "Add SD Model" button. The application will call the functions associated with that button. As shown in Figure 5-26, we can notice that:

- The model diagram appears in the Picture-Box
- The name of the model appears in the second panel of the Status-Bar placed under the Picture-Box.
- The names of the model's stocks and flows are listed in the upper List-Box, and the number of these variables appears in the small Text-Box under the List-Box.
- The names of the model's constants, initials, and lookup tables are listed in the lower List-Box in the frame labelled "Decision Variables". An item from that List-Box has been selected, that is the canal cross section, and its value appears in the first panel of the Status-Bar (as shown, it equals to 35 m^2).
- In the "Decision Variables" Frame, there are seven Text-Boxes associated with the seven variables so that the user can change their values by editing these Text-Boxes. Before the map is connected to the simulation model, the values appear in these Text-Boxes are the default values obtained from the simulation model. After the intended canal to be modelled is selected by the user and the map is connected to the simulation model, the values in these Text-Boxes will change to represent the true values of the canal obtained from the attribute table of the layer.
- The model's views appear in the Combo-Box placed in the Frame labelled "Model Views" under the Status-Bar.
- The Slider of the control gate indicates that it is fully opened.
- The values of the Start time, Stop time, and Time Step appear in the associated Text-Boxes placed in the Frame labelled "Simulation Setup". The user can change these values by editing the Text-Box next to each variable.

In the “Simulation Controls” Frame, we notice that *Play* button and *Start Simulation* button are enabled. This indicates that the model is ready to run. Pushing the button *Play* will trigger the simulation, change the Picture-Box view to display the output graph, and display the value of the stock Canal (as the changes take place during the simulation) in the Text-Box labelled “current water volume”. The result is shown in Figure 5-27. However, the simulation is running very fast and the user cannot change the control-gate value before the simulation ends and the cursor control is returned to the user. Therefore, we switch to the *Start Simulation* button to run the simulation step by step using *Step Forward, Step Backward, and End Simulation* buttons. In this way, the user can change the value of the control-gate as desired and observe the resulting behaviour. The results are shown in Figure 5-28.

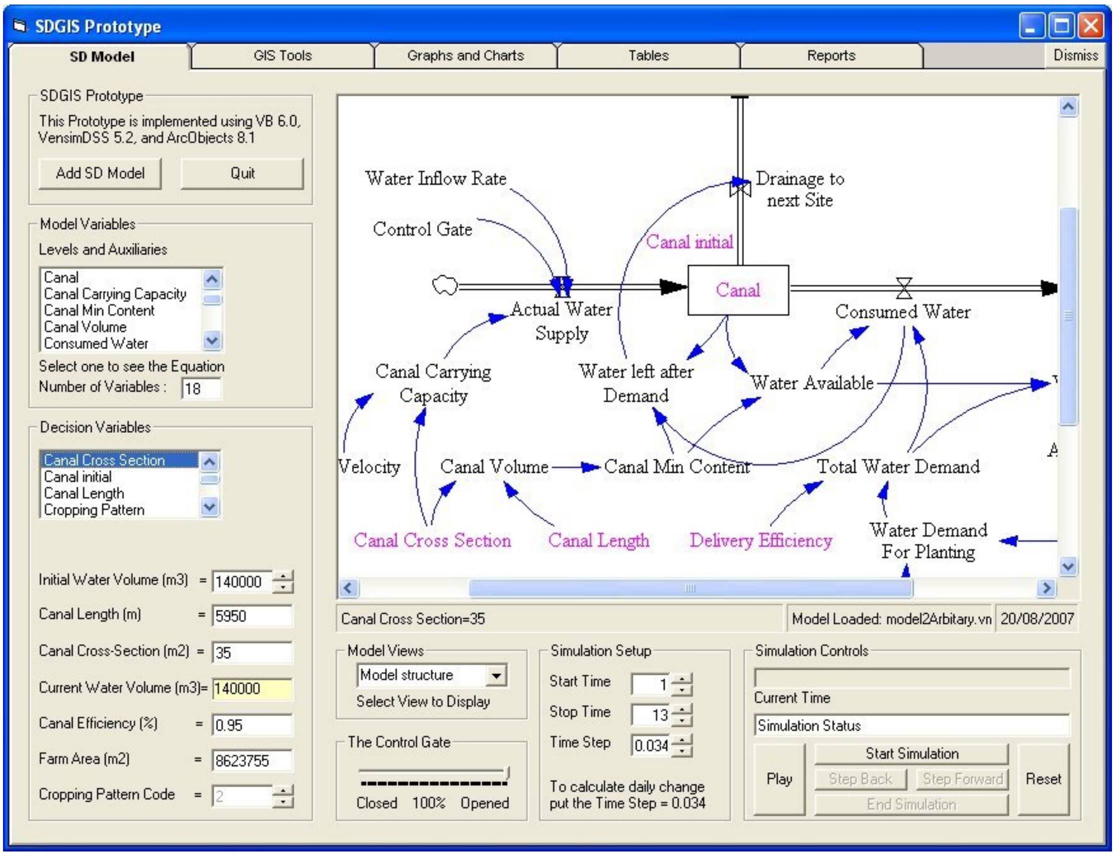


Figure 5-26: loading the SD Model into SDGIS application.

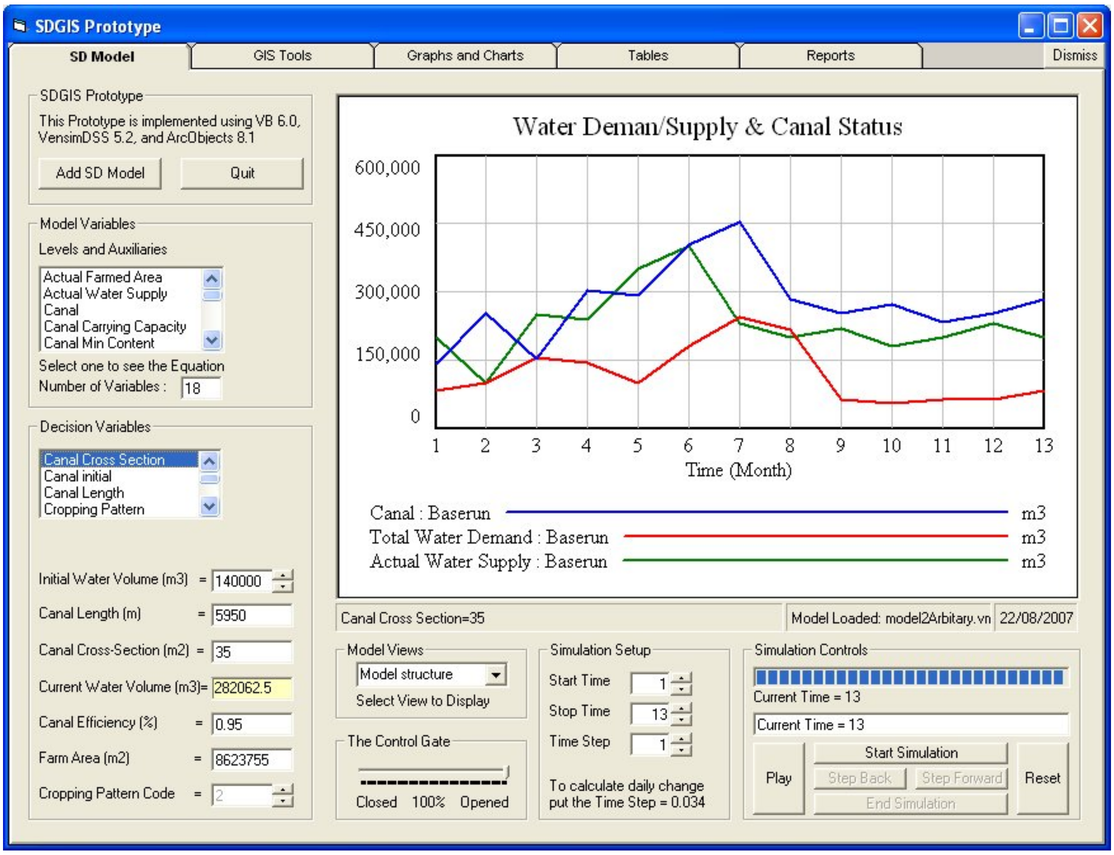


Figure 5-27: Running the simulation model from SDGIS.

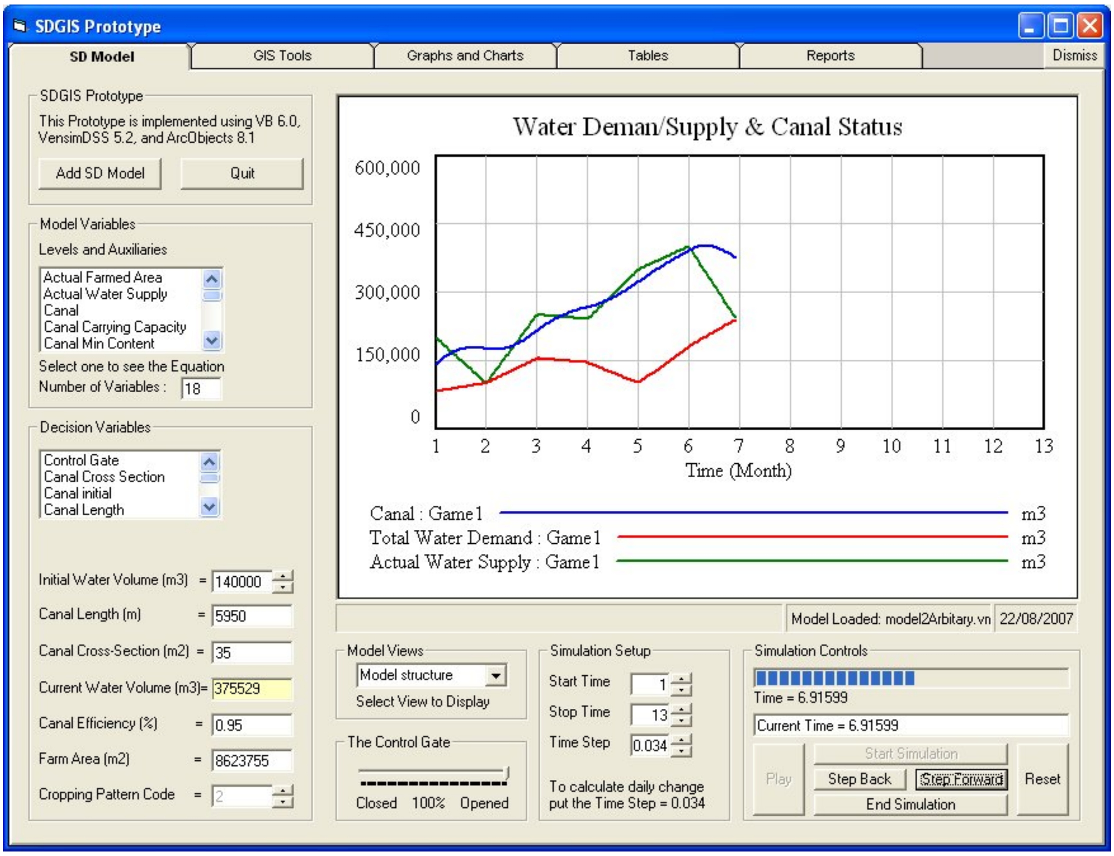


Figure 5-28: Running the model step by step.

In the second panel, that is the “GIS Tools”, we load the map document into the application by pushing the first button on the toolbar menu placed on the top of the MapControl Viewer. When the dialog box is opened as shown in Figure 5-29, we select the map document named “Gharbiya.mxd” and press OK. The map is loaded to the application as shown in Figure 5-30. Notice that, since there is no feature selected, the Text-Boxes in the panel appear empty. The “CONNECT” command button also appears inactive. To select features, we push the “Select Feature” button, the second from the end of the toolbar as shown in Figure 5-31, and then point to the Viewer and select the desired canal. The farm irrigated from this canal will be selected automatically. The selected features immediately appear with red colour. Pushing the command button “Get Farm-Canal Spatial Relation” will extract the attribute data associated with the selected features from the geodatabase and display them in the Text-Boxes in the Frames “Canal Attributes” and “Farm attribute” as shown in Figure 5-31. The “CONNECT” button is now enabled. This indicates that the application is ready to connect the selected features with the simulation model.

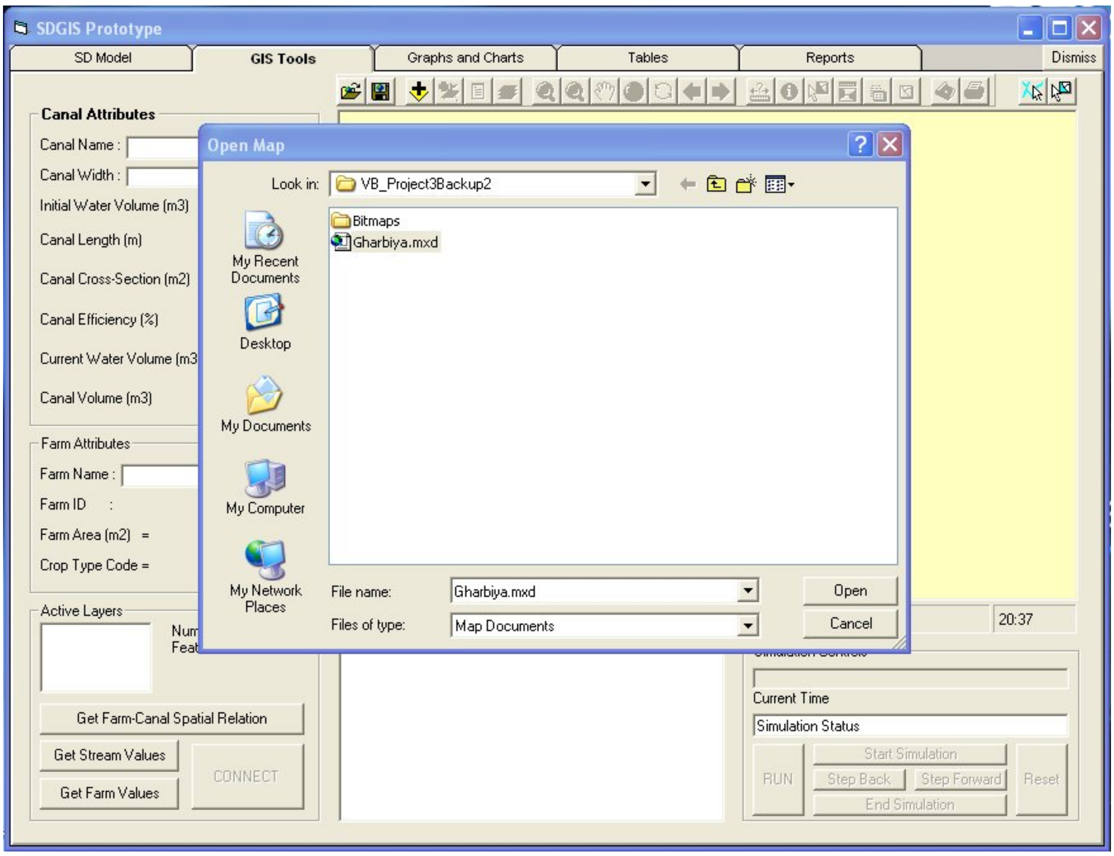


Figure 5-29: Open map dialog box is opened to select the map document.

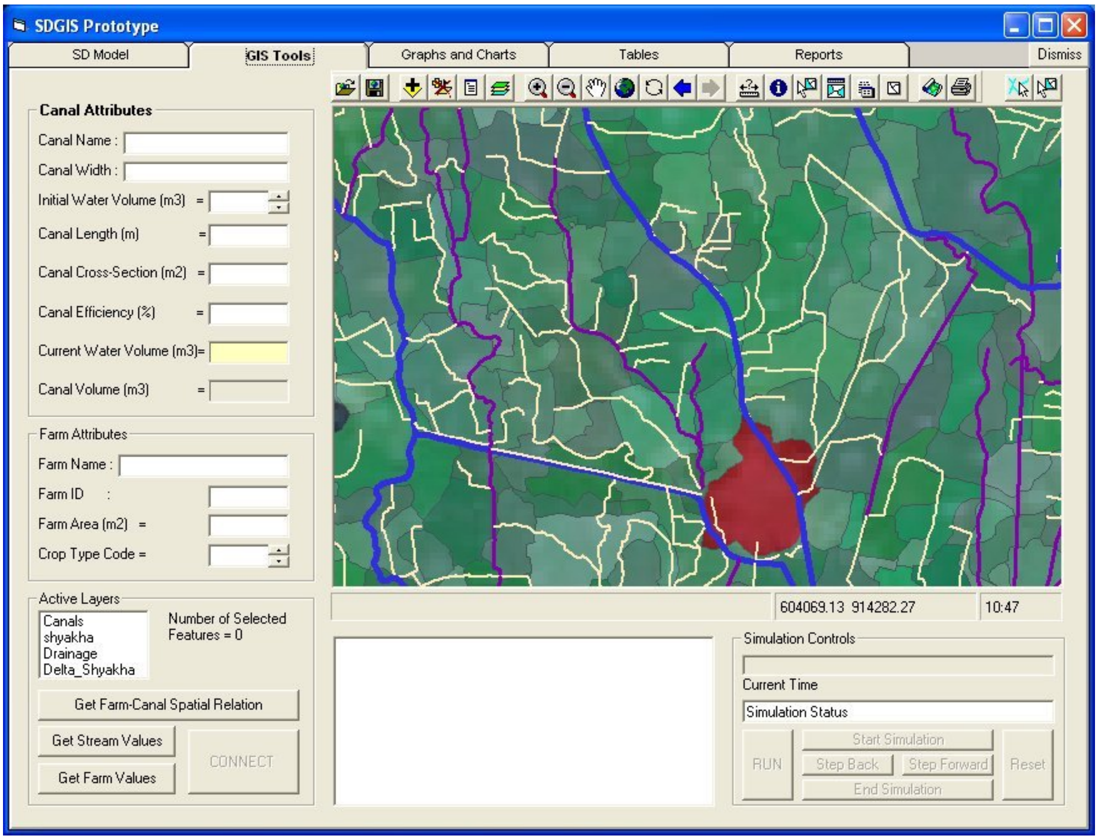


Figure 5-30: The Text-Boxes appear empty where no features are selected.

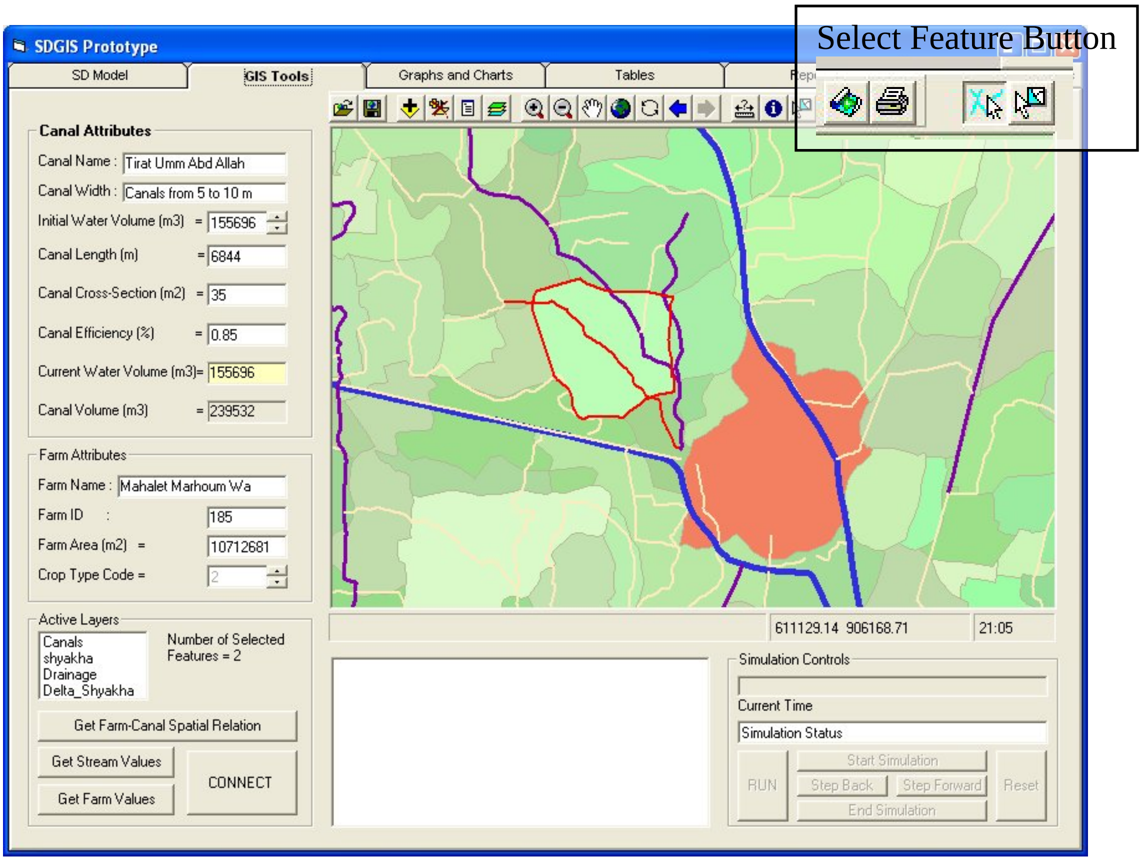


Figure 5-31: The selected features and their attributes.

Figure 5-32 shows the Frame “Decision Variables” on the “SD Model” panel to the left hand side, and the Frames “Canals Attributes” and “Farm Attributes” on the “GIS Tools” panel to the right hand side. Before the simulation model and the map are connected, the values that appear in the Text-Boxes on the two panels are different. For example, the *Canal Length* on the left side equal to 5950 while on the right side it equals to 6844. Similarly, the *Canal Efficiency* on the left side equal to 95% while on the right side it equals to 85%. This is because the values of the text-boxes on the SD Model panel has been obtained from the SD model (the default initial values of the decision variables), while the values that appear in the text-boxes on the GIS Tool panel have been obtained from the attribute table associated with the map (this is the real data associated with the selected canal that intended to be modelled). By pushing the command button “CONNECT”, the application will assign the values that appear on the right side (the attributes of the canal) to the associated variable in the simulation model and alter the values in the text-boxes on the left side as shown in Figure 5-33.

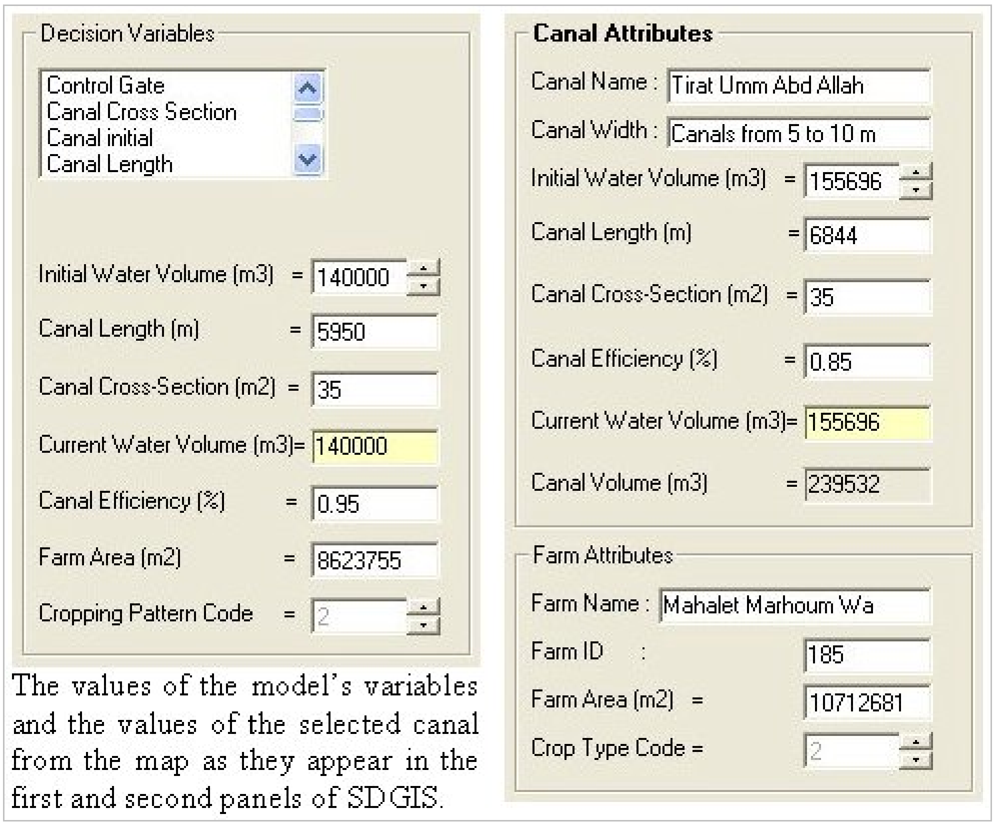


Figure 5-32: Before connecting the two models.

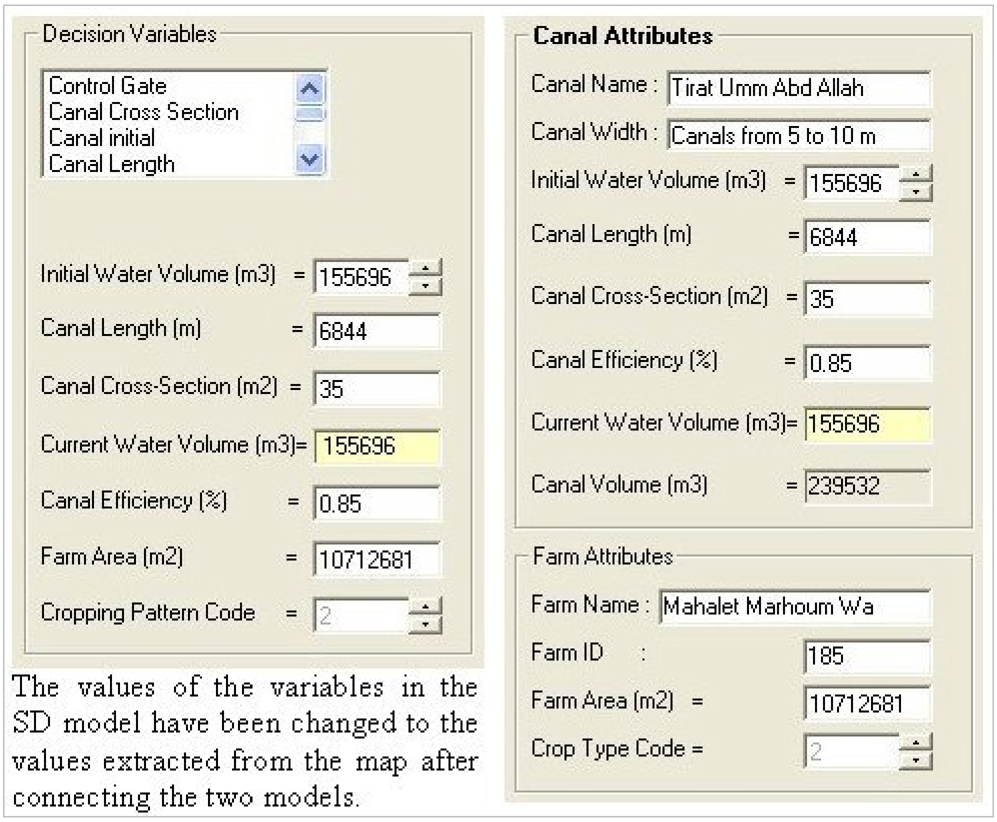


Figure 5-33: After connecting the two models.

Having connected the two models, the simulation can be started now. We chose to simulate the model step by step using the command buttons “Start Simulation”, “Step Forward”, “Step Backward”, and “End Simulation”. Figures 5-34 to 5-39 demonstrate the simulation as time advances. The selected canal appears in Figure 5-34 with a thin line having a light blue colour. Note that the line thickness and the blue colour ramp represent the water coverage in the canal so that the thicker and the darker the line, the high is the water coverage. The numeric value of the water coverage is displayed in the Status-Bar below the MapControl Viewer. As the time advances, the state of the canal is changing and the line that represents the canal becomes thicker with blue as illustrated in Figure 5-35. The water coverage in the canal reaches the pike point at simulation Time = 9, as shown in Figure 5-37. Obviously, the water demand is very low while the water available in the canal is very high as we can see in the graph appears below the MapControl Viewer. From this time (Time = 9) and until the end of the year (the end of the simulation), the status of the canal appears to be stable as shown in Figures 5-38 and 5-39.

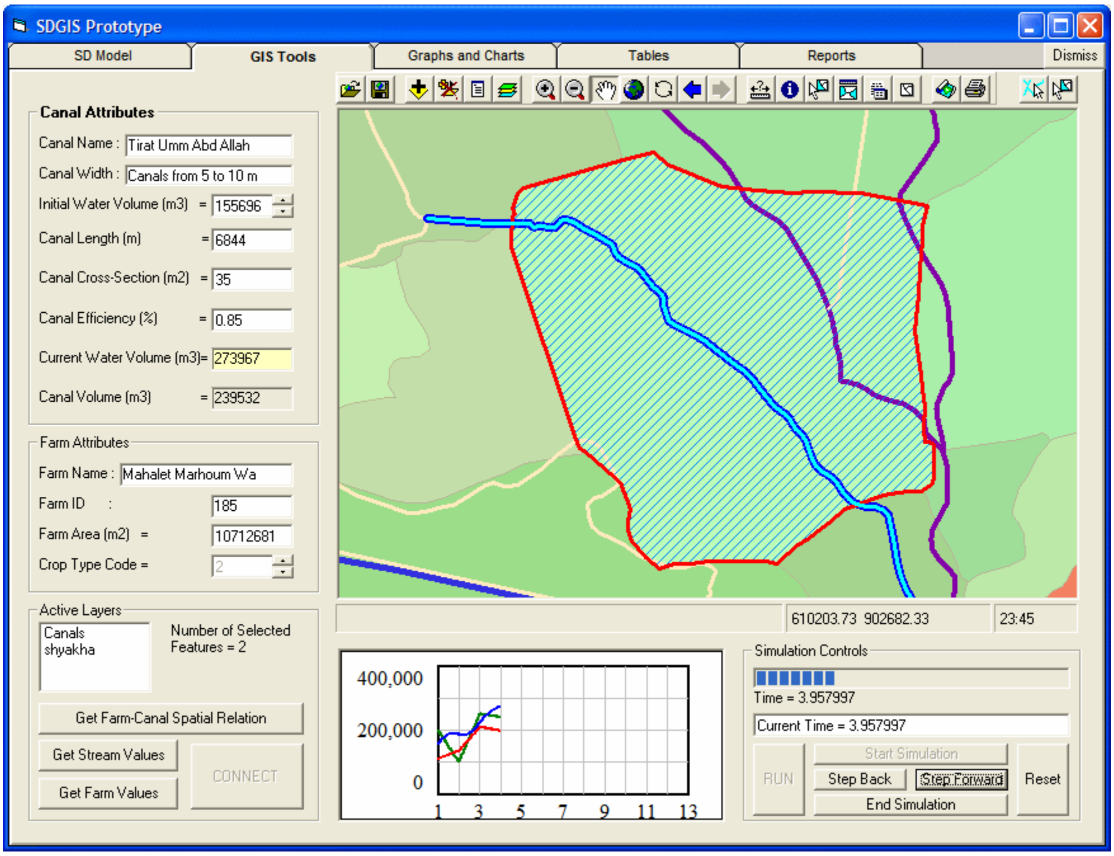


Figure 5-34: The behaviour at Time = 3.

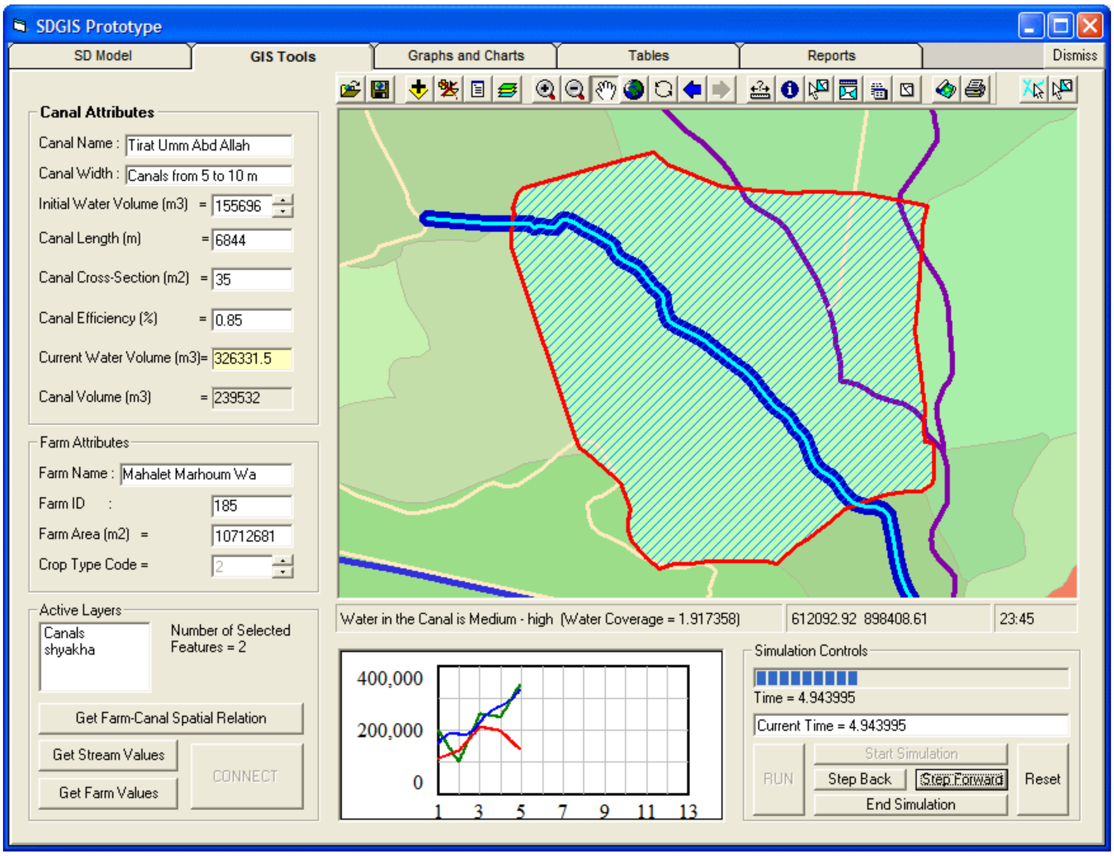


Figure 5-35: The behaviour at Time = 4.

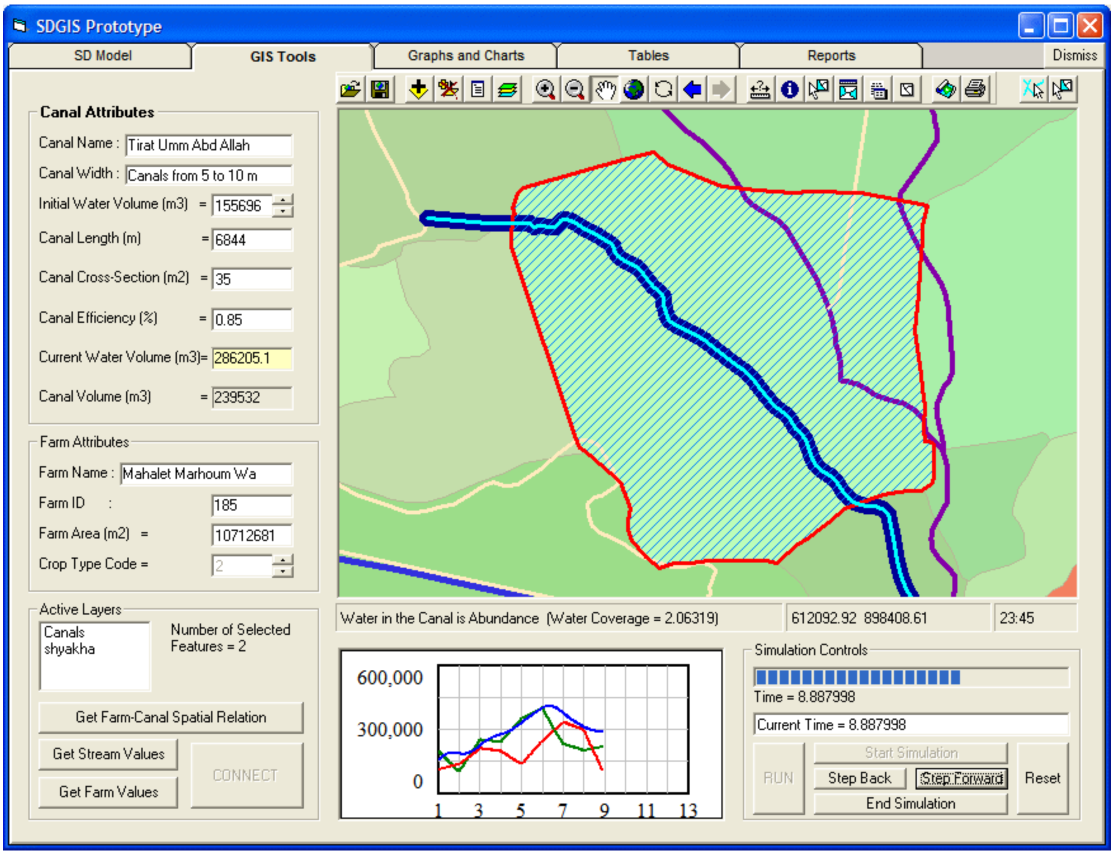


Figure 5-36: The behaviour at Time = 8.

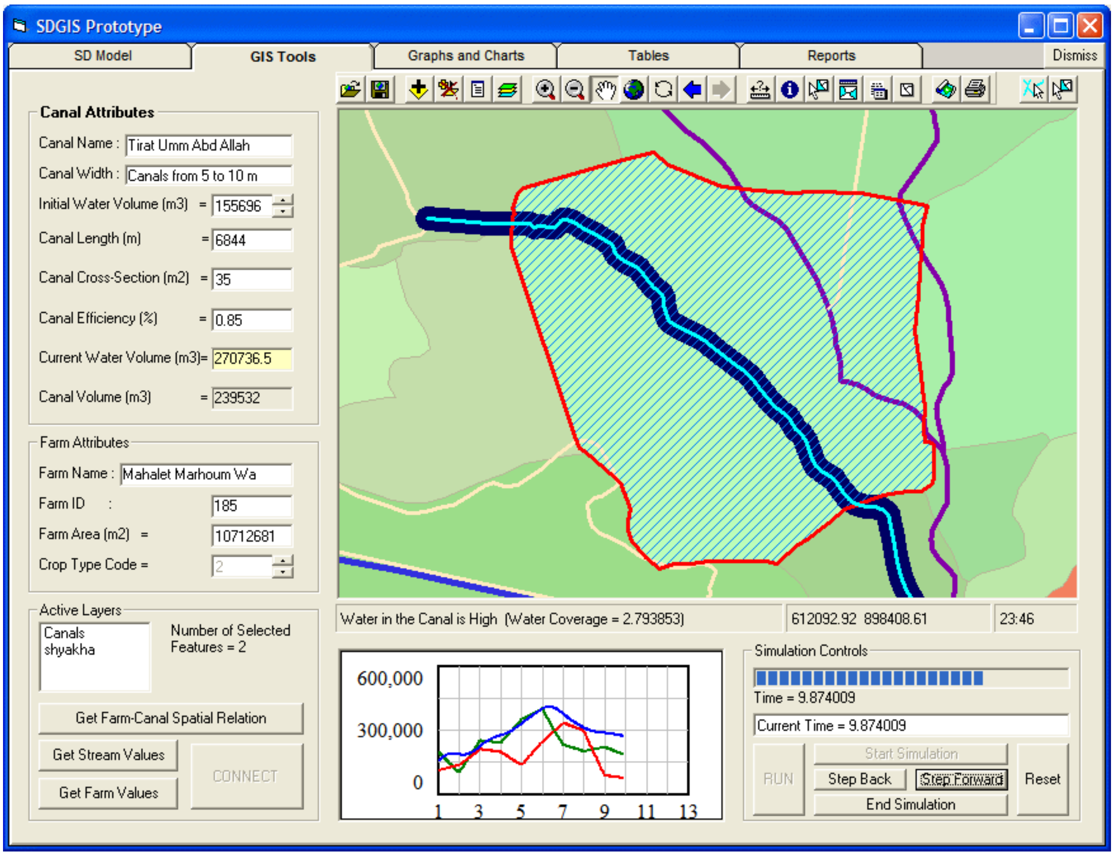


Figure 5-37: The behaviour at Time = 9.

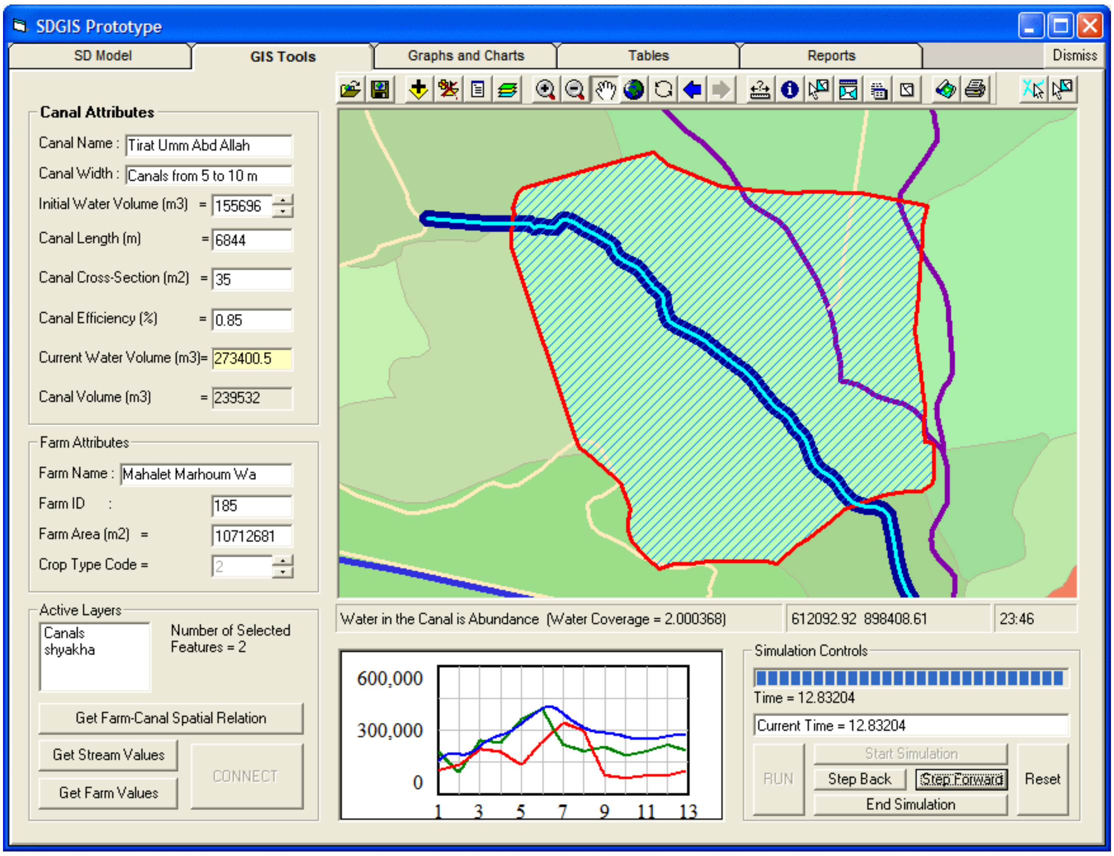


Figure 5-38: The behaviour at Time = 11

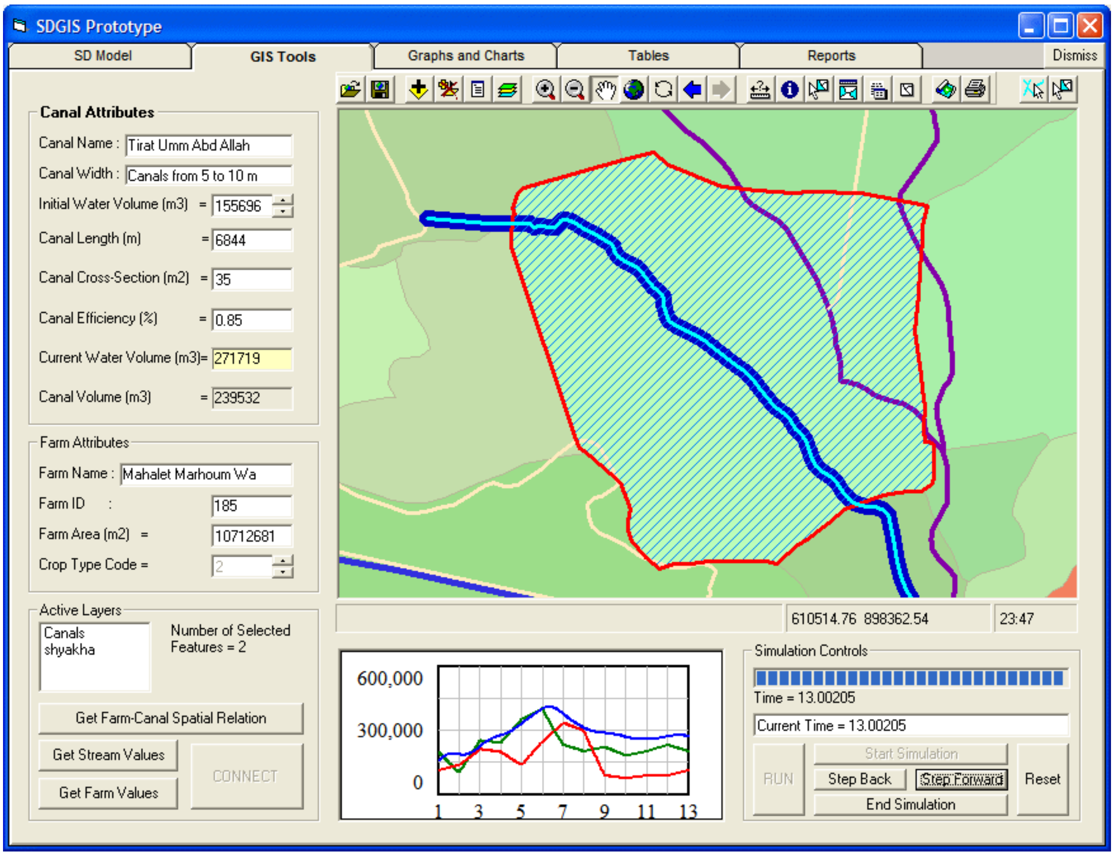


Figure 5-39: The behaviour at the end of Simulation.

5.4 Developing the Array Application

In the previous section, we make use of the molecule model developed in chapter four to test the performance of the SDGIS application. In this section, we take a step further toward improving the simulation model to cover the entire irrigation network. One way of doing this is to create array stock with elements equal to the number of canals in the network. Since each canal has its initial value, inflow, and outflow, and serves a certain agriculture area, these variables must also be modelled as arrays. In fact, the whole model thus becomes an array model.

5.4.1 The SD Array Model

At the head of the Delta, to the north of Cairo, the Nile splits into two main branches: Rashid Branch (235 kilometres long) to the west and Damietta Branch (240 kilometres long) to the east forming the Nile Delta. The Delta Barrage, known as Al Qanatir Al Kheiriya located at the head of the Delta, distributes the Nile flow across the two branches as well as three main Canals (Behary, Monofya, and Sharkawya). From this barrage the water flows into the main canal system (first level) that comprises 31200 km of canals and takes its water from head regulators. The irrigation system is a combined gravity and water lifting system. There are several small barrages to facilitate water abstraction. From the main canal system (first level), water is distributed along branches (second level) where the flow is continuous. At the third level, distributaries receive water according to a rotation schedule. Water is pumped from the distributaries to irrigate fields (lift about 0.5-1.5 m). In the remote areas located at the end of the system (at the edges of the Delta), the irrigation system is based on a cascade of pumping stations from the main canals to the fields, with a total lift of up to 50 m. Surface irrigation is banned by law in such areas. Farmers have to use sprinkler or drip irrigation, which are more suitable for the mostly sandy soil of those areas. If used efficiently, sprinkler and drip irrigation need less water than surface irrigation.

Consequently, the Delta can be divided into three geographical zones: *West of Delta* to the west of Rashid branch (8974 sq km), *Middle of Delta* embraced between Rashid and Damietta branches (9792 sq km), and *East of Delta* to the east of Damietta branch (7099 sq km). To model this landscape, we added the script "Delta Zones" to the simulation model and added the script to the variable "Farm area" as shown in Figures 5-40 and 5-41.

Figure 5-40: Adding geographical zones as a script in the model.

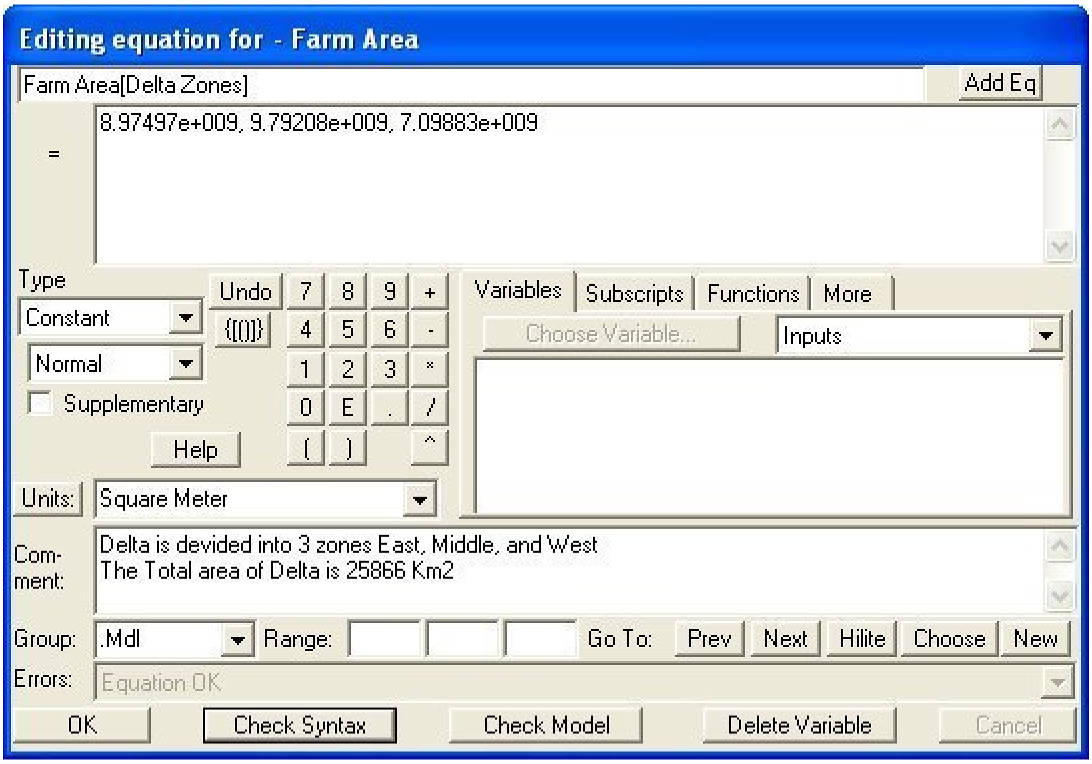


Figure 5-41: Modelling the Agriculture land as an array variable.

On the other hand, the irrigation system encompasses three levels of canals. Thus, another script named “Canal Classes” has been added to the model as shown in Figure 5-42. If we aggregate the canals within each level for each zone, we end up with nine canal classes. This is represented in the model as an array stock with nine elements as shown in Figure 5-43.

Figure 5-42: Adding Canal Classes as a script to the model.

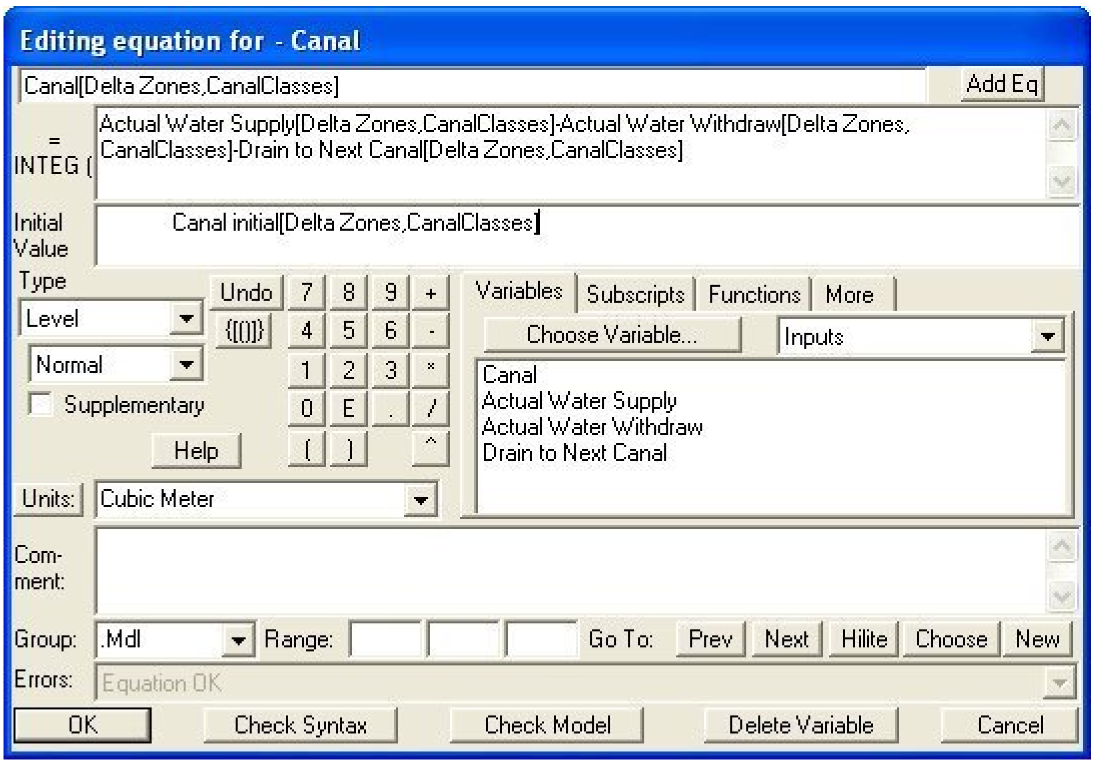


Figure 5-43: Modelling the Canals as an array stock.

As mentioned earlier, there are three cropping patterns (again added as a script in the model, see Figure 5-44). We can allocate one cropping pattern to each zone.

However, in the reality, the three cropping patterns may be found, and actually do exist, within the single zone. Therefore, each zone may include the three cropping patterns in various areas allocated across the zone. For this purpose, we added a new variable to the model called “policy variable for area allocation” to give the user the option to decide the area of the land planted with each cropping pattern. For example, within East of Delta zone, 20% of the land maybe planted with the first cropping pattern, 30% with the second cropping pattern, and 50% with the third cropping pattern (see Figure 5-45). The user can change these values through the “policy variable for area allocation”. This led to a further subdivision of the Delta to become nine clusters. The water demand in each cluster must be calculated from the area of the land and the cropping pattern. This implies that the dynamics of each variable called “Water Needed for Planting Agr Land” is governed by nine equations, as illustrated in Figure 5-46.

Figure 5-44: Adding Cropping Patterns as a script to the model.

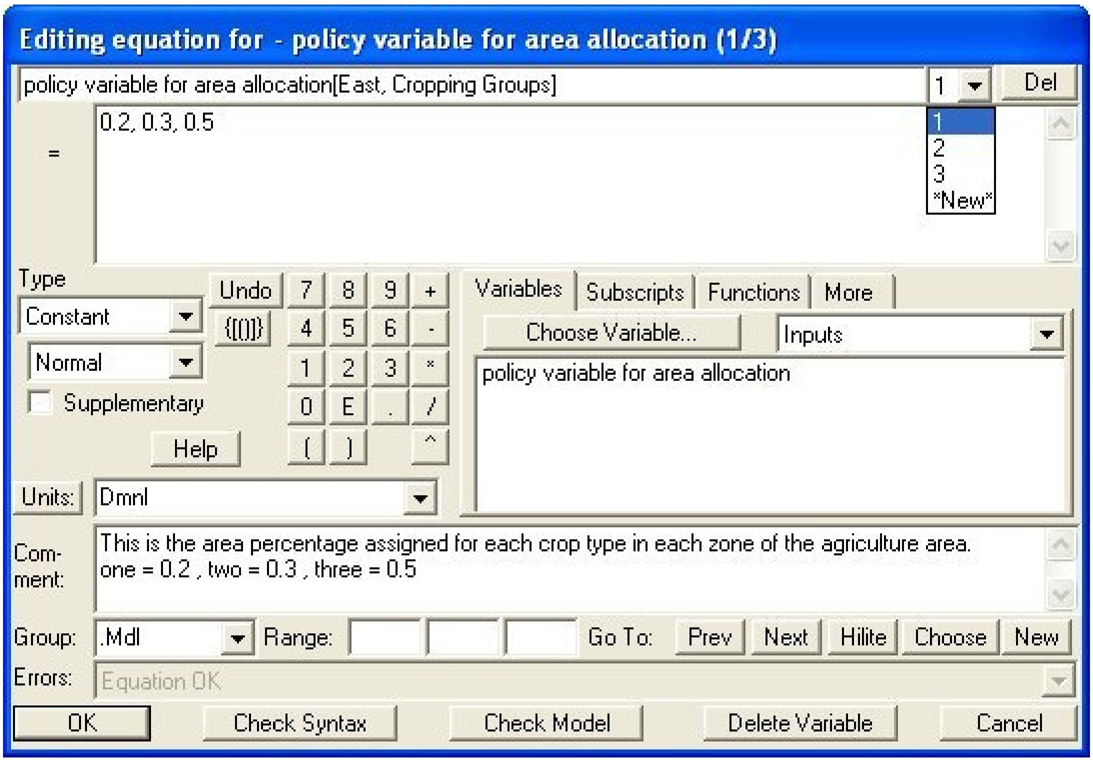


Figure 5-45: Adding Policy Variable.

The Policy variable has been added to assign various cropping patterns to the agriculture lands in the three geographical zones.

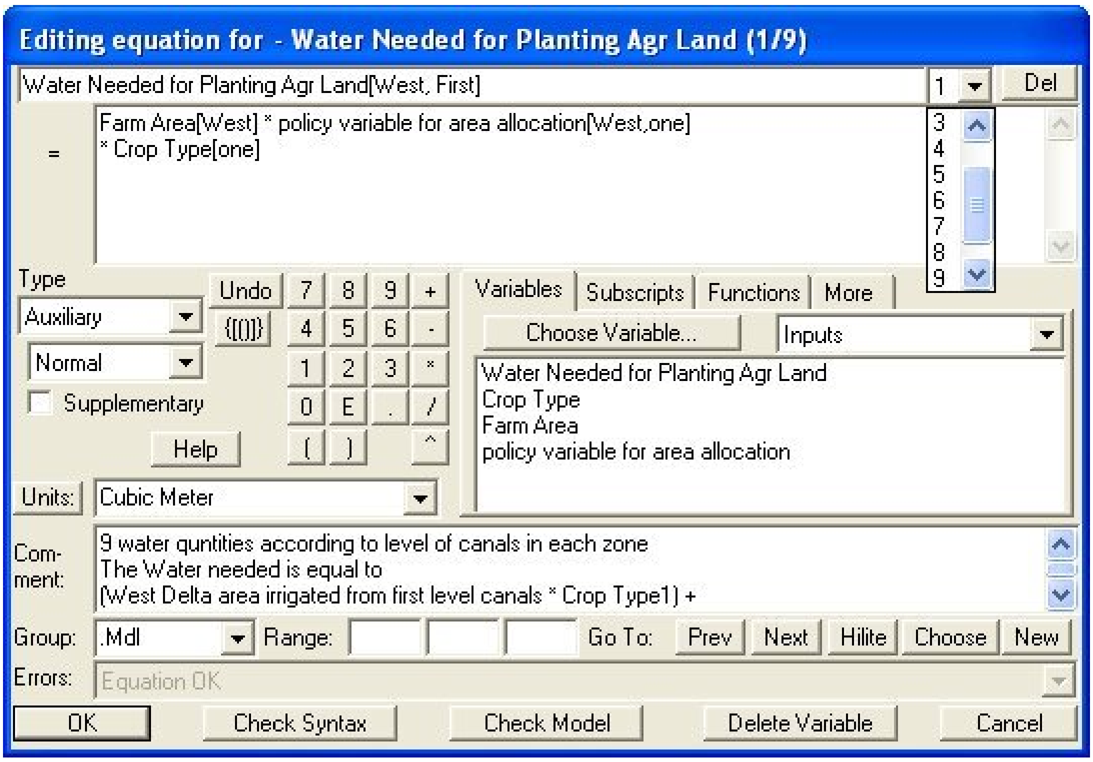


Figure 5-46: Adding nine equations to calculate the water demand in each area separately.

The same procedures have been applied to the rest of the variables in the model. The following assumptions have been made during the formulation of the equations associated with the variables *Water Supply*, *Canal Efficiency*, *Canal Cross Section*, and *Canal Length*:

- The water supply is equally distributed across the canal classes in all zones. However, the variable "Water Quote" has been added to the model to enable the user to alter the amount of water assigned to each canal class as desired in further runs.

- The Efficiencies of the canals are accounted for 95% for the first level, 90% for the second level, and 85% for the third level in the three zones.

- The average canal cross sections are 250, 125, and 50 sq meters for the first, the second, and the third level respectively in all of the three zones.

- The canal lengths have been calculated from the map and their values have been assigned manually to the associated variables in the model.

The array model, as developed in the Vensim software, is shown in Figures 5-47.

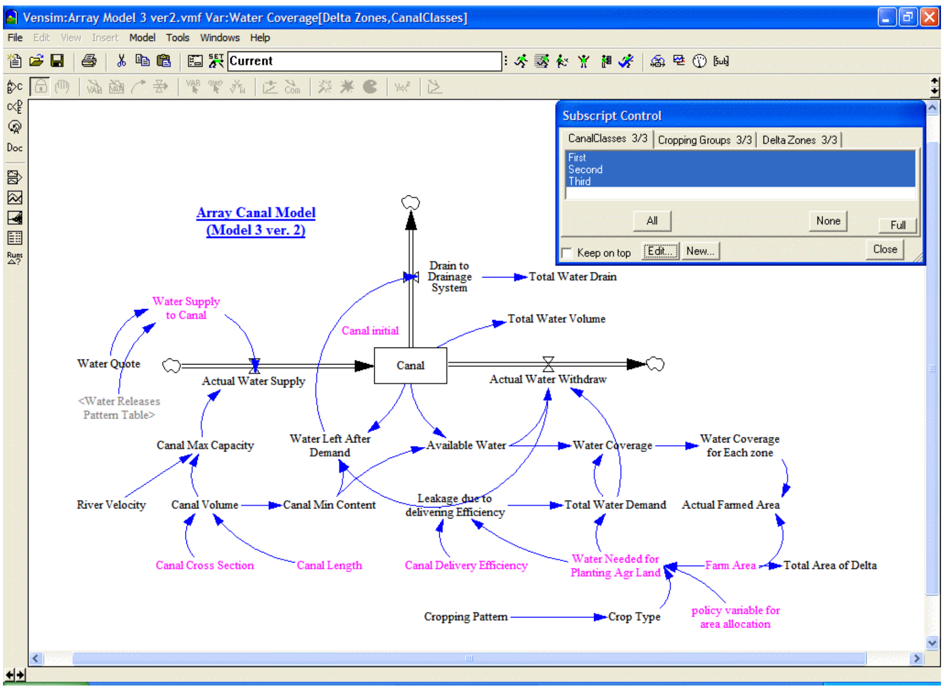


Figure 5-47: The array model with the associated scripts.

The model has been simulated for one year. The results of the simulation appear in the graphs collected in two columns in Figure 5-48. The graphs on the left hand side column portray the behaviour of the canal classes in the tree zones. The graphs on the right hand side column illustrate an example for the water demand and supply in the first canal class in the East of Delta *(T.R.)*, the water requirements for each crop type *(M.R.)* and the three levels of canal classes in East of Delta *(D.R.)*.

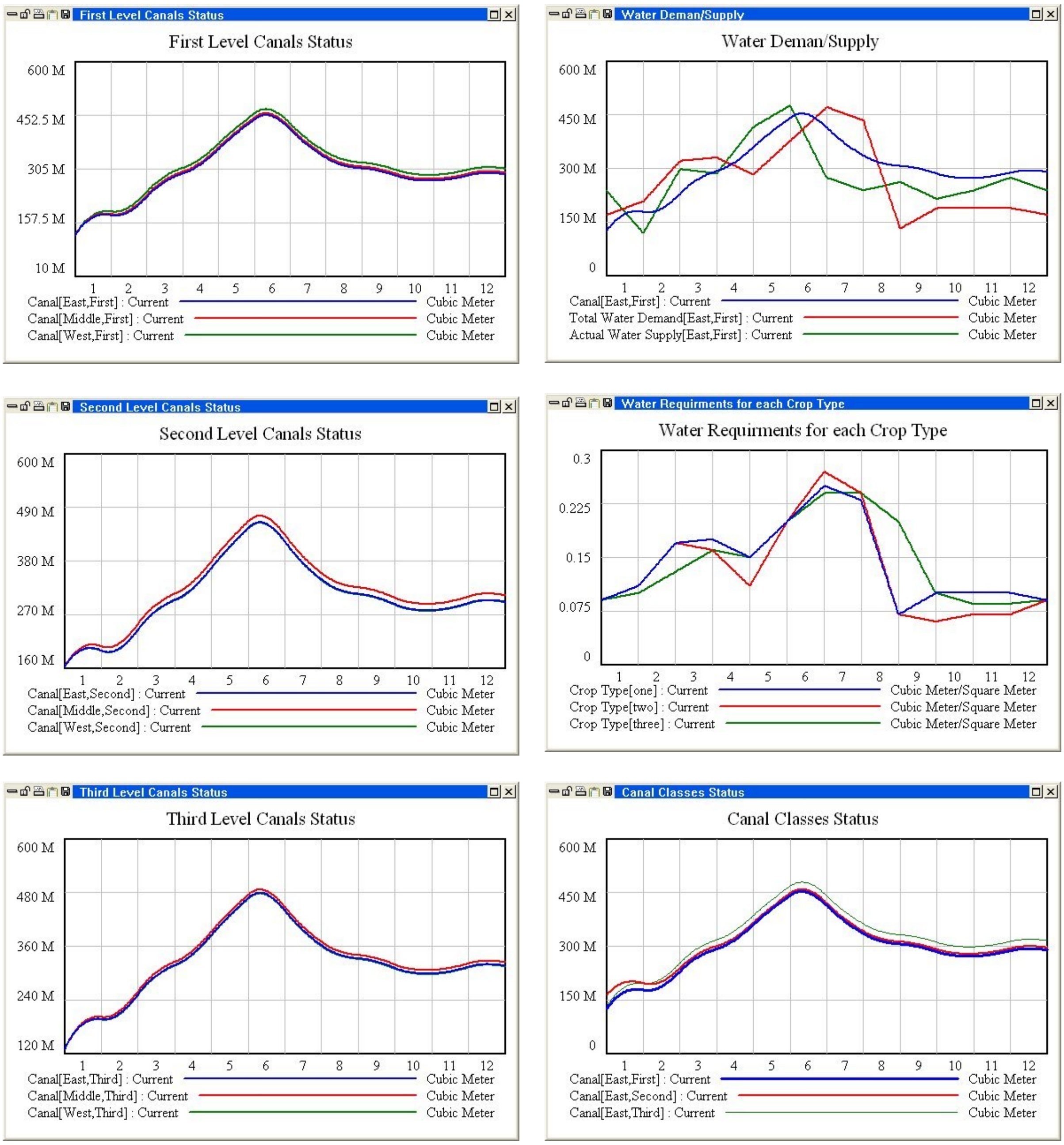


Figure 5-48: The array model results.

5.4.2 The New Classified Map

The original map of the irrigation network included an enormous number of canals (about 4277 canal) that generally have width attributes (e.g., canals more than 25m, canals from 10-25m, and canals from 5-10m). The canal width indicates the canal class (e.g., first level, second level, or third level). Using *Select by Location* tool and *Dissolve Features* from the Geo-Processing tools, we aggregated the canals within each zone based on their width. Consequently, we produced nine canal classes as shown in the attribute table in Figure 5-49.

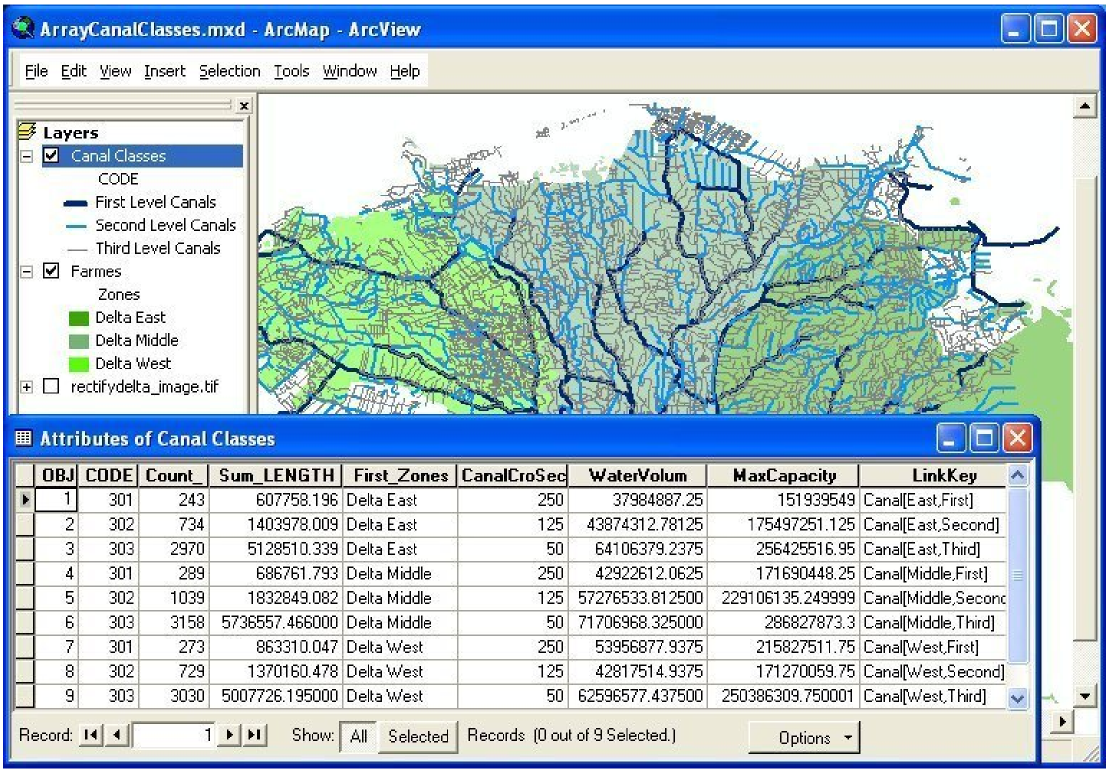


Figure 5-49: Reclassifying the irrigation network.

In the attribute table above, the values that appear in the CODE field represent the level of the canal (i.e., 301 for first level, 302 for the second level, and 303 for the third level). The field *First_Zones* points to the geographical zone. Thus, the canal classes within each zone can easily be identified. The field *Link Key* that holds explicitly the canal identification name has been added for convenient matching between the canal (object) on the map and the “full scripted name” of the stock in the simulation model.

5.4.3 The SDGIS Array Application

The improvements that have been made to the simulation model and the GIS model necessitated modifying the interface of the SDGIS to comply with the array-structure of the simulation model and the new classified map[32]. For example, in the first panel, the *SD Model* panel shown in Figure 5-50, two major changes have been made. First, the Frame “Model Arrays” that contains a List-Box to display the array variables has been added. When the user selects a variable from this List-Box, the scripts included in that variable are displayed in the Combo-Box right below the List-Box, and the Text-Box to the right will display the value of that specific script (one element of the array). The Text-Box is editable, which means that the user can change the value of that specific element of the scripted variable. The label below the Text-Box shows the “Units” of the selected variable as shown in Figure 5-51. Second, the “Current Water Volume” Frame, Figure 5-52, has been added with nine Text-Boxes to display the values of the nine elements of the array stock. Before triggering the simulation, these values represent the initial values. During the simulation, theses values are updated every time step to represent the current state.

In the second panel, the *GIS Tools* panel shown in Figure 5-53, the SSTab control object has been added to display the values of the nine canal classes retrieved from the map. The SSTab contains three tabs regarding the geographical zones. The tabs are labelled Delta East, Delta Middle, and Delta West, respectively. Within each tab there are three Frames, - each of them including three Text-Boxes to display the attributes of a specific canal class, - as demonstrated in Figure 5-54.

[32] The source code of the application and the equations of the SD Array model and the new classified map are provided in Appendix B.

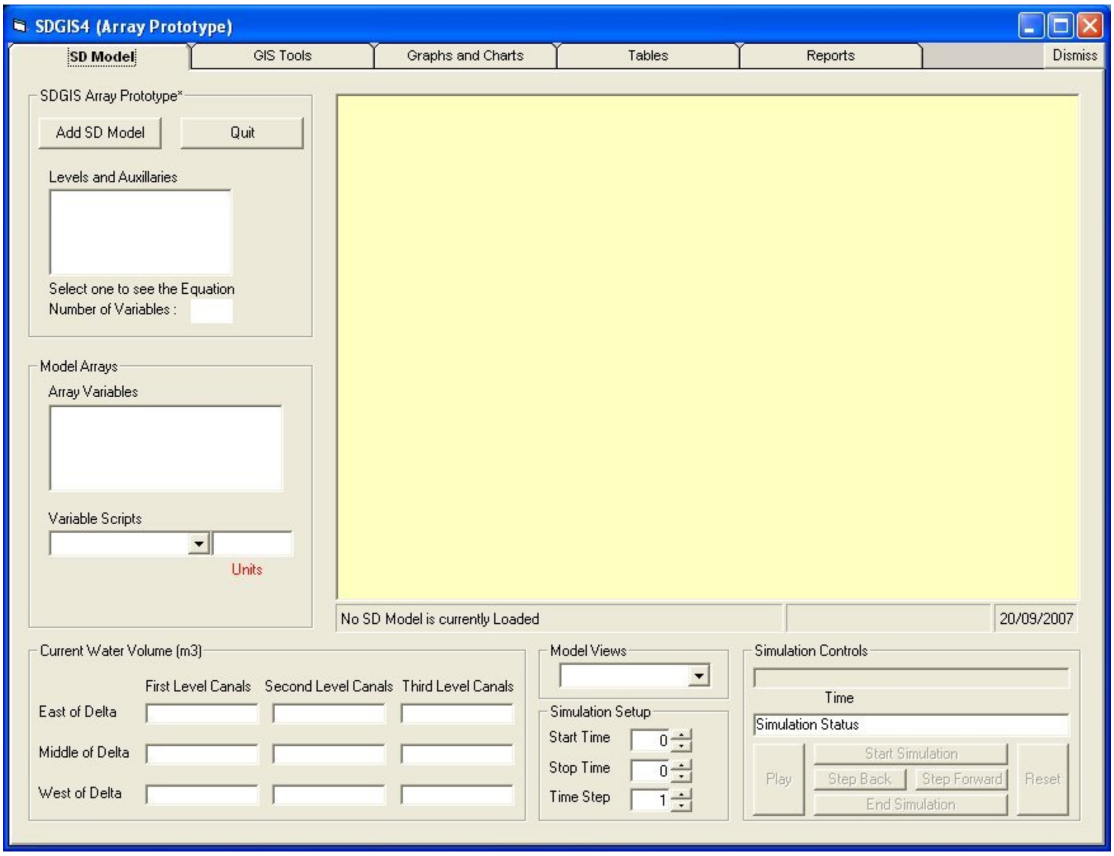


Figure 5-50: The SDGIS Array Application (SD Model Panel).

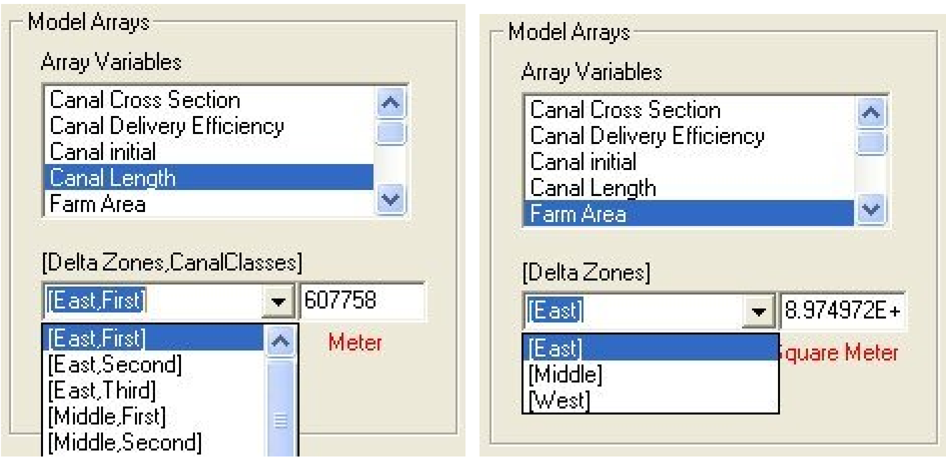


Figure 5-51: Model Arrays Frame.

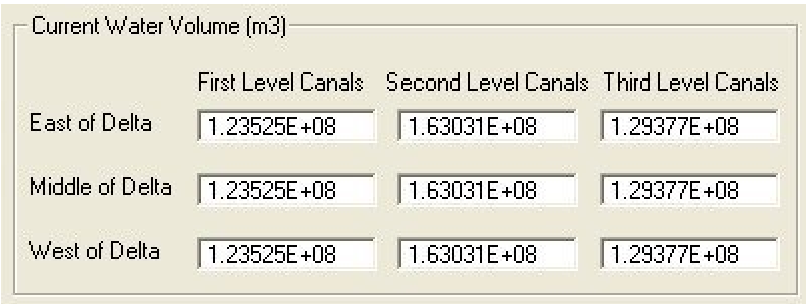


Figure 5-52: Current Water Volume Frame.

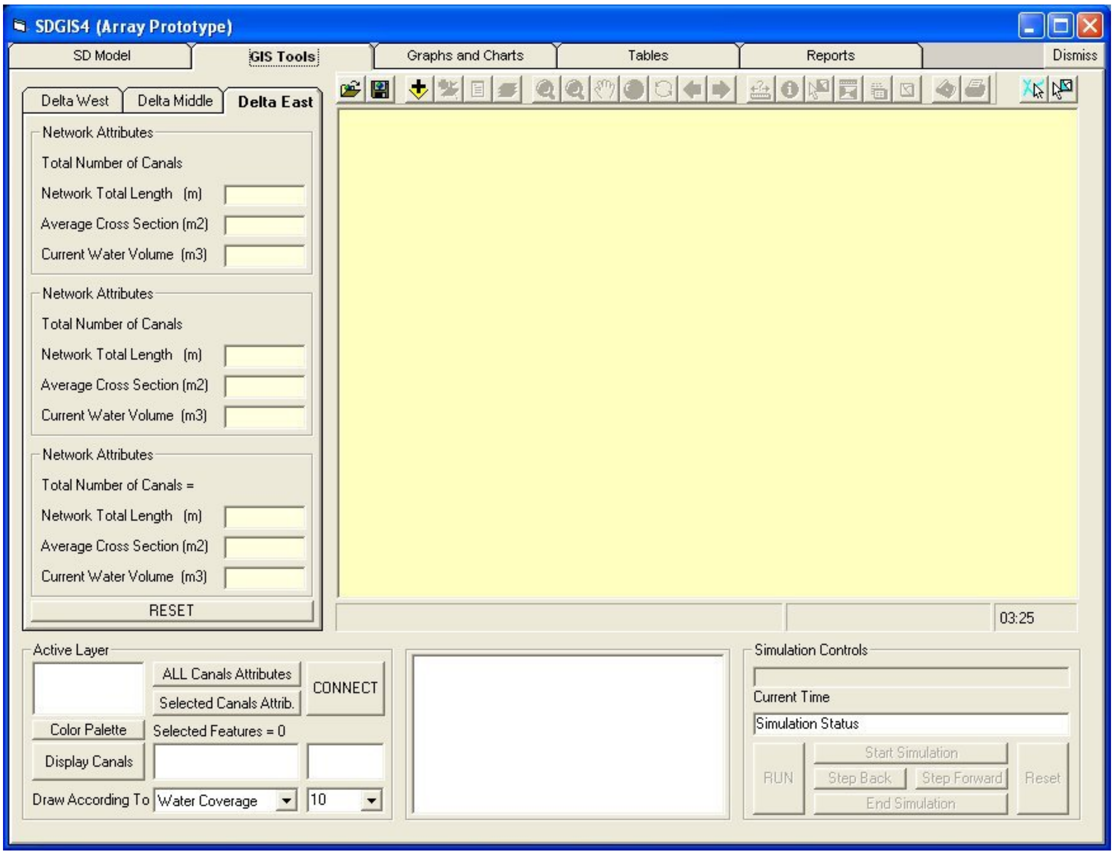


Figure 5-53: The SDGIS Array Application (GIS Tools Panel).

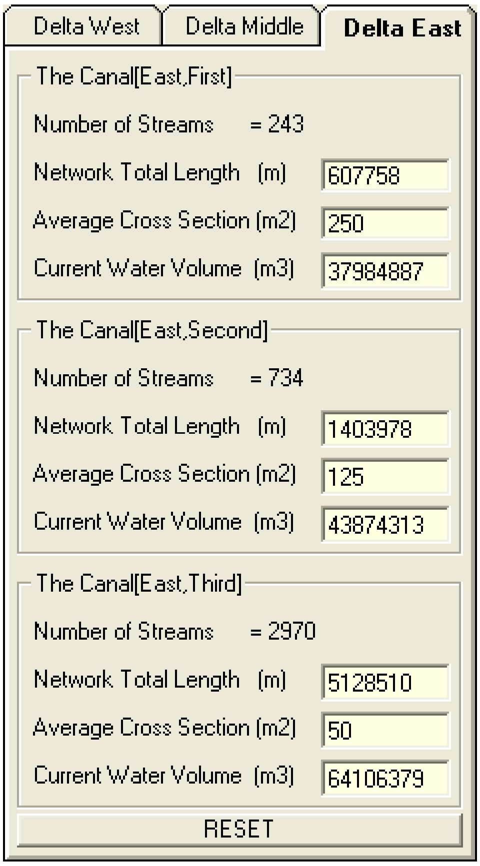


Figure 5-54: SSTab control object.

The “Active Layer” Frame that appears in the lower left corner on the panel has been modified to include:

The **All Canals Attributes** command button may be activated to execute the function that selects all the canals from the layer called “Canal Classes”, gets the canal script name, and put it in the frame title. The function retrieves the number of the canals within that class and displays it in the upper label[33]. The function retrieves also the canal length, the canal cross-section, and the initial water volume and displays them into the associated Text-Boxes.

The **Display Canals** command button has been added after testing the application. Due to the large number of canals, in particular the third level canals, the map becomes unreadable. Therefore, we decided to display only a few canals that the user must select before triggering the simulation. Yet, all canals are connected to the simulation model and the model simulates the entire irrigation network. During the simulation, the values of all canals are displayed into the SSTab, but only the behaviour of the selected canals is displayed on the map.

The selected canals List-Box is located to the right of the “Display Canals” command button. When the user selects canals for display, the full scripted name of these canals is displayed in this List-Box (see Figure 5-55).

The selected canals values List-Box: During the simulation, the values of the selected canals are displayed in this List-Box.

In the **Drawing Combo-Box** in the previous SDGIS application, the canals were drawn on the map according to their current water volume only. In this application, we evolved the visualization capabilities to draw the canals’ current state of affair. For example, the canals can be drawn according to the values of their water volume, water coverage, water inflow (supply), water outflow (consumption), or water leakage due to efficiency. In the Figure 5-55 the selected canals are the “first-level" and the "third-level" canals in "West of Delta" zone. These canals will be drawn according to their "water coverage" value that amounted to 0.66 and 0.32 respectively.

The **Line Thickness Combo-Box**: the user has also the option to choose the line thickness with which to draw the canals. This enhances the map visualization and makes it easy to read. The number that appears in the Combo-Box represents the number of pixels used to portray the canal in the map.

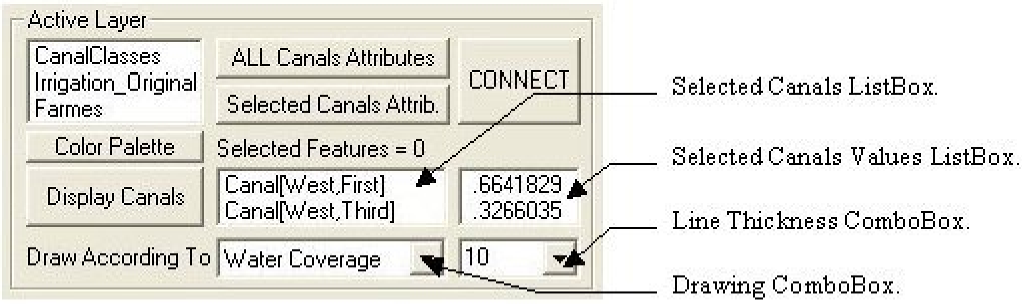


Figure 5-55: Active Layer Frame during the simulation.

5.4.4 Testing the SDGIS Array Application

To test the operability and functionality of the application, we load the array model into the application using the command button "Add SD Model". The application calls the functions associated with that button and the model diagram appears in the Picture-Box as shown in Figure 5-56. We can now see the following:

- The model's name appears in the second panel of the Status-Bar.
- The model stocks' and flows' names are listed in the upper List-Box and the number of variables appear in the small Text-Box under the List-Box.
- The models' constants, initials, and lookup tables are listed in the lower List-Box in the frame labelled "Model Arrays". One item from that List-Box, that

[33] Notice that the Dissolve process produces one object with multi-parts. The canals still exist with their geometry and location on the map, but have a single record in the attribute table.

is the "Canal Cross Section" has been selected and its scripts appears in the Combo-Box below the List-Box. The *value* and *units* of the first script, [East, First], appears in the Text-Box next to the Combo-Box (250 sq meters as shown in Figure 5-56).

- In the "Current Water Volume" Frame there are nine Text-Boxes associated with the nine elements of the array stock. The values that appear in these Text-Boxes are the initial values. During the simulation theses values are simultaneously updated.
- The model views appear in the Combo-Box placed in the Frame labelled "Model Views" under the Status-Bar.
- The values of the Start time, Stop time, and Time Step appear in the associated Text-Boxes placed in the Frame labelled "Simulation Setup". The user can change these values by editing the Text-Box next to each variable.

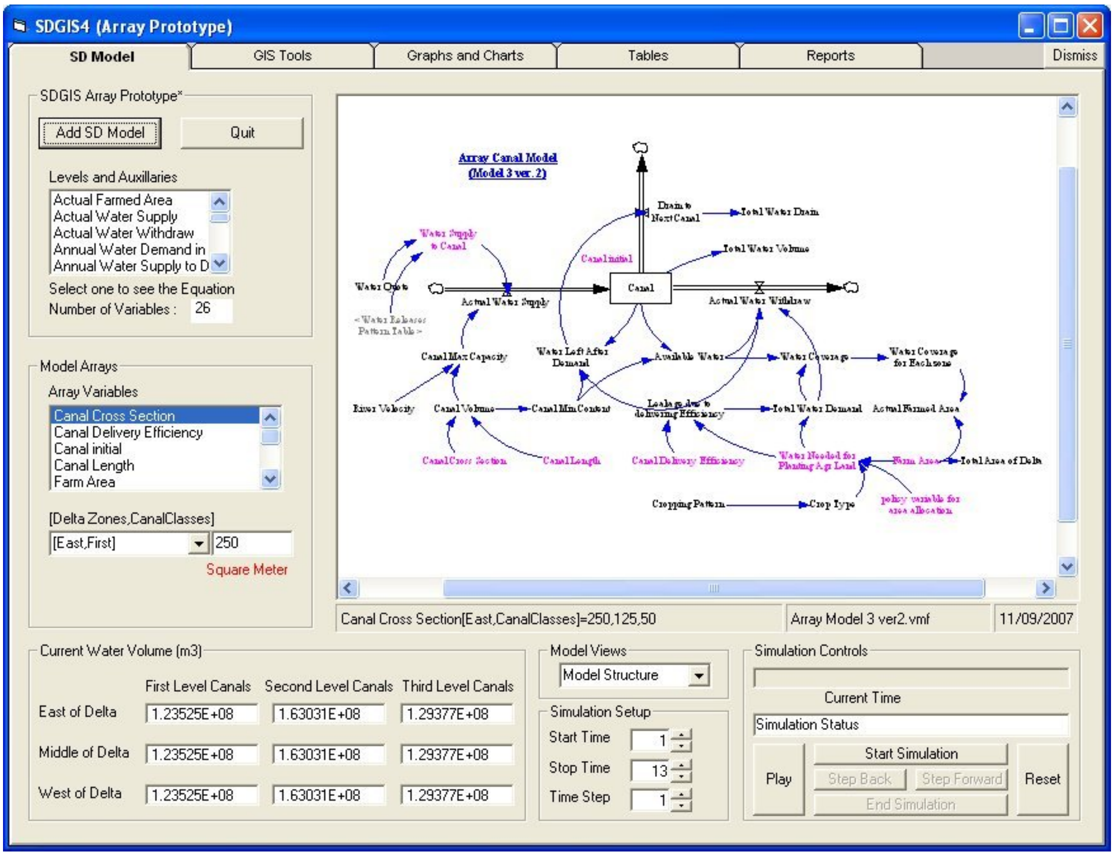


Figure 5-56: load the array Model into SDGIS Array application.

After loading the SD Array Model, the various control objects in the panel have been tested. Figure 5-57 shows that: (1) the “Available Water” variable has been selected from the upper List-Box and the associated equation appeared in the Status-Bar below the Picture-Box. (2) The “Canal Length” variable has been selected from the lower List-Box and the associated scripts are displayed in the Combo-Box. The second level canal class in the Middle of Delta has been selected and its length (with Units) appeared in the Text-Box placed next to the Combo-Box. (3) The simulation has been started using the Simulation Controls and the behaviour is represented in the Picture-Box as illustrated in Figure 5-57.

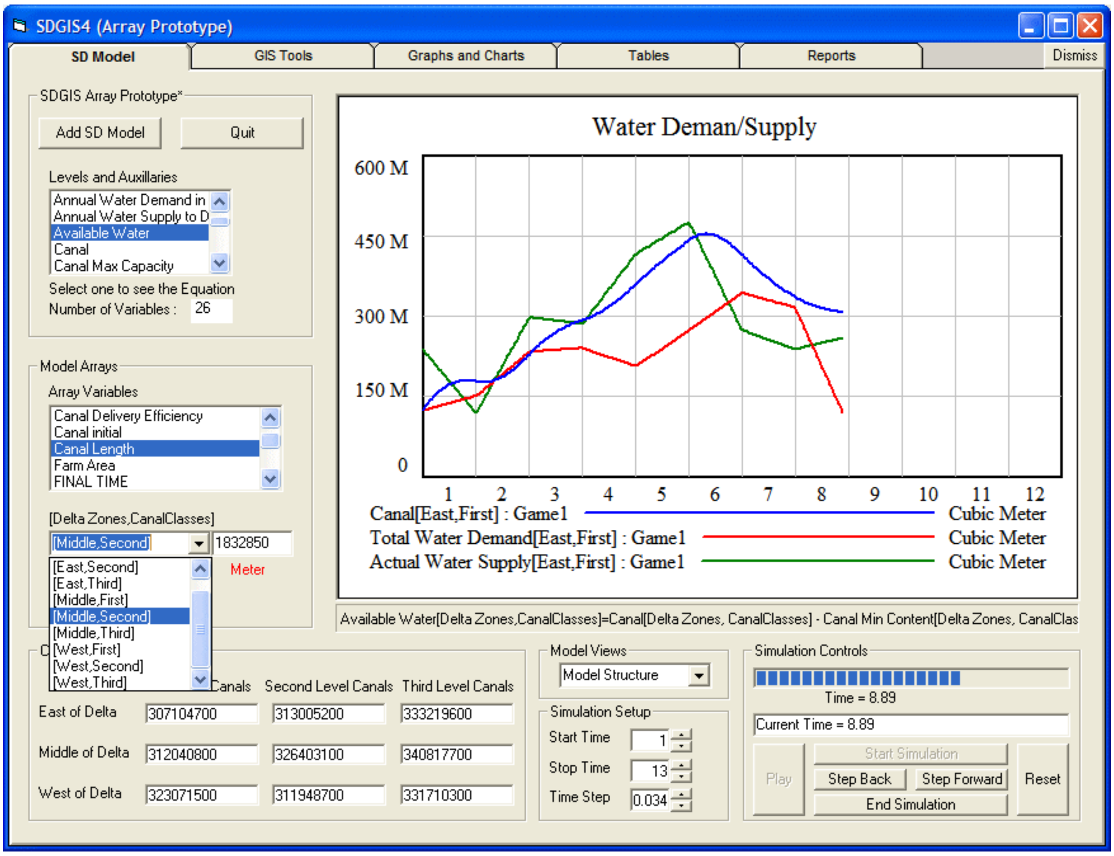


Figure 5-57: Running the Array model from SDGIS Array application.

In the second panel, GIS Tools Panel, we load the new classified map into the application by pushing the first button on the toolbar menu placed on the top of the MapControl. When the dialog box is opened as shown in Figure 5-58, we select the map document named “ArrayCanalClasses.mxd” and press OK. The map is loaded into the application as shown in Figure 5-59. Notice that the Text-Boxes on the

SSTab are empty. Pushing “All Canals Attributes” command button will select all the canals and display their attributes in the SSTab as shown in Figure 5-60. Now we can click on the “CONNECT” command button to connect the two models. Then using the select tool, we select two canals from the screen to display their behaviour (of course, we can select any number of canals and the application will display all of them). Pushing the “Display Canals” command button retrieves the scripted names of each of the selected canals and displays them in the Combo-Box next to the button, as they appear in the Figure 5-60, the selected canals are [West, First] and [West, Second].

We must also decide on the value and the line thickness that will be applied to draw the map. To do so, we select one of the items listed in the Combo-Box (in this case we selected the “water coverage”) and the line thickness (five pixels). Now we can start the simulation by pushing either the RUN button or the Start Simulation and Step Forward. The simulation advance is shown in Figures 5-61 to 5-64.

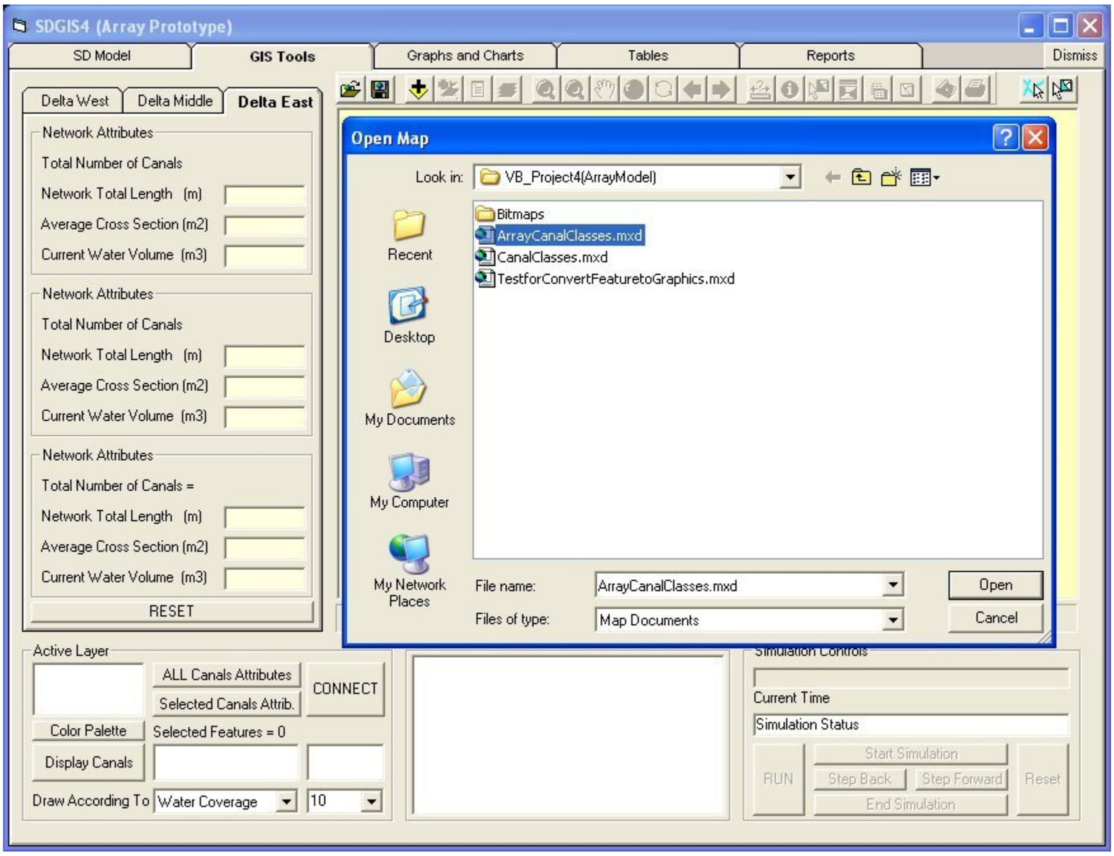


Figure 5-58: Loading the new classified map document.

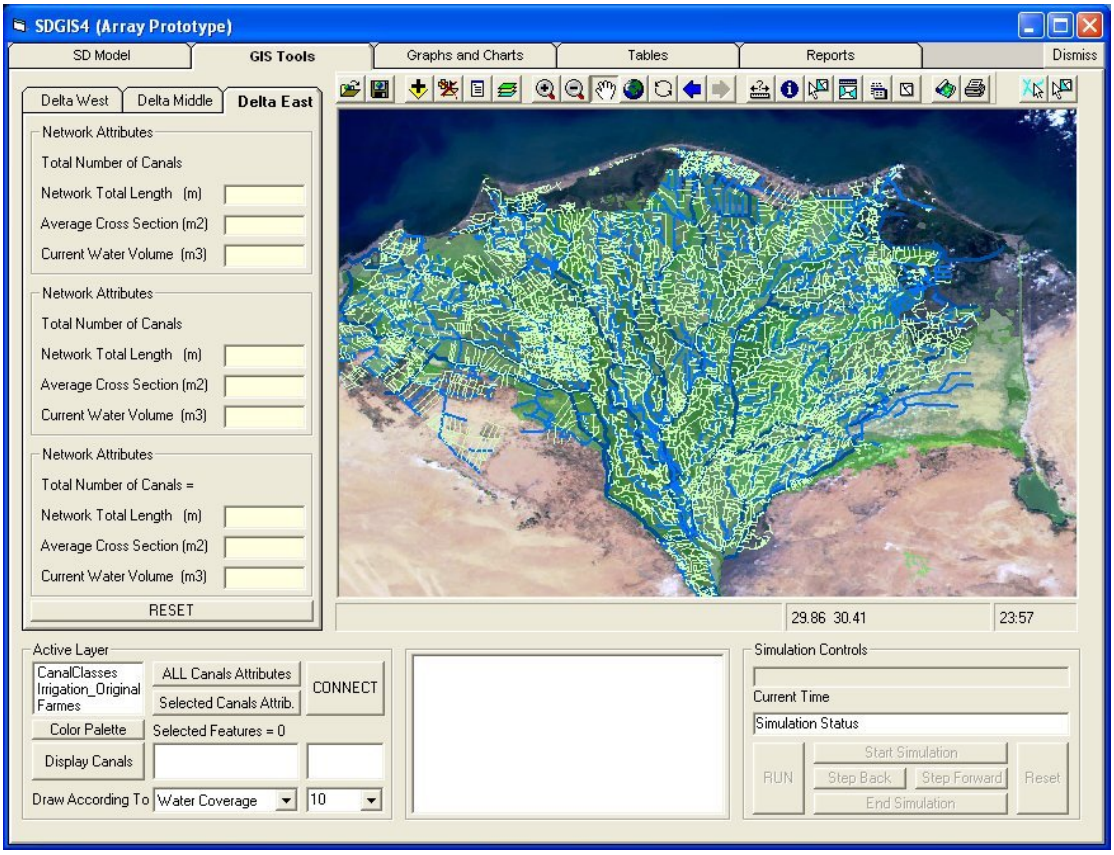


Figure 5-59: The Text-Boxes in the SSTab before retrieving the canals' attributes.

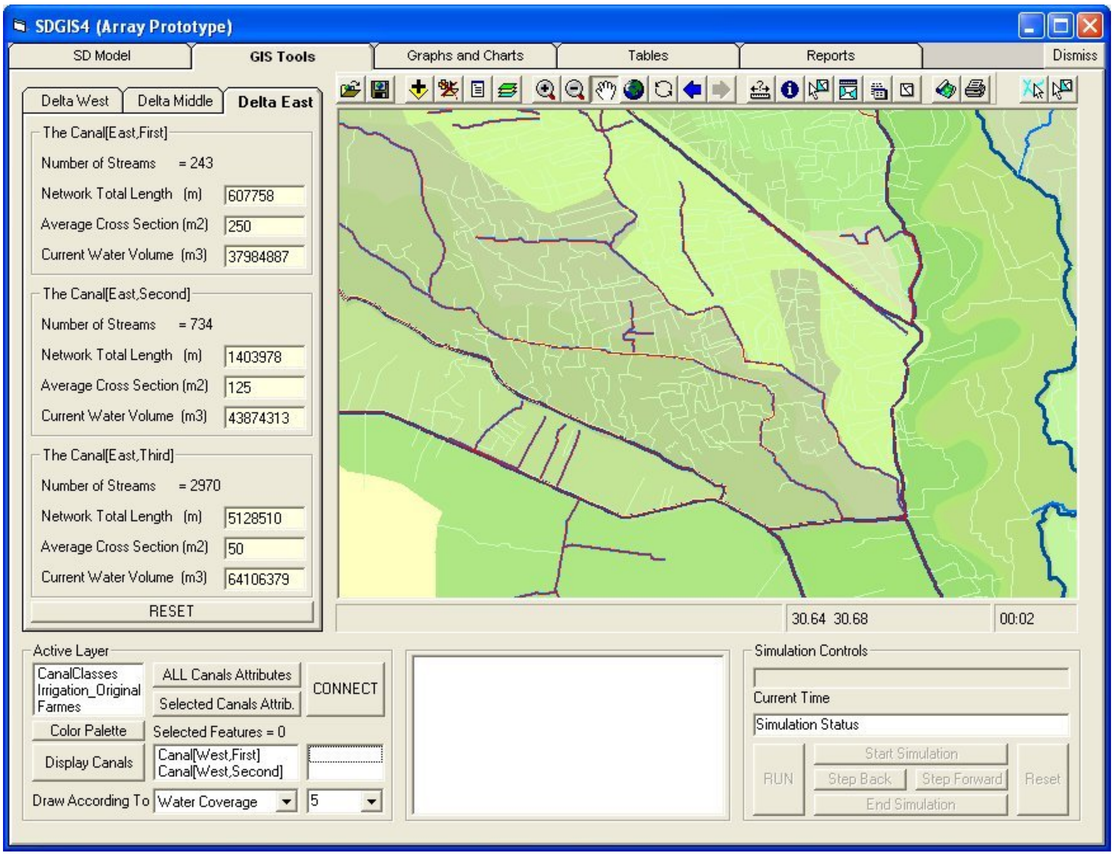


Figure 5-60: the selected canals' names appear in the Combo-Box.

The following figures demonstrate the behaviour of the model as time advances. In Figure 5-61, the first level canal class appears with darker colour than the second level. The values of the "water coverage" that appear in the List-Box indicate that the water coverage is below 100% for both canal classes.

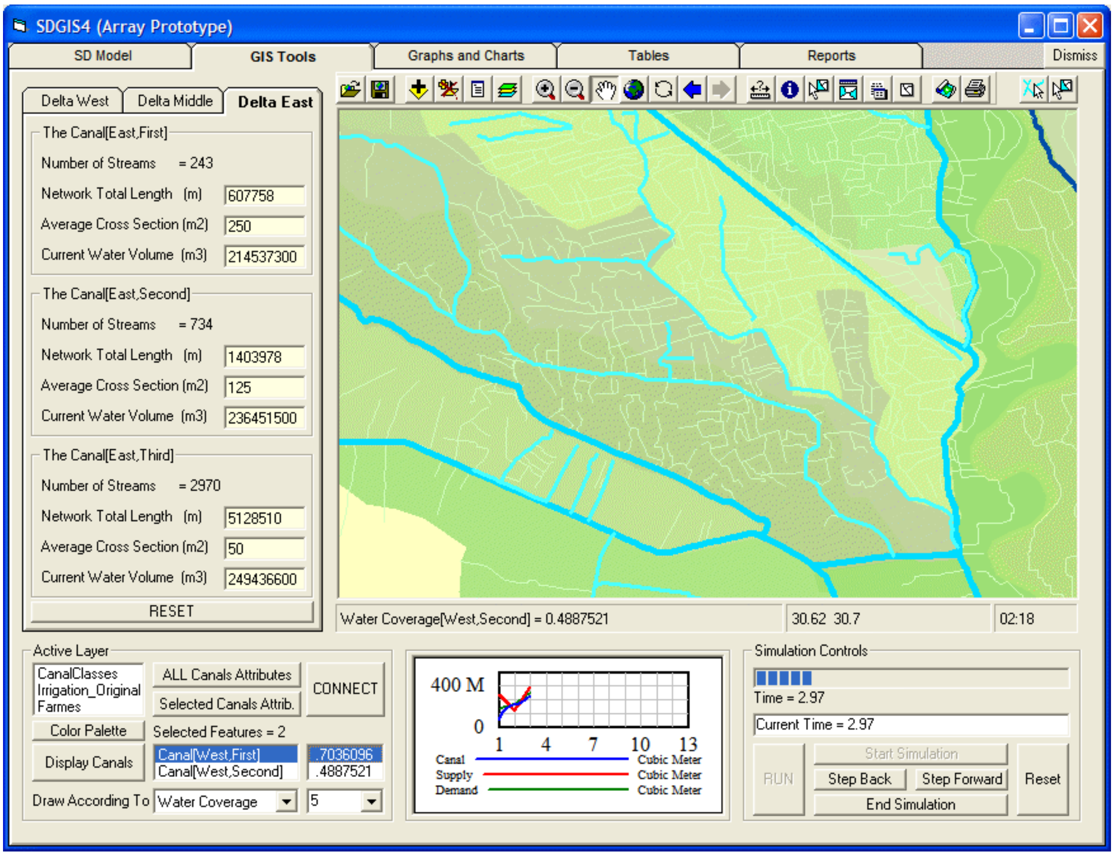


Figure 5-61: The model behaviour at Time = 3.

In Figure 5-62, the first level canal class has turned to black colour, while the second level appears with blue. This is because the values of the water coverage for both canal classes has become over 100%. As the simulation continues, the state of the canal classes is changing. Figure 5-63 shows the state of the canal classes at simulation Time = 11. The first level canal class appears with blue colour, as the water coverage has decreased, and the second level also appears with light blue colour. At the end of the simulation the first level canal class has turned to dark blue while the second level has slightly changed towards blue colour as illustrated in Figure 5-64.

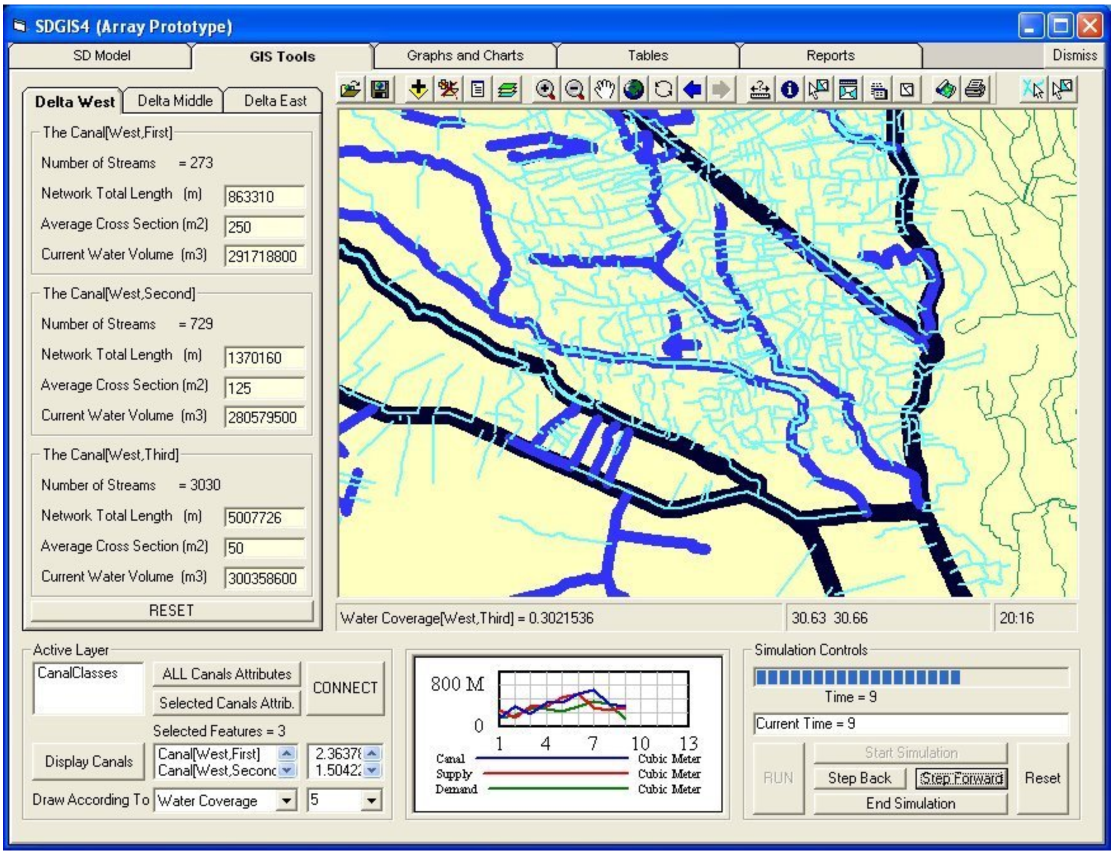


Figure 5-62: The model behaviour at Time = 9.

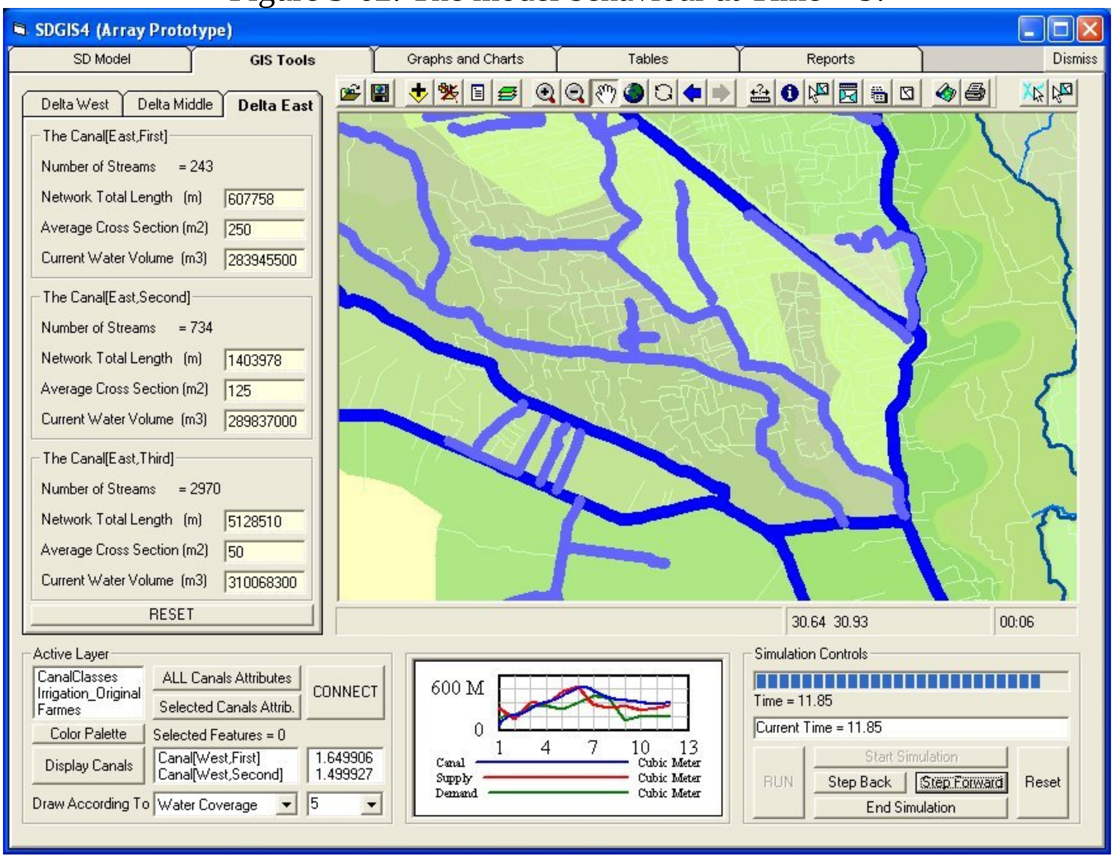


Figure 5-63: The model behaviour at Time = 11.

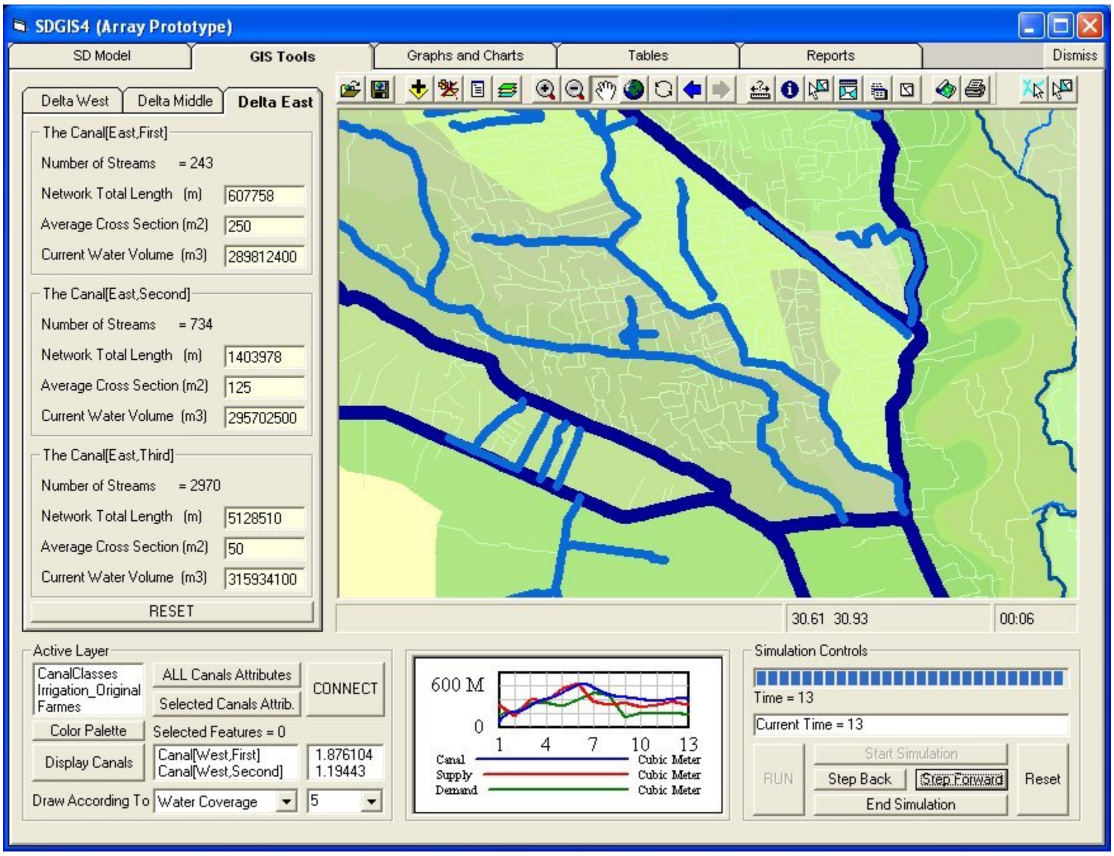


Figure 5-64: The model behaviour at the end of Simulation.

Figure 5-65 shows the simulation results in the "Graphs and Charts" panel that includes four Picture-Boxes display the graphs as being produced by Vensim simulation software.

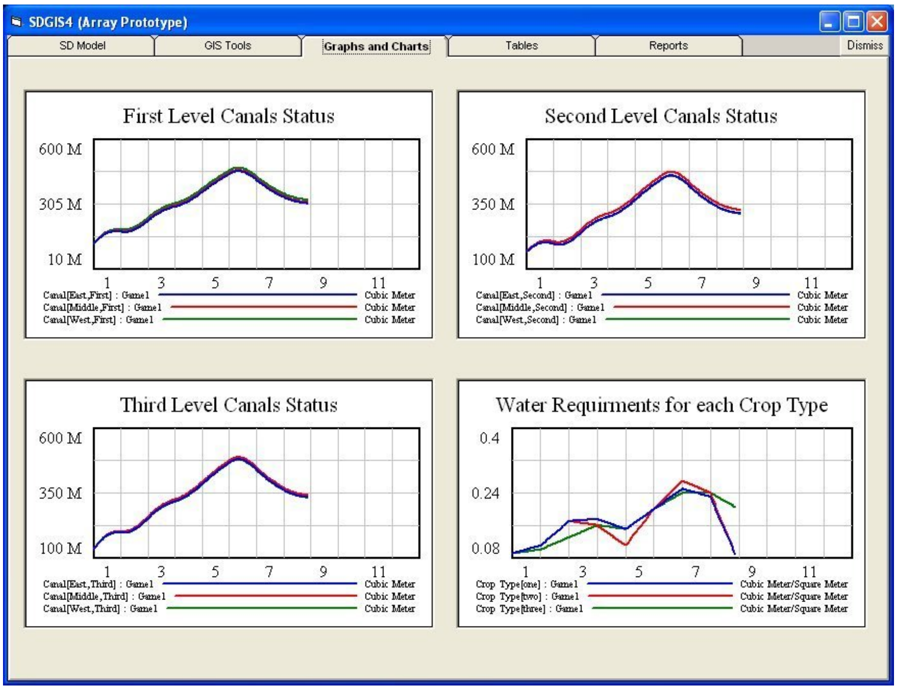


Figure 5-65: The model result graphs as appeared in the Graphs Panel.

One of the significant distinctions of this application from the previous one is that we can draw the map according to different parameters such as the current water volume in the canal, the water coverage, the water inflow (supply), the water leakage due to the efficiency of the canal, and the water consumed. In this sense, the map is employed to display a variety of different variables during the simulation. Another distinction is the colour sets used to draw the various canal classes. In the first application, only one canal was connected to the molecule model and so we used one colour set to represent the changes in the canal status. However, in this application, because there is more than one canal that may be selected for display, a number of colour sets were needed. In fact, the user can select all the canal classes (the nine canal classes) and display them using nine different colour sets that were created within the application.

It is noteworthy that, in the second application, the entire irrigation system is simulated when the map is connected to the simulation model. Only the selected features (canal classes) are drawn every time step on the map. This concept is similar to the concept found in Vensim where the user can choose one variable or more and assign it/them to a graph to draw its/their behaviour.

The development of this array application and its operability and performance is evidence that our method of integration is not limited to a certain simulation model or to a certain map. The user can develop several simulation models using different structures (i.e., single or array stocks and variables) and any number of maps can be used. The key issue here is the matching between the model components and the spatial features, and most significant is the logic behind such matching.

5.5 Conclusions

The SDGIS application, documented in this chapter is, in part, based on Microsoft Visual Basic. The documentation speaks to the feasibility and effectiveness of tightly coupling the simulation model with the GIS model for an irrigation system. The application has good potentials for extending the functionality of the current ArcGIS and enhancing the analysing capability and the visualization of the SD models. The application performance worked sufficiently fast.

Once the developer overcomes the hurdle of learning to program with Visual Basic, programming with ArcObjects and using the DLLs can be fairly simple, and in fact applications can be developed in a matter of a few hours.

The use of parallel models (built in their original software such as Vensim and ArcGIS) instead of embedded models gives the modeller the freedom to alter the simulation model as well as the GIS model at any time in response to the needs arising. There is no need to rebuild the entire core of the SDGIS application, only few adjustments to the GUI may be required.

During the development of the SDGIS application, we created a number of public functions to (a) match the SD model components with their counterpart spatial features in the GIS model; (b) define the connectivity rules; (c) perform user-selections and queries; and (d) handle graphs and adjust display of layers. These functions are stored in Standard Modules that can be used in other applications as well. In that sense, the concept of reuse, rooted in object orientation, is achieved.

During the simulation runtime, the SDGIS application enables the user to emulate the modification of the water distribution process and/or water allocations. These changes may be made in a variety of ways. The user can regulate the water volume that flows into the canal using the control gate slider (in this case the user controls the water supply), can change the cropping patterns (control the water demand), can change the delivering Efficiency (the quantity of water lost during conveyance), can increase the canal cross-section (increase the carrying capacity of the canal), and can specify release discharges from the reservoir (alter the annual schedule of the water releases) in the system. Thus, a number of different scenarios for new or planned water allocations can be developed and tested using the SDGIS application.

The SDGIS application developed in this chapter was improved and applied to the entire irrigation system in the Nile Delta region. The water scarcity problem is studied in light of this application and a number of water preservation policies are examined and discussed in the next chapter.

Chapter 6

The Adaptation of the SDGIS

Case Study: Water Scarcity Problem and the Irrigation System in the Nile Delta, Egypt.

6.1 Introduction

This chapter is the first part of our case study that deals with the application of the SDGIS to the irrigation system in the Nile Delta, Egypt. The aim of this case study is to demonstrate the capabilities of the SDGIS application and the feasibility of its application to a real problem in the real world. Although a number of water preservation policies have been discussed in the second part (i.e., chapter seven), the case study is *not* intended to draw a specific conclusion regarding how to solve the water scarcity problem. The case study has been undertaken *only* as a "proof-of-concept" for the ideas developed in this research.

In this part, we first describe the water scarcity problem that may emerge in the near future in Egypt, analyse its driving forces and highlight the factors that tend to intensify and possibly escalate the problem. Second, we describe the geographical and topological characteristics of the study area focusing on the irrigation system. Third, we explain the adaptation of the SDGIS application to the present irrigation system. This includes adapting the three components of the application: the SD model, the GIS model, and the integrating SDGIS interface. The SD molecule model, discussed in chapter four (see Figure 4-14), has been modified and used as a building block to develop the comprehensive SD model that covers the entire irrigation system within the study area (hereafter, we refer to that as the SD Spatial Model). The GIS model, that includes the various features of the irrigation system, has been improved by reclassifying the canals within the irrigation network according to their rank-order and geographical location. The interface of the SDGIS has been improved by adding: a number of control-objects distributed across, and organized into, four additional panels; and a number of functions that improve the visualization and the analytical capabilities of the application. Finally, we document the results of running the SDGIS application to test its operability and performance.

In the second part of this case study, that is chapter seven, we demonstrate the capabilities of the SDGIS application through illustrative examples for employing the SDGIS as: (i) an interactive learning environment for the educational purpose of explaining the complex irrigation system behaviour and management to non-technical individuals; (ii) an optimization tool for the irrigation network and the agriculture lands to attain the ultimate utilization of water and land resources; (iii) a spatial decision support system (SDSS) for supply, demand, and water allocation management and as a policy assessment tool for the water preservation measures.

Before we proceed further, it is worthwhile to mention that the analysis reported in this chapter, and in the next chapter as well, resulted from using the SDGIS application, and the approach behind the application, in studying the water scarcity problem and analysing the irrigation system dynamics. The SDGIS application has a unique advantage, that is, it includes the two analytical techniques provided in an integrated way. These techniques are: (i) the System Dynamics techniques for analyzing complex dynamic systems and problems with the aid of computer simulation software as a tool and; (ii) the GIS capabilities for spatial analysis. Using this application has enabled us to study and analyse the irrigation system in space and time, and to obtain a better understanding of the dynamics associated with the irrigation system operations and, at large, the water scarcity problem and its driving forces. We need this application because large irrigation systems, like the one being studied in this research, are usually complex, dynamic, and spatially distributed. Its operation and maintenance include both temporal and spatial aspects. Therefore, both analytical techniques are inevitably needed.

Irrigation, by definition, is the artificial application of water to the soil for assisting in growing crops. It is mainly used in dry *regions* that receive low annual rainfall, with specific quantities at certain periods of *time* during the crop growing period. The irrigation system is a composite of canals, laterals, structures, and equipments involved in the transport of water from where it is available to where it is required. The larger the volume or capacity of the irrigation system, the more sophisticated its various supporting components, and the greater is the skill that is required to operate and maintain it. It is complex because of the large variation in the interactions between the components of the system. These interactions in many respects are characterized by nonlinearities (e.g., the effect of climate on crop production, use of fertilizers on land yields) and uncertainties (e.g., the water supply from the Nile flood season in terms of timing and quantities), and affected by external factors such as topography, the local economy, and the nature of the agriculture and industry of the area. Consequently, the experience gained in operating some parts of the system can not be repeated or being applicable to other portions.

A common source of dynamics within the irrigation system is the interaction between the various groups of actors involved in the system such as: the water users, the government officials, the operators, and stakeholders. The objective of any irrigation system is to serve the water-users who may have conflicting interests. It is managed by government officials who attempt at retaining their political power through subsidizing the irrigation operations and affording irrigation water for free. The irrigation system is operated by teams of operators who must be able to respond rationally and not be prone to panic when they run into such problems as equipment failures, power outages, canal bank failures or confronting furious farmers. Because the system is spatially distributed and consists of subsystems, each of them in many respects unique, effective and efficient operation depends on each team of operators knowing how to balance their portion of the system to deliver water as required. Operators must know how their operations fit in and are affected by or affect other portions of the system. They must realize, for example, that the location of their portion of the system – e.g., at the head or at the tail of the system, has a direct influence on the water supply that affects the farmers' decisions to plant certain crops. Therefore, operators must learn by the fundamental structural insight the peculiarities of their portion of the system.

The analytical capabilities associated with the SD approach enable us to analyse the irrigation system and the water scarcity problem over time, and to understand, for example: (i) the process of water accumulation in the various parts of the system; (ii) the effects of the resulting delays in water delivery; (iii) the effects of uncertainty of water delivery in terms of volume and timing; and (iv) the feedback loops and nonlinearities of the underlying causal structure that governs the behaviour of the system. Yet, it is equally important to analyse the system in the space. Spatial analysis focuses on the spatial bounds between the components of the system and the properties that vary with the geographical location. A fundamental concept in geography is that nearby entities often share more similarities than entities which are far apart [Goodchild, 1987]. This idea is often referred to as “Tobler's first law of geography” and may be summarized as “everything is related to everything else, but nearby objects are more related than distant objects”. This means that characteristics at proximal locations appear to be correlated, either positively or negatively. There are at least three possible explanations. One possibility is there is a simple spatial correlation relationship: whatever is causing an observation in one location also causes similar observations in nearby locations. For example, planting certain crops in nearby areas within a province tend to be similar due to factors such as socio-economic status, the features that attract one farmer will also attract others. Another possibility is spatial causality: something at a given location directly influences it in nearby locations. For example, the broken bank of a canal due to the farmers’ misbehaviour resulted from the unequal distribution of water between farms tends to breed more violation of this kind of behaviour due to the apparent breakdown in order and the lack of maintenance. A third possibility is spatial interaction: the movement of people, goods or information creates apparent relationships between locations. For example, the emergence of certain crop-markets occurs as a result of “friction of distance” to where these crops are produced, or other key locations in farmers’ daily activities. Another example is the distance decay: a wide variety of services are characterised by the phenomenon of distance decay, including retail, health care, education, and many others. This simply means that individuals are less likely to utilize a service if it provided at a distance.

The above discussion is an example for the temporal and spatial aspects that are involved in the irrigation system operation. To obtain a better understanding of the irrigation system dynamics, both temporal and spatial analyses are needed. The SDGIS application provides the user with the tools to perform these analyses. This is why using this synergizing application is more favourable and valuable than using a single method of analysis.

6.2 Water Scarcity Problem

"As water is the font of life, irrigation has been the font of civilization. It underlay the rise of the first sedentary societies organized on a large scale, in Mesopotamia, Egypt, the Indus Valley and China. Irrigated agriculture appears to have been developed as early as the 7th century B.C." [Roger D. Norton, 2004]. It has been estimated that: 2.4 billion people depend on irrigated agriculture for jobs, food, and income; and over the next 30 years, an estimated 80 percent of the additional food supplies required to feed the world will depend on irrigation [FAO, 1993]. In playing this fundamental role for food production, irrigation has become the largest consumer of fresh water worldwide, accounting for more than 80 percent of water use in Africa [World Bank, 1994] and comparably high percentages in other developing regions of the world. In the year 1992, for low-income countries as a whole, irrigation accounted for 91 percent of water withdrawals, and for medium-income countries the corresponding figure was 69 percent [World Bank, 1992].

In the past, many irrigation strategies tended to treat water as an inexhaustible resource, and the emphasis was placed on the construction and financing of new systems to serve farmers. Now the growing demands for water in all sectors (agriculture, urban, and industry) have made it clear that water is a scarce resource, and the former irrigation strategies are no longer viable in many areas.

Ever larger numbers of countries are seeing their annual renewable water supplies fall below the critical level of 1000 m^3 per capita, below which they become a severe constraint on development prospects. Some of those countries, and their projected renewable water supplies per capita for the year 2000, in cubic meters, are: Saudi Arabia (103), Libya (108), United Arab Emirates (152), Yemen (155), Jordan (240), Israel (335), Kenya (436), Tunisia (44-5), Burundi (487) and Egypt (934)[34].

[34] These figures include river flows from other countries, some of which may not be reliable sources in the future [FAO, 1993, p. 238].

Per capita fresh water availability in Egypt dropped from 1893 m^3 per person in year 1959 to 934 m^3 in year 2000 and tends to decline further to the values of 670 m^3 by 2017 and 536 m^3 by 2025 [UNCCA 2001; UNCSD 2003; MWRI 2002a; Abdel-Hai 2002]. The obvious reason behind this rapid fall is the predetermined quota of water from the Nile (55.5 BCM) and the raising pressure from population growth. The last is not the only reason, behind the scene, there are significant driving forces escalating the water stress in Egypt. These driving forces fall into four categories: *Social*, *Economical*, and *Political* forces, as well as forces arising from *Natural Resources* (i.e., agricultural lands and water).

Social Forces comprise the population growth impacts, poverty in rural territories, cropping patterns, unequal distribution of water for irrigation, and the farmers' behaviours. These forces affect the **Natural Resources** (i.e., land and water) establishing enormous pressure for agricultural land expansion, which in turn exhaust the current water resources and boost the demand for water. The incremental demand for domestic water consumption due to the population growth makes the situation even worse. **Economical Forces** indicated that the annual freshwater consumption for agriculture sector in year 2001 amounted 83 percent of the freshwater available. Despite its high water consumption levels, the agriculture contribution to the GDP accounts only for 16.5 percent versus the industrial and service sectors with 33.3 and 50.2 percent share in GDP respectively. Agriculture can be affected by increasing water scarcity due to growing demands from other sectors that seem to be more profitable and thus increased water costs. **Political Forces** attempt at keeping these driving forces in balance. Political power representatives apply an "Irrigation subsidies strategy" claiming that there are positive social effects from irrigation subsidies that have influence on the generation of social benefits such as increments in employment and income. Through the "affordability" of water for irrigation, agriculture absorbs 50 percent of the labour force in rural areas, and prevents rural households from being pushing out of agriculture and into cities that cannot provide shelter, jobs, and food for millions more.

6.2.1 Analysing the Driving Forces

6.2.1.1 The Social Forces

Social forces include: (i) the population growth that considered as the obvious primarily cause of the problem. However, its impacts are likely to take place in the future; (ii) Farmers and farms' conditions (i.e., quality of farmers' life, poverty, unequal distribution of water between farms, cropping patterns, and farmers' misbehaviours). The impacts of these factors contribute to the water shortages already in the present. Water stress influenced by those factors has discreet character in space even within boundaries of one village. These factors (farmers and farms' conditions) are influenced by other factors, such as awareness and cultural patterns. The latter can be seen as a consequence of information availability, literacy and education-level.

The Population Growth

The growing population of Egypt and the associated industrial and agricultural activities has increased the demand for water to a level that reaches the limits of the available supply [ICID, 2005]. The population of Egypt has been growing in the last 25 years from a mere 38 million in year 1977 to 78 million in 2007 and is expected to grow up to 83 million in year 2017. The present population is concentrated in the Nile Valley and the Delta. About 95% of the population lives on 4% of the land of Egypt. To relieve the pressure on the Nile Valley and the Delta, the government has embarked on an ambitious plan to increase the inhabited area by means of horizontal expansion projects in agriculture and the creation of new urban and industrial areas in the desert. The expansion of the agriculture land and the reclamation projects are also needed to increase the food production to support the increasing population. Undoubtedly, these projects require additional water. However, the water availability from the Nile River is not increasing and opportunities to gain additional supply are very limited. Up till now, Egypt had sufficient water available and the current management is very successful in distributing the water to all its users. Thanks to the enormous storage capacity of the High Dam Lake. The supply of water to these users is fully provided and nearly constant. Now that Egypt is reaching its limits of exploiting the water available, the country will have to face the consequences of scarce supply.

Quality of Life

The standard of living has improved remarkably over the last 30 years due to the accelerated economic growth. The main indicators of the social and human development programs and health services have made advances in life expectancy, from 55 years in 1976 to 67.1 years in 2001. Infant mortality was subjected to more than a three fold reduction during the same period. The fraction of population who has access to the piped water has increased from 70.9% in 1976 to 91.3% in 2001. Almost 100% of urban households have access to sanitation facilities versus 78.2% in rural areas [HDR, 2003]. However, in terms of access to piped water and sanitation, there is a great disparity between the regions behind the average figures. For example, in some provinces only 79.6% of the population are being supplied with piped water and 18.6% do not have access to sanitation. These figures are among the lowest in the country, leaving room for further improvements in life quality. These improvements can impose additional constraints on the water supply at large in Egypt as a result of a boost in the water consumption levels. Advancements in standards of living, together with population growth, have already been reflected in the expansion of water consumption levels for domestic use. Water consumption rose from 3.1 BCM in year 1990 [Abu-Zeid, 1991] to 5.23 BCM in year 2000 [FAO-ASD, 2003]. Further augmentation of the life quality and the population growth will push water demands up even further.

Poverty

In contrast to the significant changes in the quality of life, poverty is still a problem in Egypt. The Human Development Report (2003) estimated that 20.4% of total rural population of Egypt is poor and 6.1% is ultra poor[35]. The high poverty incidence in rural parts of the country indicates a concentration of poverty in the rural areas. The distribution of poor households in Egypt is quite uneven and shows significant differences among regions. For example, some provinces in the Delta have higher poverty rates that reach 35.4% while the ultra poor people account for 10.9 % of population. In other provinces in South Egypt, the proportion of poor is as high as 58.1 percent. Often low-income levels and poverty in rural areas trigger the increase of water use through shifting the cropping patterns towards the water thirsty crops (e.g. rice, sugarcane) that do not require large investments (cheap seeds and very low running cost for growing).

Cropping Pattern

Cropping pattern plays a vital role in determining the irrigation water demand. During the 1950s, 1960s, and 1970s, the agricultural sector was characterized by heavy government interventions in the production, trade and prices. The reform in the 1980s resulted in liberalization of prices and government control of the cropping was abolished. Consequently, some changes in cropping patterns have occurred favouring the production of high value-added crops. Among them are the rice and the sugarcane, resulting in the highest water requirements among the crops cultivated in Egypt. For example, the annual production of rice rose from 2.4 to 4.5 million tons [UNCCA, 2001] and fields of rice expanded by almost 50 percent (from 1 million to 1.5 million faddan[36]) [MWRI 2002a]. The cropping patterns that sometimes lead to water shortages, serve the welfare interests of rural families. According to the UNCCA (2001), 57 percent of the population lives in rural areas, and a major portion of them are engaged in the agricultural activities. As the agriculture is completely dependent on irrigation, it becomes the largest user of water with 83 percent share in water consumption.

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[35] The poverty line used in HDR 2003 for rural area is 3963 EGP (Egyptian Pound). Poor is defined person whose expenditure is less than specified poverty line. Those who are bellow food poverty line (3752.6 EGP) are considered as ultra poor.

[36] One faddan equals 4200 square meters or 0.42 hectare.

Expanded fields of rice require additional amounts of water and, therefore, rice cultivation is restricted by the state. However, the fields of rice sometimes are out of control and there are observed violations of the quotas set by the government. Even though official reports explain the increase in the cultivated rice areas by the increase in Nile flows during the 1990s [MWRI, 2002a], the national survey (1998) shows that the main incentive behind the choice of crops to be cultivated is the profitability of those crops compared to other crops. The explanation based on a profit driven cropping pattern, seems more relevant in this case if we take into account the poverty levels in rural areas that forces people to take benefit of crops that yield high profit. The rice is a high value crop and is likely to be an important contributor to raising the income [Poverty Reduction in Egypt, 2002]. Thus, the fields of rice and sugarcane tend to expand, driven by the welfare needs of farmers.[37]

Unequal Distribution

The unequal distribution of irrigation water is another factor that contributes to the emerging water stress conditions. This is a result of water overuse at the head of the canal bringing less water toward its tail. Thus, the farmers at the tail of the canal and downstream suffer from water shortages and are forced to abandon cultivation of some part of their land in order to avoid yield losses, whereas at the head of the canal peasants enjoy the abundance of irrigation water.

Unequal distribution of water can be linked to the bounded behaviour of farmers who cannot see far reaching consequences of their actions (i.e. behaviour such as mistreatment of irrigation infrastructure in order to get wider access to water. The low cooperation levels and the low communication facilities preventing spreading the feedback of downstream farmers to the upstream ones is another aspect

[37] Some argue that not only the low-income farmers stand behind the rice filed expansions but profit driven motivation of big farmers can lead to the same result as well. However, we must note here the subsistence character of the farms in Egypt with the average landholdings of 2.6 faddan and 40 percent of farmers hold less than one faddan [Malashkhia, 2003]. Therefore it has been assumed that main contributor to augmentation of high water demanding crop fields is the low income levels, beside the “free water” factor which will be discussed later on in the Political forces paragraph.

of this complicated issue. Farmers cannot always be blamed for their ignorance or low consciousness since the over-irrigation practices that lead to water shortages downstream are often induced by the unreliability of the water provision in canals. Uncertainty in water availability pushes them to over-irrigate, as they are not sure of the water delivery (volume and timing) next time [Holmen, 1991]. Obviously, the water scarcity, in this sense, is not bounded in time or space. Water shortage can occur in the present within one village boundary, masking an abundant fresh water availability at the head of canal.

Consumers' Behaviours

The water stress conditions are also tied to the conscious behaviour of the consumers (i.e., the farmers) emerging from the level of education, accessibility and availability of information and cultural patterns. A good example of the education level effect is the resistance of the farmers to use the new irrigation methods. Regardless of the presence of new irrigation systems in the new cultivated lands, farmers are still using the "surface flood irrigation method" [MWRI, 2002a]. They prefer the old methods they had used to and resist the innovations.

Another example is the difficulties to expand the cultivation of "the short-duration rice" despite its lower water requirement. One of the reasons is the taste of rice that Egyptian farmers do not like. Thus, they refuse to cultivate rice for taste preference reasons, - i.e. in part for cultural reasons. A second main reason for such a bias against this kind of rice is the lack of information about availability of such varieties. Moreover, this behaviour is enhanced by the accessibility to the inexpensive (almost free) irrigation water.

Lack of information among the farmers causes lack of *awareness*. A national survey was carried out in year 1998 intended to identify the farmer's awareness, attitudes and practices concerning the water resource management. The study shows that about 61% of male and 29% of female farmers know that the available water resources in the country are fixed. The "inexhaustible resource" perspective mentioned above is widely spread throughout the country. Only 21% of the farmers consider the scarcity problem that can emerge in the future as serious, whilst 23.6% do not see the problem at all. 57% of the farmers hold the hopes that a larger water quota is negotiable. The response of the farmers differs significantly according to the education levels, pointing to higher awareness of the problem among higher-educated respondents. The low awareness can be explained with the low literacy level (53.1%) in the rural community [HDR, 2003], and the poor accessibility to the information.

Awareness about water preservation measures is low as well. Farmers are poorly informed about opportunities available to decrease the water consumption. As the survey indicates, only 20% of male and 4% of female farmers had ideas about how to irrigate with less water, however about half of the respondents were aware of advantages of night-irrigation and almost all of the farmers use land levelling [El-Zanaty & Associates, 1998].

6.2.1.2 The Natural Resources

The natural resources include water resources and agricultural land. The Nile River is the main source of fresh water in Egypt and most fertile agricultural lands lay on the Nile banks alongside its course from the south of the country to the north of Cairo where the diverge into two main branches forms the Delta to the north.

Water Resources

The Nile River provides more than 96 percent of all fresh water resources in Egypt [UNCCA, 2001]. Egypt is entitled to 55.5 BCM of water from the Nile annually [Abu-Zeid, 1991]. The current water demand in Egypt is estimated at 67.47 BCM annually. Therefore the Nile becomes the almost exclusive source of water for the country. The rest of the water demand is met by: the renewable groundwater (4.8 BCM), the drainage-water reuse (4.5 BCM), and the treated municipal (0.7 BCM) and industrial wastewater (6.5 BCM), which returns to the closed system. About three BCM out of the 55.5 BCM is lost in the surface evaporation from the irrigation network [MWRI, 2002a]. Water demand is expected to rise up to 87.9 BCM by year 2017. It has been planned to meet the rapid growth of water demand *partly* from additional water resources that can be obtained from non-renewable groundwater aquifers in Sinai Peninsula and the Eastern and Western deserts [UNCCA, 2001].

Table 6-1 indicates the present and the projected water resources. The water balance for year 2017 can meet the demand if the irrigation improvements plan, drainage water reuse, and treated wastewater reuse achieve the target figures. The objectives cause some concern regarding whether meeting these targets is realistic. In particular this is true in the case of the 2.35 BCM possibly provided by the Jonglei canal in Sudan[38] that has not been completed, and the drainage water reuse (4.7 BCM in 1990) which should reach up to 7 BCM in year 2000, Unfortunately the figure has remained 4.5 BCM even in year 2001, [Malashkhia, 2003].

Table 6-1: Present and projected water resources in BCM based on CCA materials.

Source	1990	2001	2017
The Nile River	52.5*	52.5*	55.5**
Renewable ground water	2.6	4.8	7.5
Agricultural drainage water	4.7	4.5	8.4
Treated domestic waste water	0.2	0.7	2.5
Treated industrial waste water	6.7	6.7	6.7
Desert aquifers	0.5	0.57	3.77
Rainfall and flush harvesting	-	-	1.5
Saving from management	-	-	1.5
Total	67.20	69.77	87.37

* The 3 BCM of surface evaporation is subtracted.
** Including the 2.35 BCM possibly yield from Jonglei project.

Land Expansion

Due to the present development of the manufacturing sector and the land reclamation projects, a considerable increment in water demand is emerging in the agriculture and industry sectors. Despite the present conditions of continuous declining “per capita crop area” and “per capita crop production”, the current

[38] The Jonglei Canal, started in 1980, is a hydro-construction project in Upper Nile Province of southern Sudan designed to reduce the evaporation by altering the course of the White Nile as it passes through a swampy area in southern Sudan known as the Sudd. According to Egyptian officials, the purpose of the canal was to ensure the flow of 4.7 BCM of water annually, to be equally distributed between Egypt and Sudan. However the project was put to a halt in 1983 following the outbreak of the North-South civil war.

population growth rate (1.721%) obliges the agriculture sector to provide food for a considerably larger number of people in the near future.

The problem of “limited land resources” is not only restricted to the food security issue, but linked to the employment issue as well. The rural area accommodates 57% of the population, 50% of them are engaged in the agricultural sector [HDR, 2003]. The food demand, the habitation requirements, and the increased demand for jobs, force the government to adopt land reclamation policy. Such a policy has been considered the most realistic and effective way to generate jobs to meet the population growth problem. The national plans promise to add 3.4 million faddan of desert land to the cultivated land area [UNCCA, 2001]. This means that, given the present water use practices, land expansion would place an enormous stress on water supply.

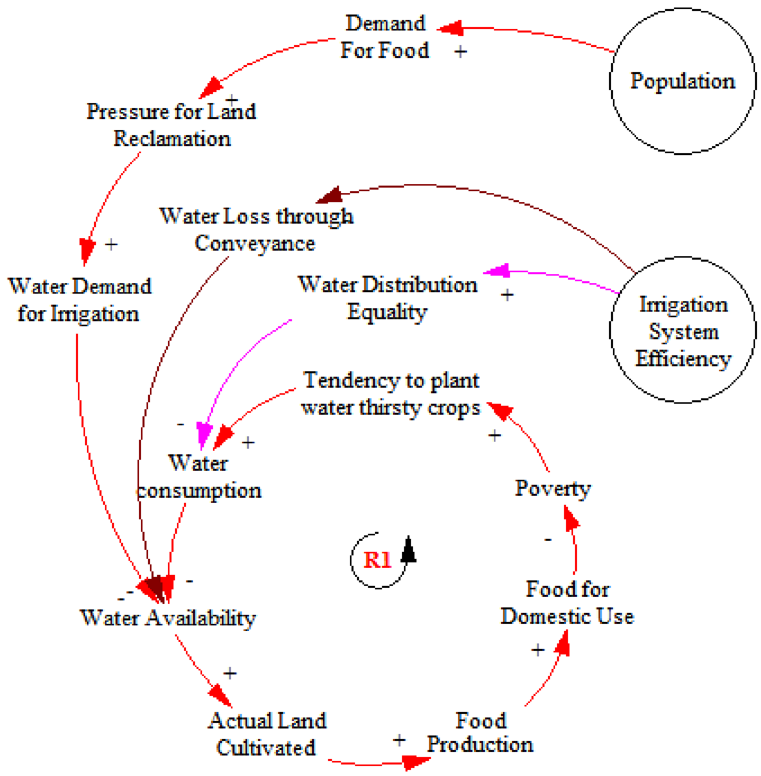

Figure 6-1: The CLD for Social forces and Natural resources.

The causal loop diagram shown in Figure 6-1 has been developed to describe the causal relationships between the social forces and natural resources (water and land). As the population continues to grow, the demand for food will increase. This puts more pressure on both the government and the private sector to adopt a land reclamation policy and to expand the agriculture land. Such reclamation projects raise the demand for irrigation water significantly and exhaust the current water resources. At the same time, the inadequacy of the present irrigation system infrastructure leads to unequal water distribution service, and large quantities of water are lost as a result of the conveyance process. These water losses decrease the opportunity to cultivate even the present agricultural land that suffers from land-yield deterioration. As a result, the food production will slow down in these areas, a slow-down that may only partly be compensated by production in the new areas. This will increase the poverty leading to inadequate cropping patterns and inefficient farming. Consequently, the water consumption will boost adding additional stresses and shortages.

6.2.1.3 Economic forces

As supplies fail to catch up with the growing demands, the competition for water will intensify. As illustrated in Table 6-2, the agricultural sector is the largest consumer of water resources in Egypt (and so it is worldwide) with a contribution to the GDP of only 16.5 percent share. In comparison, the industrial and services sectors contribute with 33.3 and 50.2 percent share respectively. Thus, from a macro-economic perspective, the agriculture sector is the most vulnerable one to loose its share in the water resources being the one that utilizes water the least effectively. As some analysts point out, agriculture can be affected by increasing water scarcity due to growing demands from other sectors. It has to compete with high value consumers. In the long run, this may lead to the release of water from agriculture to the other sectors [Engelbert et al, 1984]. The consideration about water reallocation becomes relevant taking into account the Egyptian government's support to the development of the industrial sector [MWRI, 2002a].

Table 6-2: The present water distribution between various sectors [39]

Water Users	Worldwide (%)	Egypt (%)		
	1999	1990	2001	
Agriculture	65	84	83	*78*
Industry	25	7.8	10	*14*
Domestic use	10	5.2	6	*8*
Total water use in BCM	-	59.2	67.47	*68.67*

The water demand from the industry sector has increased in the last decade from 7.8% to 10% (to 14% according to FAO), mainly at the expense of other sectors. The water demand from the domestic sector has increased from 5.2% to 6% (8% according to FAO) while the water used for agriculture declined by one percent (6% according to FAO) during the same period. Thus, the impacts of increased competition among sectors are already becoming evident. It is important to emphasize the fact that, for economic reasons, the water reallocation may shift towards a use of water characterized by a higher productivity. This may lead to the emergence of a water scarcity condition in the agriculture sector resulting from the fact that it is the least effective water consuming sector.

The economic forces have been added to the causal loop diagram portrayed in Figure 6-1 to produce Figure 6-2. The figure shows that the improvement of the irrigation system and the water distribution services are driven by the investments in the operation and maintenance processes. With a delay, these investments lead to an increase in the efficiency of the irrigation system and to a minimization of the water losses, resulting in more water being provided for cultivation and reclamation processes. This will provide more food for export, which, in turn, will help in cost-recovery and magnify the contribution of the agriculture sector to the GDP, encouraging for additional investments for water preservation purposes.

[39] Based on [Abu-Zeid, 1991] and [UNCCA, 2001]. Figures given by FAO are indicated in italics.

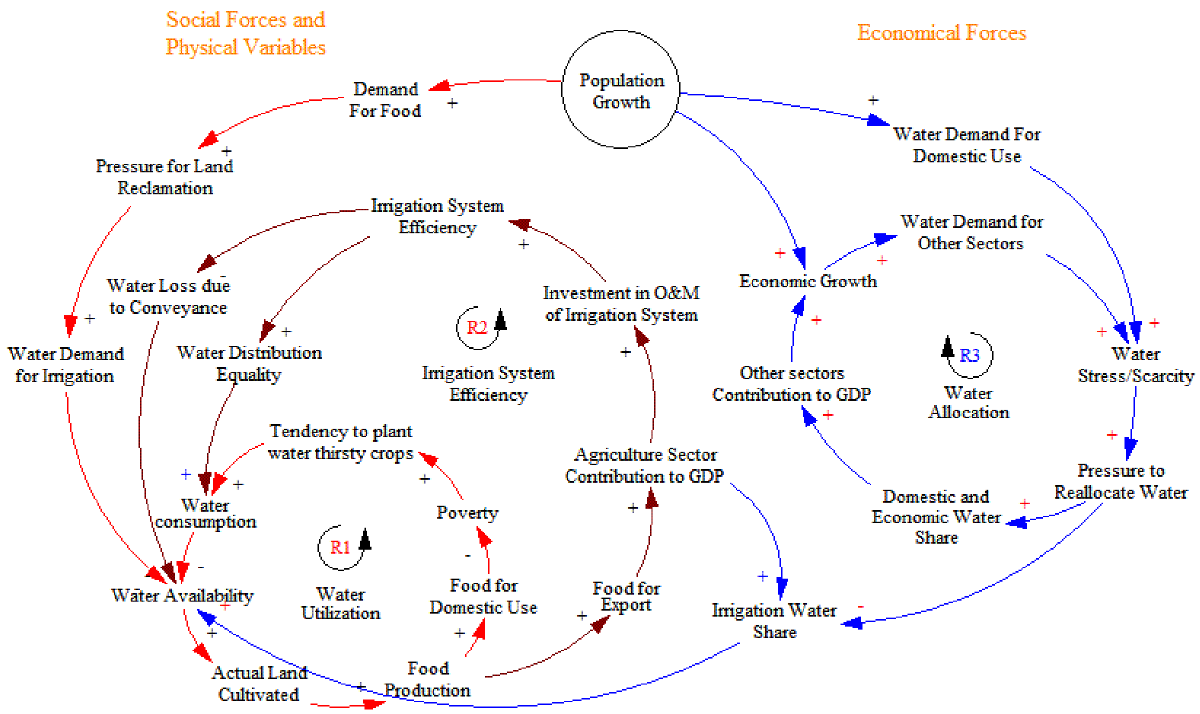

Figure 6-2: The CLD for Social and Economic Forces.

6.2.1.4 Political Forces

Although water is crucial for the sustainable development in Egypt, the limited water resources are not treated as scarce commodity. On the contrary, the government is heavily subsidizing the water supply. This action unintentionally induces wasteful practices and hinders the emergence of rational use of resources [Ahmad, 2002]. The *subsidy* issue, and its removal, would have a wide variety effects on the whole society. The interactions of subsidy-related variables are shown in Figure 6-3. Subsidies mean to grant water for free. This strengthens the present political power, which aims at providing more employment in agriculture sector and improving farmers' welfare. The higher the income, the more satisfied the farmers are. This facilitates the retaining of the present political power. The urban low and middle-income classes benefit from the subsidy as well, as they are provided with relatively inexpensive food. On the other hand, the higher the subsidies are, the lower is the cost recovery and the less the governmental ability to grant public funds. Therefore, the incentive to invest in agriculture diminishes. It negatively affects the performance of the irrigation system and decreases its efficiency which in turn intensifies the water stress conditions. The subsidies also promote water intensive crops, which aggravate the water scarcity problem even more. Scarcity leads to lower income and poverty. The more severe the poverty the more subsidies are needed. The relationships here are reinforcing. The subsidies in the irrigation sector are aimed at sustaining the agriculture economy, ensuring the self-sufficiency of farmers. However, the heavily subsidized access to the irrigation service boosts water demand and discourages farmers from investing in efficient technologies and carrying out water saving practices [Postel, 1996, 1997; Rogers et al., 2002].

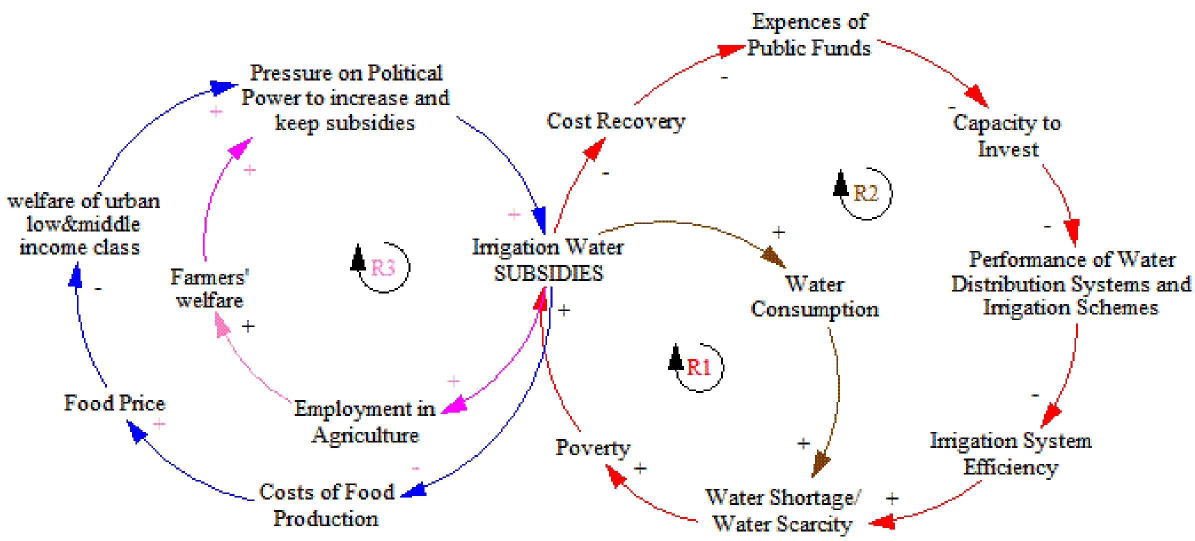

Figure 6-3: The CLD for Subsidies

Different sources give diverse information about the price of water delivery for irrigation. [Postel, 1997; Wichelns, 1998; Ahmad, 2002] state that the provision of water in irrigation canals is free of charge, whereas the representatives of NGOs operating in some provinces indicate that farmers are charged for irrigation services through land tax. However, the current land tax is 22 EGP per faddan annually[40]. The newly reclaimed lands are not subjected to land tax. While the annual investment budget for operating and maintaining irrigation and drainage system (including main canal system and distribution works) amounts to 100 EGP per faddan annually [MWRI, 2002b]. The figures give evidence to the fact that water and irrigation services are largely subsidized regardless of the operating costs.

The main justification behind the subsidy reasons pointed out by the government officials and NGO's representatives was the *affordability*[41] [Malashkhia, 2003]. However, the affordability is not the single driving force behind the government policy. There are other social benefits from subsidizing the irrigation water. From a food security perspective, irrigation subsidy is instrumental since food production is completely dependent upon irrigation. Subsidy causes the price of food produced sufficiently low to benefit the urban poor and the middle class [El-Quosy et al., 1999]. Increments in employment and income per capita are other positive social benefits. Through the affordability of irrigation water, agriculture employs 50% of labour force in rural Egypt [HDR, 2003] and prevents rural households from being pushed out of agriculture into cities that cannot provide shelter, jobs, and food for millions. Thus, the subsidy on irrigation prevents increasing poverty, crime, and social unrest that can lead to political instability in the cities. As Young (1992) stated, farming serves as an instrument of public policy, "the farmers and the public are in food producing and employment creating partnership and the government's (tax-payer's) part of the bargain is to provide the water." Here one can assume that the government retaining the power is part of the bargain as well. There are very few incentives that promote cost recovery, and concerns regarding the farmers' welfare might not be the only reason behind the low political will [Young, 1992; Shatanawi and Salman, 2002]. Removal of subsidies becomes politically infeasible for the political elite as it might threaten to cause a change in the political power and stability.

There are other aspects of subsidy that, in the long run, will result in harmful effects on the environment, the economy, and the society. "Free water" conditions

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[40] 22 Egyptian Pounds equal 22 Norwegian Kroner which equal 3.8 USD

[41] Affordability means the ability of the farmers to bear the costs of the agriculture inputs including, in this case, the water charges. In housing sector for example they say: "the price to income ratio is the basic affordability measure for housing in a given area". It is generally the ratio of median house prices to median familial disposable incomes (i.e., the gross income minus tax on that income), expressed as a percentage (e.g., no more than 30% of household income should be allocated to housing Principal, Interest, Taxes and Insurance). Typically, pricing calculations that define "workforce housing" use 30% of household income as the maximum threshold of affordability.

contribute to the rising demand against the limited supply options and therefore are considered to be one of the driving forces behind water scarcity [Myers and Kent, 1998; Rogers et al., 2002]. As discussed in the paragraph on social forces, some wasteful practices and the cultivation of high water demanding crops are deeply rooted not only in the income levels or behaviour as such, but are reinforced by the subsidy policy. A “free” resource sends misleading signals to the farmers and serves as an incentive to grow water inefficient crops and overuse the water imposing water scarcity conditions to future generations. Moreover, this also gives rise to negative environmental effects such as drainage problems, water-logging, and salinization [Sur et al., 2002].

There is a need for investments in improving the maintenance of irrigation schemes. Because of the very low cost recovery, the main source for the operation and maintenance (O&M) is the public fund causing additional pressure to arise and a diversion of the financial sources from other social or human development programs that might have a higher priority if the agriculture would fully recover its costs. Tight public funds do not allow carrying out improvement plans, resulting in a further deterioration of the system. This leads to lower efficiency rates and to fostering the water shortages, having a direct negative impact on the farmer’s welfare. The relationships are illustrated in Figure 6-3 and show the impact of subsidies on farmers’ welfare in the long run causing the problems to effect not only the present generation, but future generations as well.

6.3 Adapting the SDGIS to the Nile Delta

As part of this research, we developed a number of simulation models using a variety of software (i.e. Powersim and Vensim) to demonstrate the interactions between the main driving forces and their influence on the water stress conditions. By default, the simulation models included the irrigation network. Several aggregation levels had been used (e.g. aggregating the irrigation network into a single stock, a stock array, and a single stock for each canal) to study the effect of the spatial dimension on the behaviour of the system. Eventually, we concluded that: (1) driving forces such as farmers' behaviour, economic forces, and political forces do *not* have significant spatial characteristics, while cropping pattern, irrigation network components, and agriculture lands do share a spatial significance. Quality of life and poverty distribution could be presented on administrative maps; however, such a representation requires a very detailed demographic data and sophisticated statistical analysis. (2) The irrigation network is the dominant sector in the model. In fact, it is the core of the model because most variables in other sectors are directly influenced by modest changes in the characteristics of that network. Therefore, we decided to focus on the irrigation network and developed the *spatial model* that represents comprehensively the irrigation system (a very modest aggregation was applied). In the following paragraphs, we first describe the study area, the characteristics of the irrigation system, and the spatial simulation model resulting from the careful analysis of the irrigation system that we have undertaken using the system dynamics approach, the GIS spatial analytical tools, and the modelling skills gained through the development of the pervious models (i.e., the first simple model, the molecule model and the array model). We also describe the improvements added to the previous SDGIS application to comply with the newly developed simulation model (spatial model) and the classified maps. Finally, we run and test the performance of the SDGIS spatial application and discuss some of the most interesting observations.

6.3.1 The Study area

The Nile Delta region is located in the northern Egypt. North of Cairo the Nile spreads out over what was once a broad estuary that has been filled by silt deposits to form a fertile, fan-shaped delta about 300 kilometres wide at the seaward base and 160 kilometres from north to south (see Figure 6-4). The Nile Delta extends over approximately 25,000 square kilometres with about 34 million inhabitants, meaning that about half of Egypt's population live there. This figure does not include Cairo's inhabitants that account for about 16 million who depend on Delta for food supplies. It is among the most densely populated agricultural areas in the world, with 1360 inhabitants per km^2. According to historical accounts from the first century A.D., seven branches of the Nile once ran through the Delta. Later accounts stated that the Nile had only six branches by around the twelfth century. Since then, nature and man have closed all but two main outlets: the east branch Damietta (240 kilometres long), and the west branch Rosetta (235 kilometres long). Both outlets are named after the ports located at their mouths. A network of drainage and irrigation canals supplements these remaining outlets.

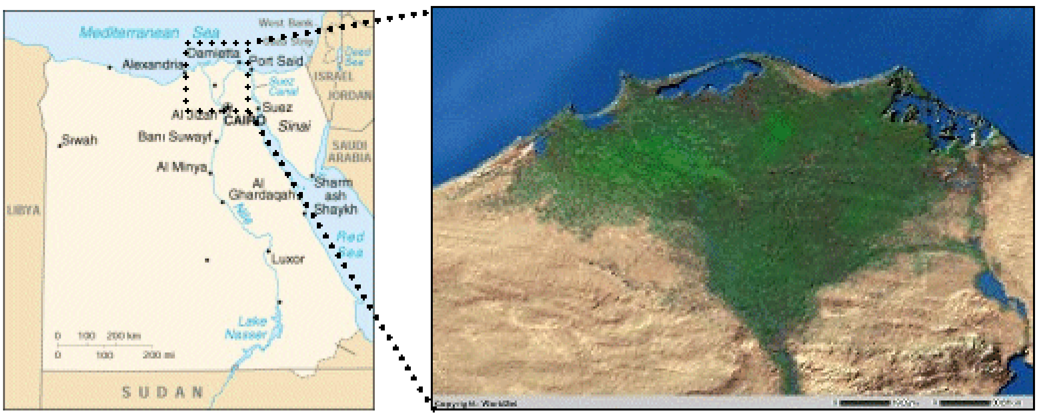

Figure 6-4: Map of Egypt and satellite image for Delta region.

The area belongs to the Mediterranean climate with two main seasons: hot dry summers and cool winters, with 20.7°C average air temperature and a total of 38 mm precipitations per year. The area contains different types of land cover and land use: (1) the central area is the old agricultural land with the traditional irrigation system (flood surface) cultivated with annual crops, fruits, and vegetables following two main agricultural rotations (two years and three years rotations). The main soil type in this area is Vertisols[42] [Abdulla *et al.,* 1997]; (2) surrounding the central area is the old reclaimed lands that are totally cultivated also using traditional irrigation methods. The major soil type is Aridisols[43] [Abdulla *et al.,* 1997]; (3) then there is the new, reclaimed areas with modern irrigation system (e.g. circular pivot) cultivated with different crop types; (4) then comes the *Desert* that have not been included in any reclamation effort; (5) at the north of Delta there are a series of salt marshes and lakes; most notable among them are Idku, Al-Burullus, and Al-Manzilah. The Delta is remarkably flat, with a gentle gradient slope to the north. The Nile mainstream descends only about fifteen meters along its course from Cairo to Damietta, a distance of about 160 km. This topography is easily adapted to irrigation-based agriculture.

In terms of fertility, productivity, land integration, population density, and the existence of large industries related to agriculture sector (such as textile), the land of the Delta is considered the primary agriculture land in Egypt. It is a highly productive land serving local, regional, and international food needs. The Nile Valley from Aswan in the south to Cairo in the north comes in the second category while the Fayoum depression, the New Valley, and the Oases in the Western Desert come in the third category.

6.3.2 The Irrigation System Characteristics

Although irrigation has taken place in Egypt for nearly 5000 years, it is only in modern times, starting around 1850, that the erection of water control structures such

[42] In both the FAO and USA soil taxonomy, a vertisol is a soil in which there is a high content of expansive clay known as montmorillonite that forms deep cracks in drier seasons or years. Alternate shrinking and swelling causes self-mulching, where the soil material consistently mixes itself, causing vertisols to have an extremely deep *A* horizon and no *B* horizon. (A soil with no B horizon is called an A/C soil). This heaving of the underlying material to the surface often creates microrelief known as gilgai. [From Wikipedia, the free encyclopaedia]

[43] Aridisols (or desert soils) are a soil order in USA soil taxonomy.

as barrages, canals, and weirs was begun. Except for the Nile itself and the two main branches, Rashid and Damietta, every fragment of the irrigation system is man-made.

The Egyptian irrigation system is tremendous in size and complexity. It consists of the Aswan High Dam, eight main barrages, approximately 30,000 km of public canals, 17,000 km of public drains, 80,000 km of private canals (mesqas) and farm drains, 450,000 private water-lifting devices (sakias or pumps), 22,000 public water-control structures, and 670 large public pumping stations for irrigation. By way of this system, about 59 BCM of water is distributed annually, not only for cultivated land, but also for municipal and industrial use, for the generation of hydro-electricity, and for the navigation of freighters and tourist boats on the Nile [Hvidt, 1998].

The simple scheme of the irrigation system can be portrayed as following: Water is released from the main reservoir (i.e., the High Dam Lake) flow to the Nile mainstream that contains a number of barrages at certain locations, commonly at the head of the main branches. The water flows from the mainstream and the branches into the main canals from which the water is delivered to the farms passing the secondary canals and the water distribution system that consists of tertiary canals and ditches [Holmen, 1991; Tiwari and Dinar 2002]. Part of the water carried by the irrigation scheme is lost to seepage and percolation as a result of topography and another part evaporates during conveyance.

After transmission, the water is allowed into and spent in the fields. The planting process consumes part of it, another fraction ends up in the drainage network and a third part is lost to seepage. Thus, considering the structure of the irrigation scheme, the efficiency of water utilization can be split into conveyance (or distribution) efficiency and application efficiency. Whereas the conveyance efficiency refers to the ratio between “the quantity of water released from the storage facilities and the quantity of water received at farm level” [Martinez, 1994], the application efficiency refers to the water utilization at the farm level [Tiwari and Dinar, 2002]. For the purpose of this research, we consider only the conveyance efficiency, since that is directly related to the irrigation network, which we have represented in our simulation model. The application efficiency may well be considered in further work.

The Nile flood season usually begins in July when the water rushes from the Ethiopian highlands into the Nile mainstream. The floodgates of the High Dam are left open[44], as well as the main barrages alongside the Nile course. By first of December, the muddy flow is practically ceased, so that the Nile flow depends on the continuous supply from Victoria Lake through the White Nile. The floodgates are closed to accumulate water behind the High Dam. The sluices are closed gradually to allow a sufficient quantity of water for irrigation purposes to escape. Normally, the dam is filled to capacity by first of March. The Nile becomes very low by April and consequently, it is necessary to support the flow from the stored up water in the reservoir (High Dam Lake). From this time until the next flood season in July, irrigation is carried on largely using dammed-up water.[45]

6.3.3 The GIS Irrigation Model

The original map of the irrigation network has been reclassified according to the rank-order of the canals (hereafter, we refer to that as Canals' levels) and their geographical locations. Regarding the canals' levels, the classification resulted in five canals at the first level, eight canals at the second level, and eleven canals at the third level. The canals are distributed across three geographical zones: the West of Delta (the area located to the west of Rashid Branch); the Middle of Delta (the area between Rashid Branch and Damietta Branch); and the East of Delta (the area located to the east of Damietta Branch). The original map included an enormous number of private canals (mesqas) as shown in Figure 6-5. These canals have been extracted and saved in another map layer (i.e., *Feature Class* in terms of GIS terminology). Therefore, we have retained the main layer that contains only the various canals in the three levels as shown in Figure 6-6.

[44] Floodgates are left open for the double purpose of keeping the reservoir free from silt and allowing the sediment to enrich the lower country land, as it has done for centuries.

[45] It is estimated that a flow of 905 cubic meters of water per second throughout the year is necessary to provide perennial irrigation. Since the river supplies a constant flow of only 226.4 cubic meters per second, while the flood flow of from 8490 to 14150 cubic meters per second, the High Dam making up the deficiency in constant flow by storing a surplus in flood season.

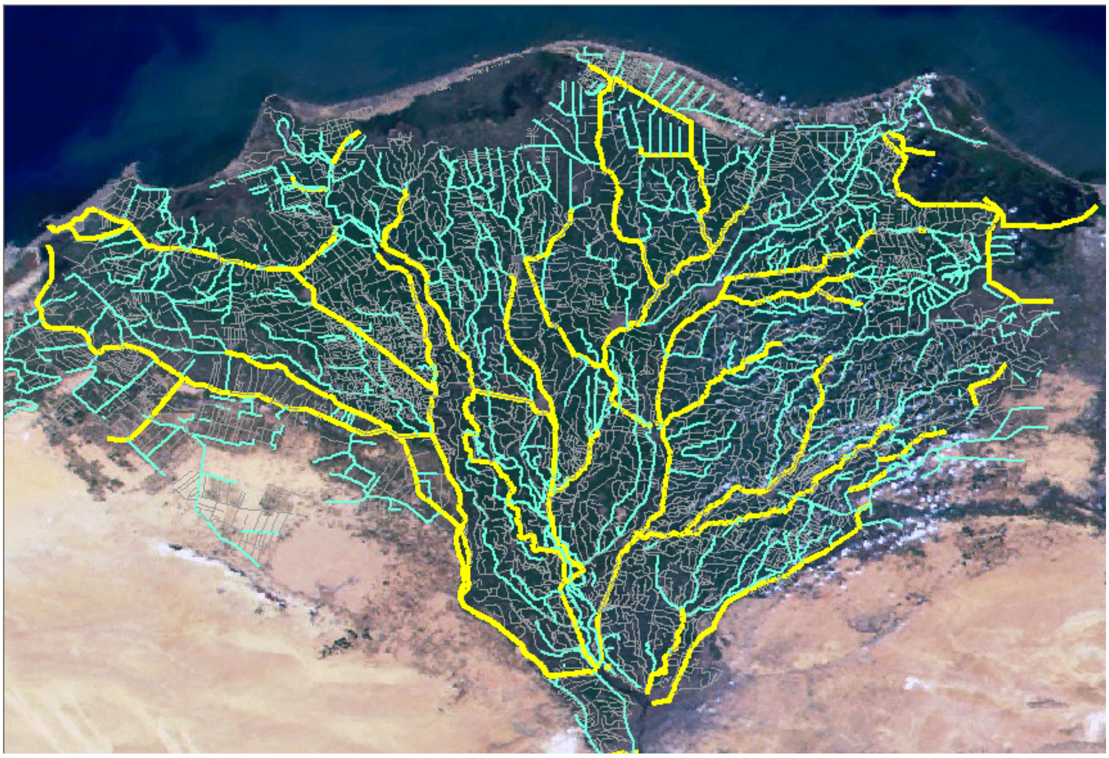

Figure 6-5: The irrigation network in Delta including the private canals.

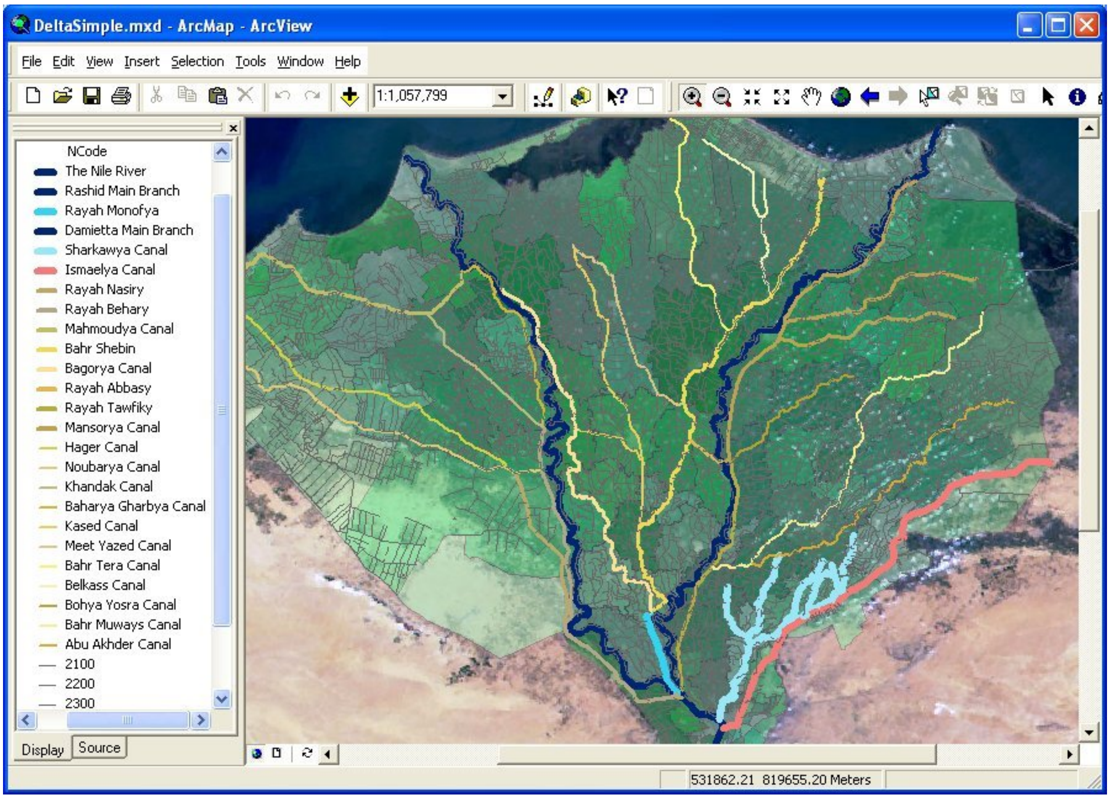

Figure 6-6: The irrigation network in Delta.

This layer, that includes the three levels of canals, also includes some fragmented canals (i.e., represented by several polylines, meaning that there are several objects that have several records in the attribute table). This is because these canals were distinguished by their names when the map was originally produced. However, these canals are physically one canal even though it passes through several provinces and take on different names. Therefore, the map was processed to merge such canals into one object that has only one record in the attribute table. A new field labelled *NCode* (appearing in the attribute table in Figure 6-7 and in Table 6-3) has been added as a unique key identifier that is used to connect each canal with its associated molecule-model in the SD spatial model. The new classified map that includes only the three levels of canals (24 canals) is shown in Figure 6-6.

Attributes of Irrigation24

OBJECTID	NCode	ENAME	Sum_LENGTH	CanalC	Efficiency	AgrArea	Crop
1	1100	Nile River	47833.615868	500	0.950000	963874713.501765	1
2	1101	Rashid Branch	227984.084351	500	0.950000	1314847737.4741	1
3	1102	Rayah Monofya	23584.457	250	0.950000	316560763.430332	1
4	1103	Damietta Branch	237812.771578	500	0.950000	1368092441.42004	1
5	1104	Sharkawya Canal	164615.888	250	0.950000	718076315.157161	1
6	1105	Ismaelya Canal	128537.992	250	0.950000	2031608847.8124	1
7	1201	Rayah Nasiry	101820.527	250	0.950000	2774561112.47489	1
8	1202	Rayah Behary	98626.285	250	0.950000	289718344.0359	1
9	1203	Mahmoudya Canal	79387.62	125	0.950000	1718329503.90324	1
10	1204	Bahr Shebin	163578.177	250	0.950000	1588156543.73779	1
11	1205	Bagorya Canal	138296.987	250	0.950000	714632483.456722	1
12	1206	Rayah Abbasy	10144.36	250	0.950000	215808680.643788	1
13	1207	Rayah Tawfiky	68842.597	250	0.950000	570782696.479261	1
14	1208	Mansorya Canal	219934.638	250	0.950000	1898035125.33517	1
15	1301	Hager Canal	86860.032	250	0.900000	658528784.650012	1
16	1302	Noubarya Canal	138812.64	250	0.900000	2651194588.9189	1
17	1303	Khandak Canal	43897.08	125	0.900000	698547273.509703	1
18	1304	Baharya Gharbya Canal	54297.113	125	0.900000	233193442.29521	1
19	1305	Kased Canal	106993.731	125	0.900000	1183120292.32542	1
20	1306	Meet Yazed Canal	60094.568	125	0.900000	527628910.040423	1
21	1307	Bahr Tera Canal	79122.937	125	0.900000	1117583594.27233	1
22	1308	Belkass Canal	65008.573	125	0.900000	761650788.129578	1
23	1309	Bohya Yosra Canal	44861.651	125	0.900000	888892874.49899	1
24	1310	Bahr Muways Canal	122335.393	125	0.900000	1262890809.5164	1
25	1311	Abu Akhder Canal	97184.579	125	0.900000	620491648.2848	1

Record: 0 Show: All Selected Records (0 out of 25 Selected.) Options

Figure 6-7: The attribute table of the reclassified map.

6.3.4 The SD Spatial Model

In chapter four we developed the molecule model that represents a single canal and the agriculture land associated to it in one-to-one relationship. The model also included three cropping patterns that may be assigned to the agriculture land to study the variation in the water demand and the behaviour of the canal over time. The model was improved in chapter five by: (i) adding the control-gates (as a gaming variable that provides the user with the capability to regulate the water flow during the simulation runtime); (ii) connecting several agriculture lands to the same canal in one-to-many relationship. The model has been coupled with the Gharbiya map that covers the central province in the Delta (i.e., the Gharbiya province) and both models were used to test the operability and the performance of the SDGIS application. Based on that SD model, we developed the *Array Model* that covers the entire irrigation network using array structures. For simplicity, we aggregated the canals based on their geographical location (i.e., Delta zones) and their rank in the irrigation system (i.e., first level, second level, and third level). The *Array Model* included nine canal classes. On the other hand, the agriculture area was divided into nine clusters reflecting their location and cropping pattern. The relationship in that model is many-to-many. The *Array Model* was coupled with the new classified map that covers the entire Delta. A new version of the SDGIS application was developed (i.e., SDGIS Array Application) to comply with the new model structures. In this chapter, we took a step further and develop: (i) a new classified map includes the three levels of canals and covers the entire irrigation system in Delta; (ii) the spatial simulation model that includes the 24 canals listed in Table 6-3; and (iii) a new version of the SDGIS application (hereafter, we referred to it as SDGIS Spatial Application) associated with the newly developed classified maps and the SD spatial model. In the following paragraphs, we briefly provide an overview of the structure of the spatial simulation model by way of illustrative diagrams. The equations and formulations included in the model are fully described in Appendix C.

Table 6-3: The canals represented in the spatial model

	First Level		Second Level		Third Level	
	Canal Name	Ncode	Canal Name	Ncode	Canal Name	Ncode
Delta West	Rashid Main Branch	1101	Rayah Nasiry	1201	Hager Canal	1301
					Noubarya Canal	1302
			Rayah Behary	1202	Khandak Canal	1303
					Baharya Gharbya Canal	1304
			Mahmoudya Canal	1203		
Delta Middle	Rayah Monofya	1102	Bahr Shebin	1204	Kased Canal	1305
					Meet Yazed Canal	1306
					Bahr Tera Canal	1307
					Belkass Canal	1308
			Bagorya Canal	1205		
			Rayah Abbasy	1206		
Delta East	Damietta Main Branch	1103	Rayah Tawfiky	1207	Bohya Yosra Canal	1309
					Bahr Muways Canal	1310
					Abu Akhder Canal	1311
			Mansorya Canal	1208		
	Sharkawya Canal	1104				
	Ismaelya Canal	1105				
No. of Canals	5		8		11	24

Table 6-3 shows the names and the codes assigned to the 24 canals considered in the spatial model. There are five main canals at the first level that convey the water to eight canals at the second level which in turn distribute water among eleven canals in the third level. The table is organized in a way that reflects the connectivity of these canals. For example, in the West of Delta there is the Rashid branch (with *Ncode* 1101) at the first level that delivers the water to the three canals at the second level (Rayah Nasiry 1201, Rayah Behary 1202, and Mahmoudya canal 1203). These canals deliver the water to the canals at the third level in the following way: (i) The Rayah Nasiry 1201 convey the water to the Hager canal 1301 and the Noubarya canal 1302. (ii) The Rayah Behary 1202 conveys the water to the Khandak canal 1303 and the Baharya Gharbya canal 1304. (iii) The Mahmoudya canal 1203 delivers the water directly to the private canals (mesqas) before it, eventually, drains to the Sea. The connectivity between these canals and the directions of the water flow are sketched in Figure 6-8.

The molecule model, developed in Chapter four, is used as a building block in this SD spatial model, to represent the canals that deliver the water to the private canals (i.e., mesqas that irrigate the fields) and, eventually, drain to the sea (these canals are shaded in the Table 6-3). These canals are mainly at the third level and the Sharkawya canal 1104 and the Ismaelya canal 1105 are at the first level. The four canals at the second level (shaded in the Table 6-3) have multiple sources of water supply (e.g., Mahmoudya canal receives water from three sources) and some of them drain to other canals (such as the Rayah Abbasy that drains to the Bahr Shebin). Therefore, the molecule model applied for these canals has been modified slightly to reflect the variation in structure in these canals.

The water demands from various agriculture lands in different locations are calculated in the reverse direction of the water distribution. In this sense, the water demands from agriculture lands irrigated from the canals at the third level are calculated first and added up to the demands from those lands irrigated from the canals at the second level and so forth upstream to the main distribution point (the Delta Barrage). Consequently, the molecule model has been modified to include the structures that represent: (i) the distribution of the water between the successor canals according to their water shares, and (ii) the accumulation of the water demand from the lower levels. This modified model is applied to the main canals at the first level (except the Sharkawya and the Ismaelya canals) and to the rest of the canals at the second level.

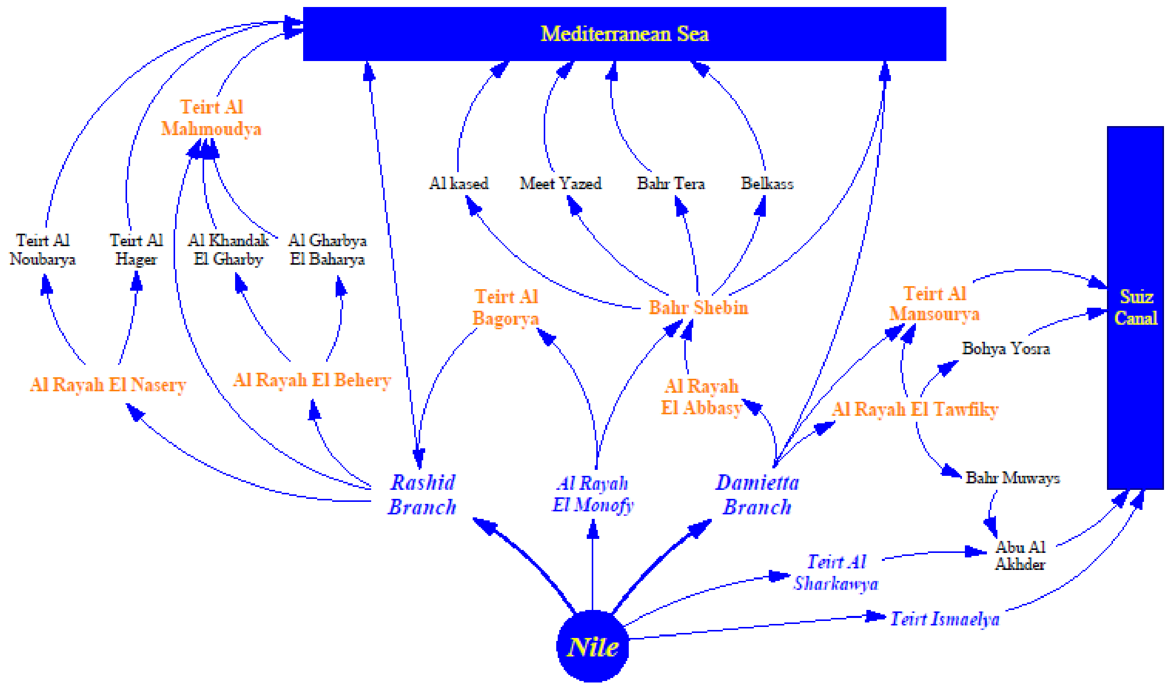

Figure 6-8: The irrigation network diagram.

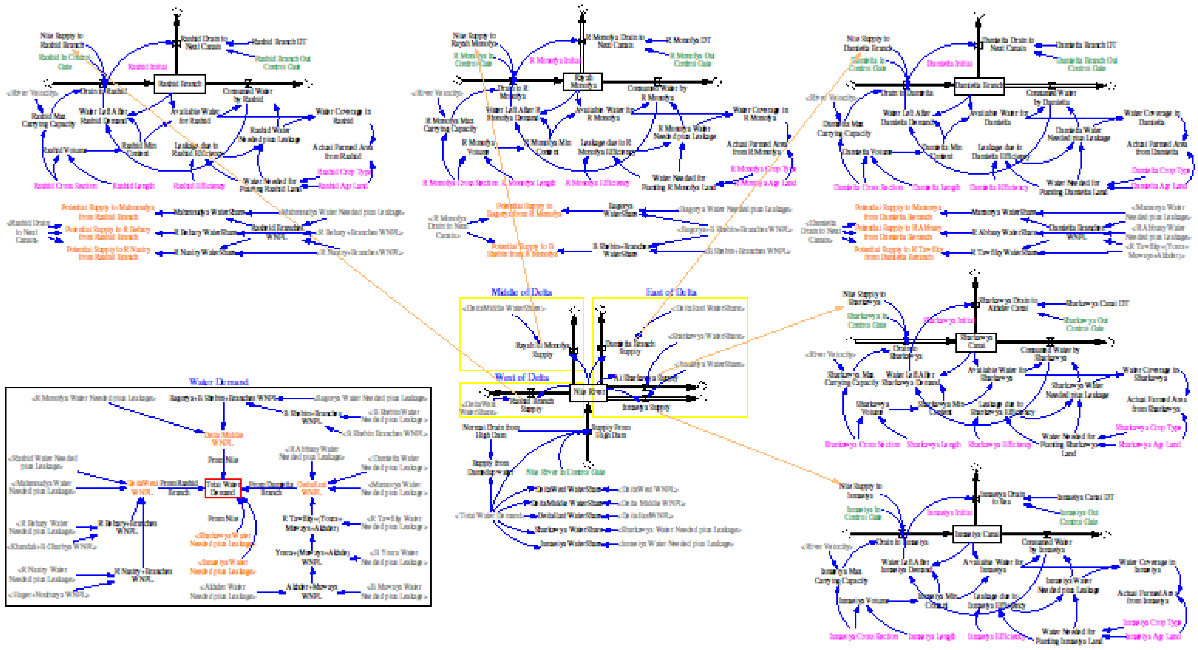

Figure 6-9: The Canals in the First Level[46].

The SD spatial model is organized in several views due to its size. The views are developed according to the geographical location and the levels of canals (e.g., Delta West-Second Level, Delta West-Third Level, Delta Middle-Second Level, etc.). In the following figures, the model views are exhibited with brief descriptions. The first view in the model, shown in Figure 6-9, includes the sub-models of the first level canals. These canals are: the Rashid Branch *(T.L.)*, the Rayah Monofya *(T.M.)*, the Damietta Branch *(T.R.)*, the Sharkawya canal *(M.R.)*, and the Ismaelya canal *(D.R)*. The view includes also the water distribution *(Centre)* and the water demand calculations *(D.L.)*[47]. These canals receive the water directly from the Nile through the Delta Barrage. The distribution of water between these canals is shown in Figure 6-10. In the initial state, we assumed that the quantity of water released from the reservoir equals to the quantity of water needed (i.e., the supply equals the demand). However, when the demand exceeds the supply (e.g., the water coverage is less than 100%) the water is distributed between these canals according to the water shares that calculated

[46] In the electronic copy, for the Figures 6-8 to 6-42, double click on the figure to enlarge, Acrobat Reader 4 or later is needed.
[47] Abbreviations: Top Left (T.L), Top Middle (T.M), Top Right (T.R), Middle Right (M.R), Down Left (D.L), Down Right (D.R).

reflecting the demands associated with each agriculture zone. The water demand calculations for each zone are shown in the sub-model of each canal and collectively in Figure 6-11.

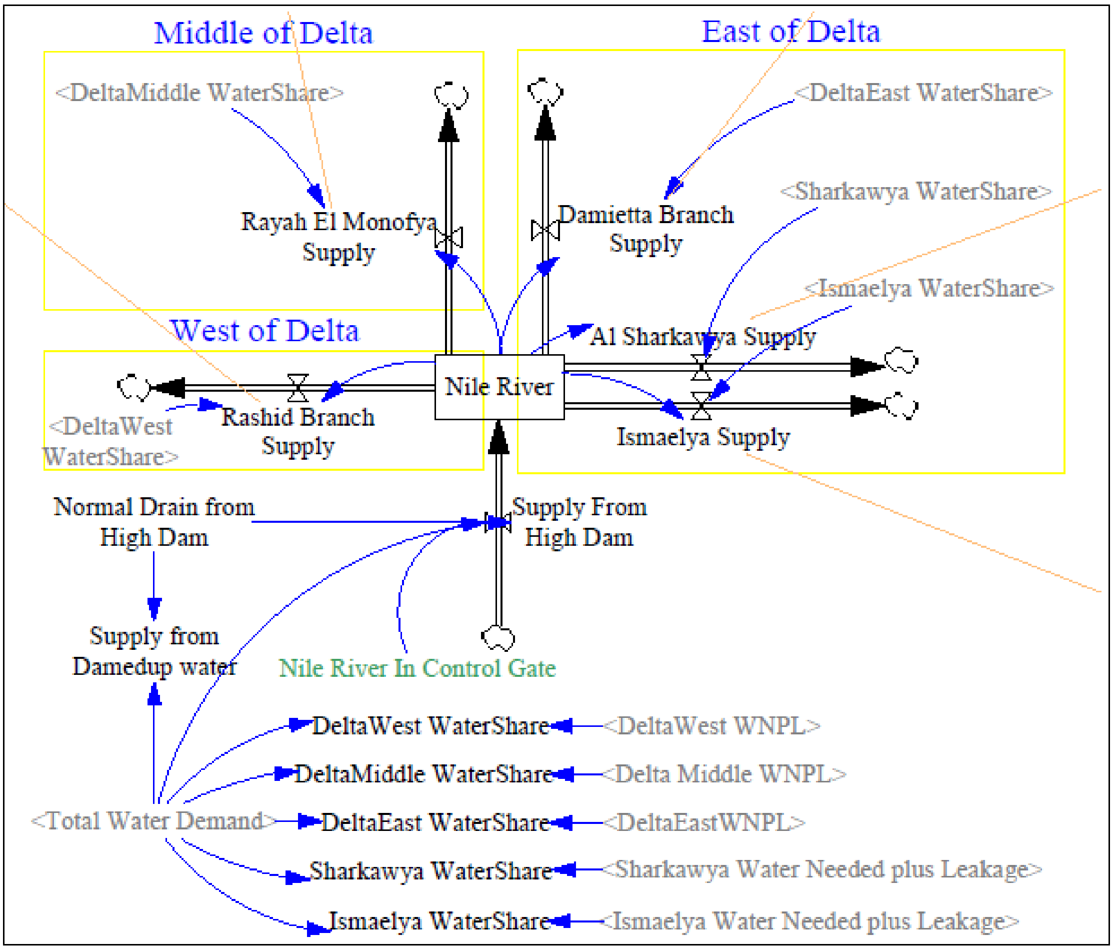

Figure 6-10: The water distribution among the first level canals.

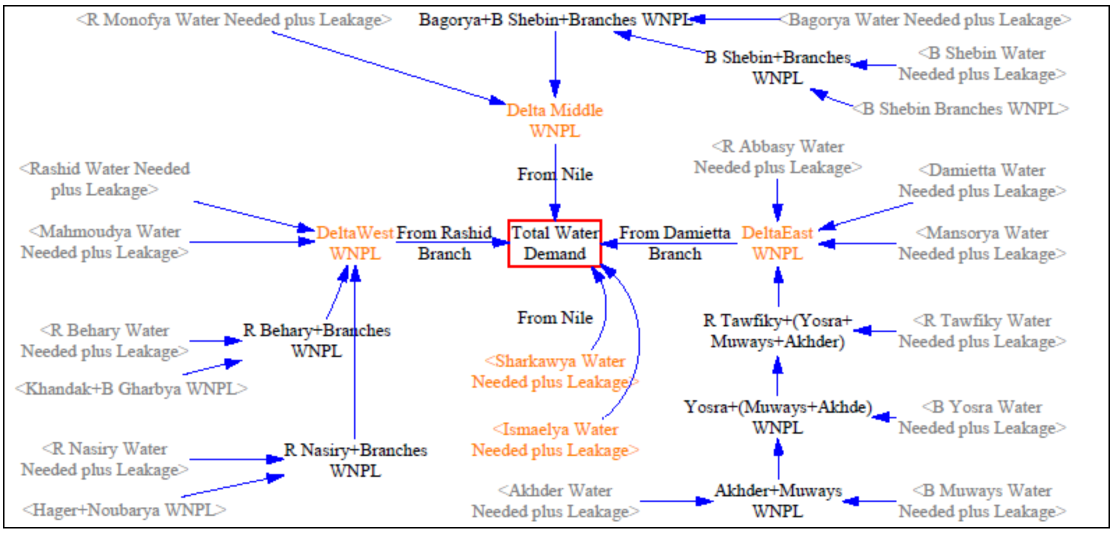

Figure 6-11: The water demands calculation diagram.

To trace the distribution of water through the irrigation network, we consider the three geographical zones of the Delta in the following section.

West of the Delta

This is the area located to the west of the Rashid branch that is considered the main source of water supply. The area includes two man-made canals, built in the 19th century, the Rayah Nasiry and the Rayah Behary. These two main canals further split into the Noubarya canal and the Hager canal. There is also Mahmoudya Canal (which takes water directly from the Rashid Branch) that has been excavated to server the north part of the West of the Delta (to the south to Alexandria city). These are the primary canals that support the irrigation at the West of the Delta. Figure 6-12 shows the sub-model that represents the Rashid branch (appearing in the top left corner in Figure 6-9). This branch receives its water directly form the Nile and delivers the water to the three canals at the second level, i.e. to the Rayah Nasiry, the Rayah Behary, and the Mahmoudya canal as shown in Figure 6-13.

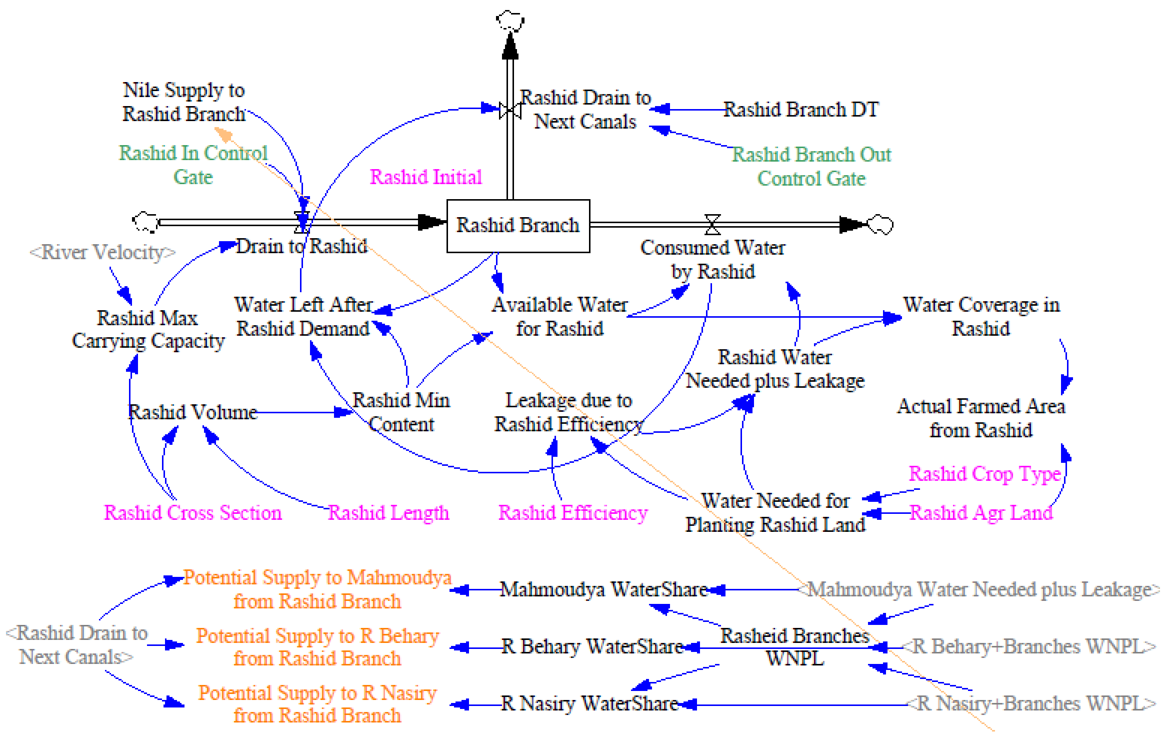

Figure 6-12: The Rashid Branch sub-model.

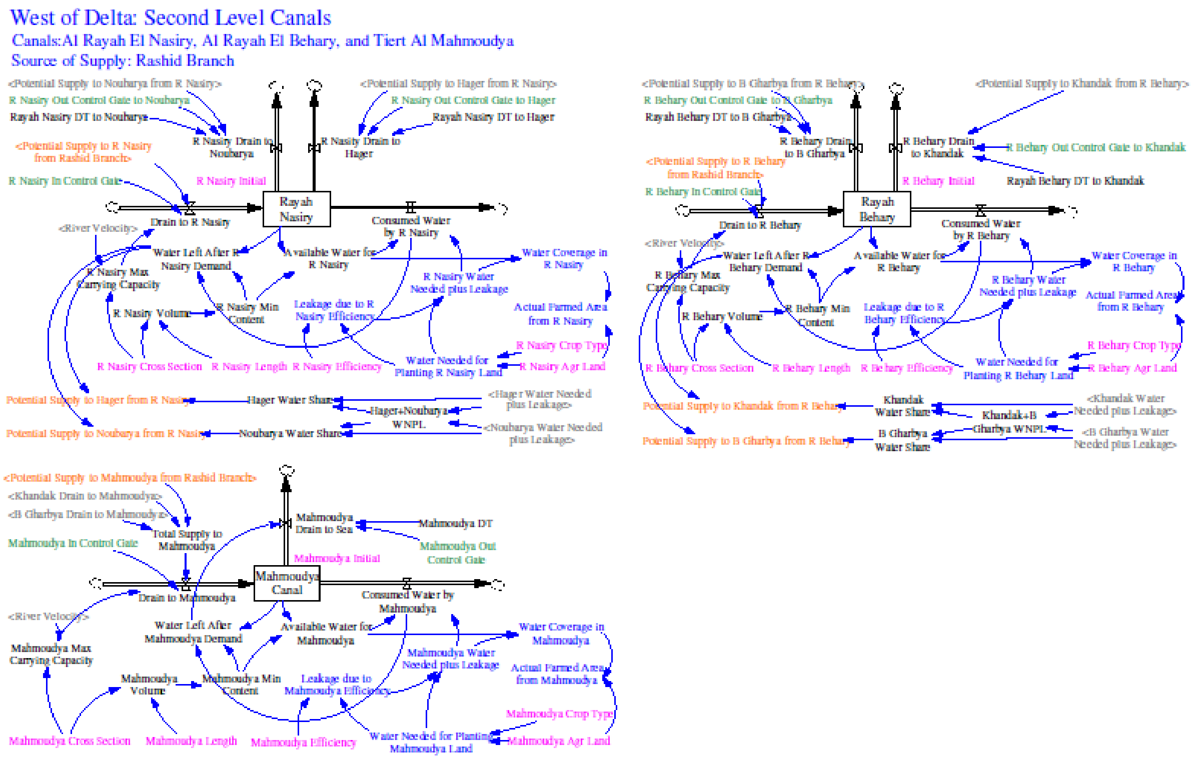

Figure 6-13: The second level canals at West of the Delta.

This view includes the sub-models that represent: Rayah Nasiry *(T.L.)*, Rayah Behary *(T.R.)*, and Mahmoudya canal *(D.L.)*. Closer shots are shown in Figures 6-14 to 6-16.

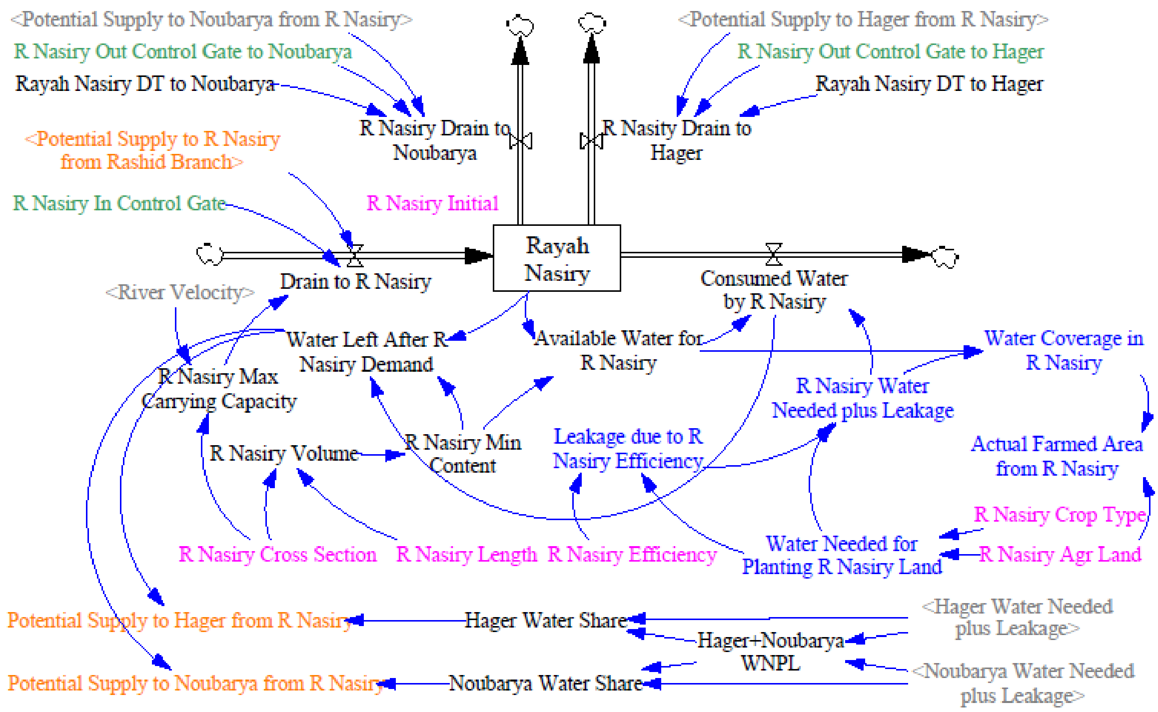

Figure 6-14: The Rayah Nasiry sub-model.

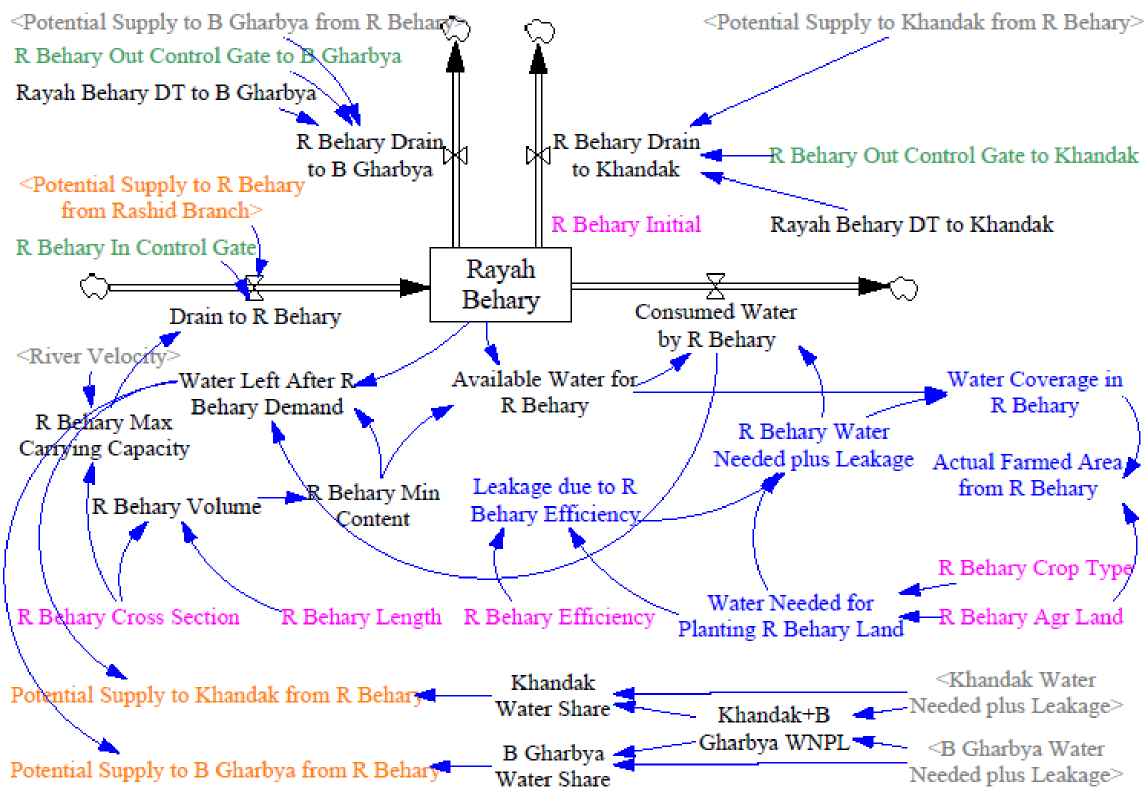

Figure 6-15: The Rayah Behary sub-model.

Noteworthy, both Rayah Nasiry (Figure 6-14) and Rayah Behary (Figure 6-15) receive water from the Rashid branch at the first level. However, Rayah Nasiry delivers the water to the Hager canal (1301) and the Noubarya canal (1302), whilst Rayah Behary delivers the water to the Khandak canal (1303) and the Baharya Gharbya canal (1304) at the third level. The calculations of water demands appear at the bottom of each figure.

The third canal in this second level is the Mahmoudya canal (see Figure 6-16). This canal receives water form three different sources. The main source is the Rashid branch (1100) at the first level, but the Khandak Canal (1303) and the Baharya Gharbya canal (1304) at the third level drain to this canal as well. The canal serves only the agriculture lands located to the north of the Behara province and to the south of Alexandria and, eventually, it drains to the Sea.

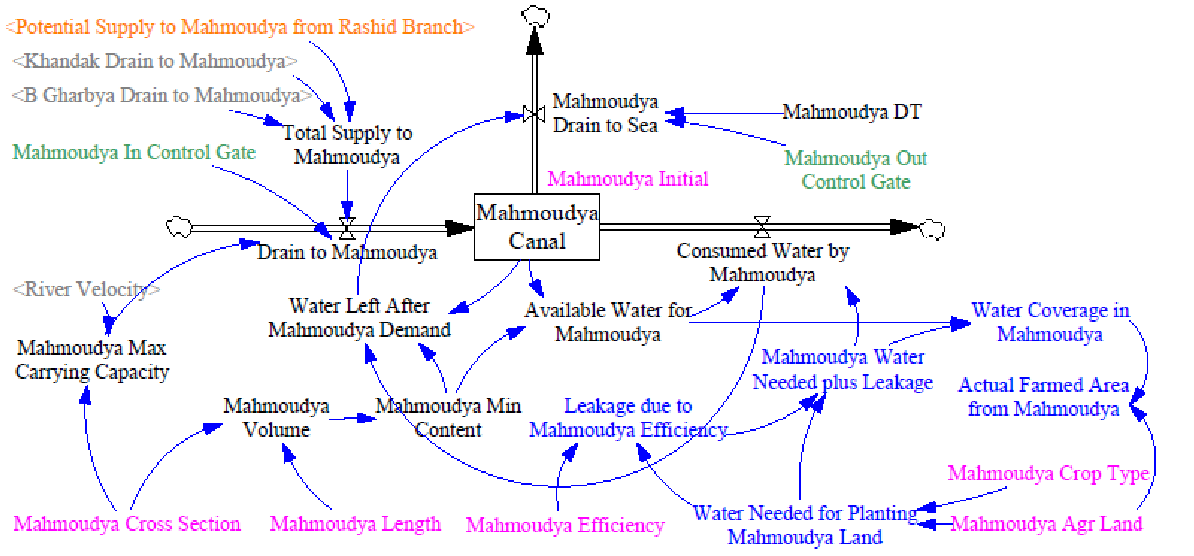

Figure 6-16: The Mahmoudya canal sub-model.

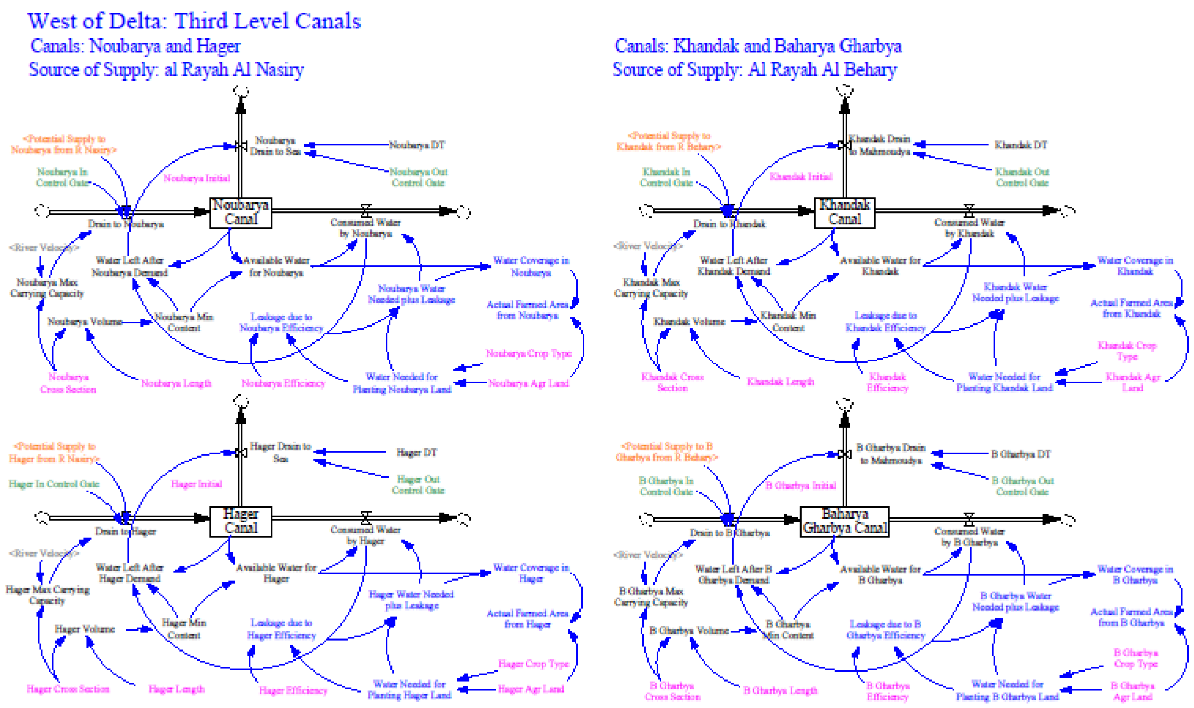

Figure 6-17: The third level canals at West of the Delta.

This view, shown in Figure 6-17, includes four canals; the Noubarya Canal *(T.L.)*, the Khandak Canal *(T.R.)*, the Hager Canal *(D.L.)*, and the Baharya Gharbya *(D.R.)*. These are the canals at the third level West of the Delta. The Figures from 6-18 to 6-21 show the sub-models associated with each of these canals.

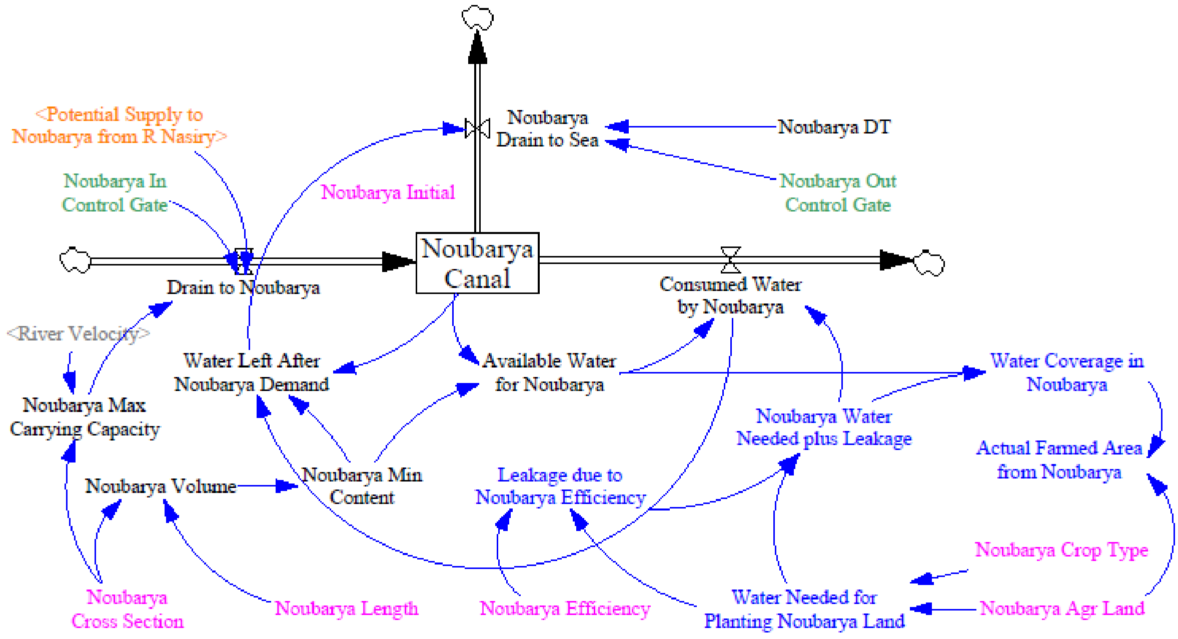

Figure 6-18: The Noubarya Canal sub-model.

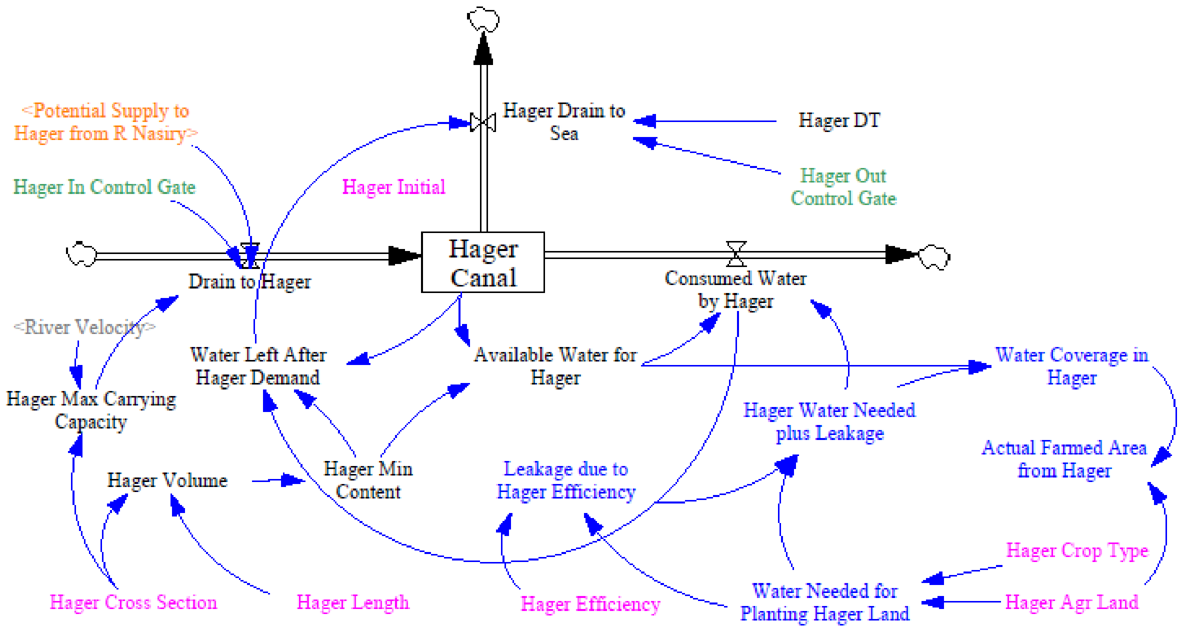

Figure 6-19: The Hager Canal sub-model

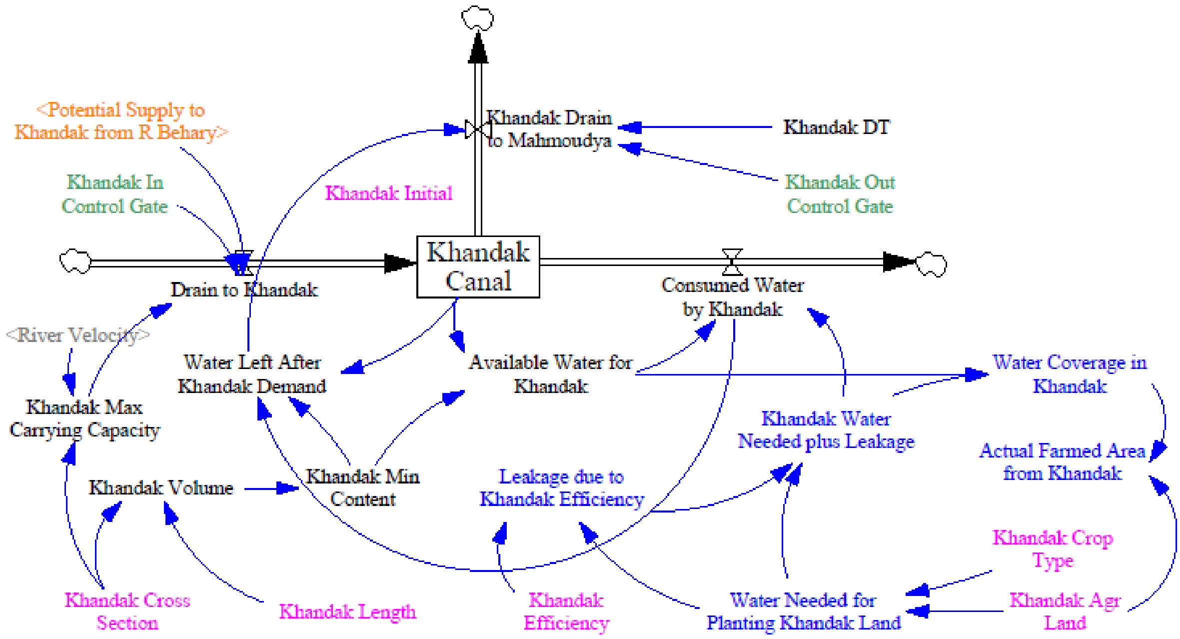

Figure 6-20: The Khandak Canal sub-model.

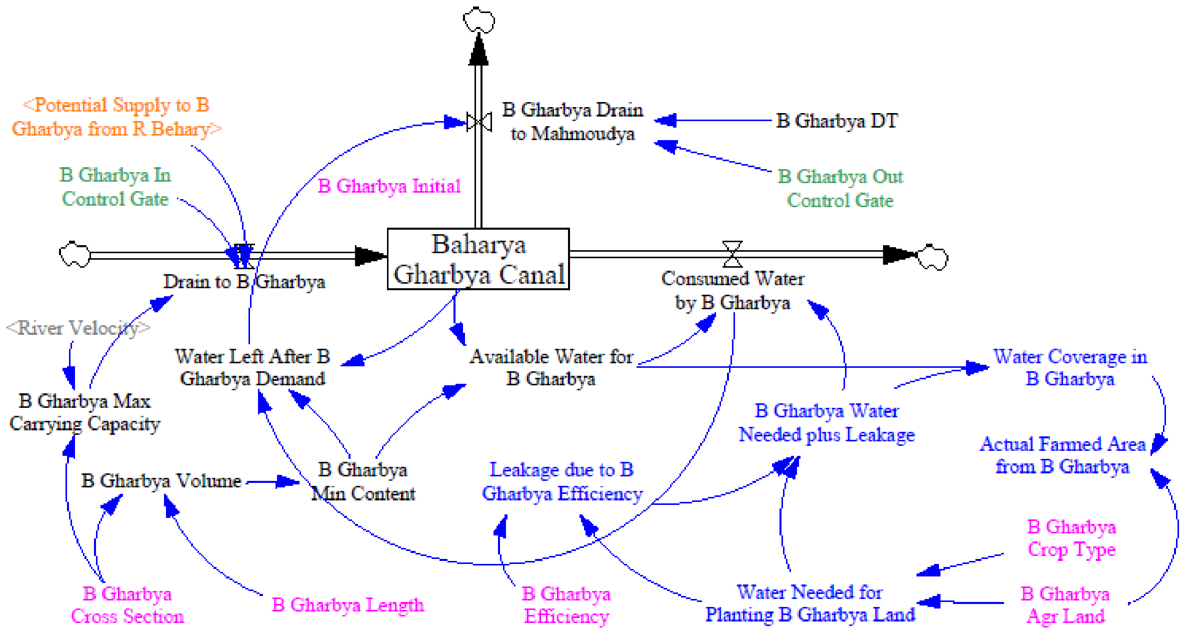

Figure 6-21: The Baharya Gharbya Canal sub-model.

The Middle of the Delta

This is the most fertile land in the Nile Delta region. The area is seized between the two main branches of the Nile River, Rashid and Damietta. The main source of water supply is Rayah Monofya (1102) represented by the sub-model shown in Figure 6-22. It is relatively short in length but carries a significant amount of water to supply Bahr Shebin (at the second level) which supports alone four further canals at the third level. A considerable part of the agriculture area in the Middle of the Delta is also irrigated form Rayah Abbasy which originates from East of the Delta but serves the Middle and ends to Bahr Shebin to support the flow.

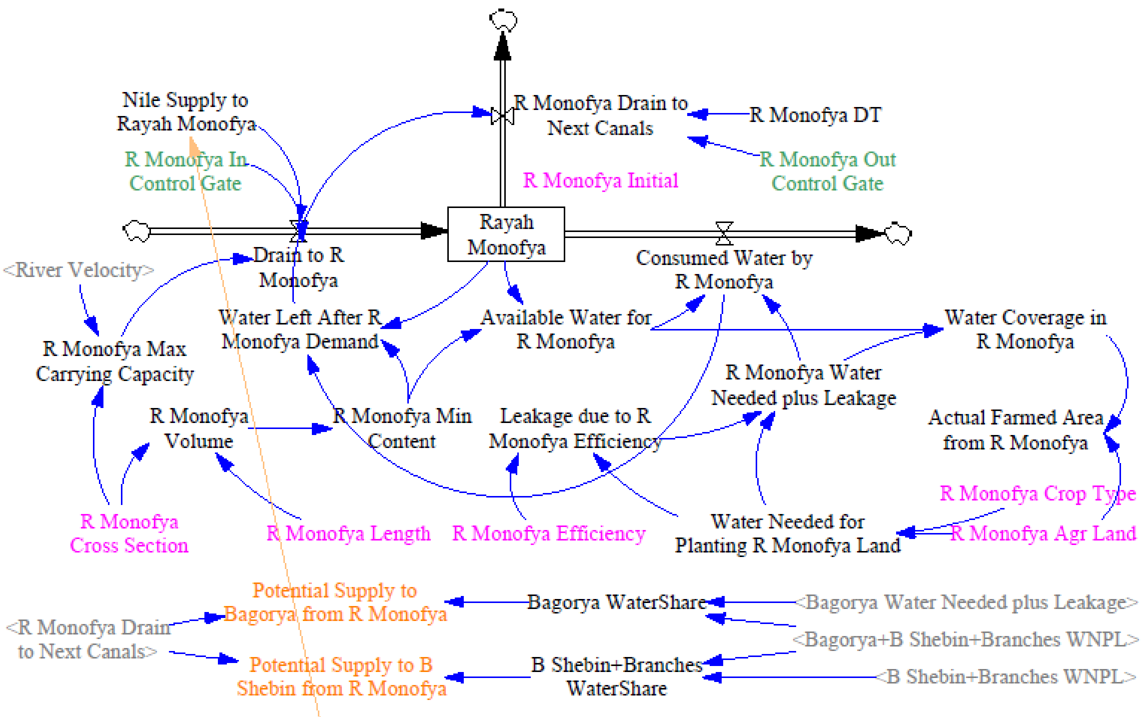

Figure 6-22: The Rayah Monofya sub-model

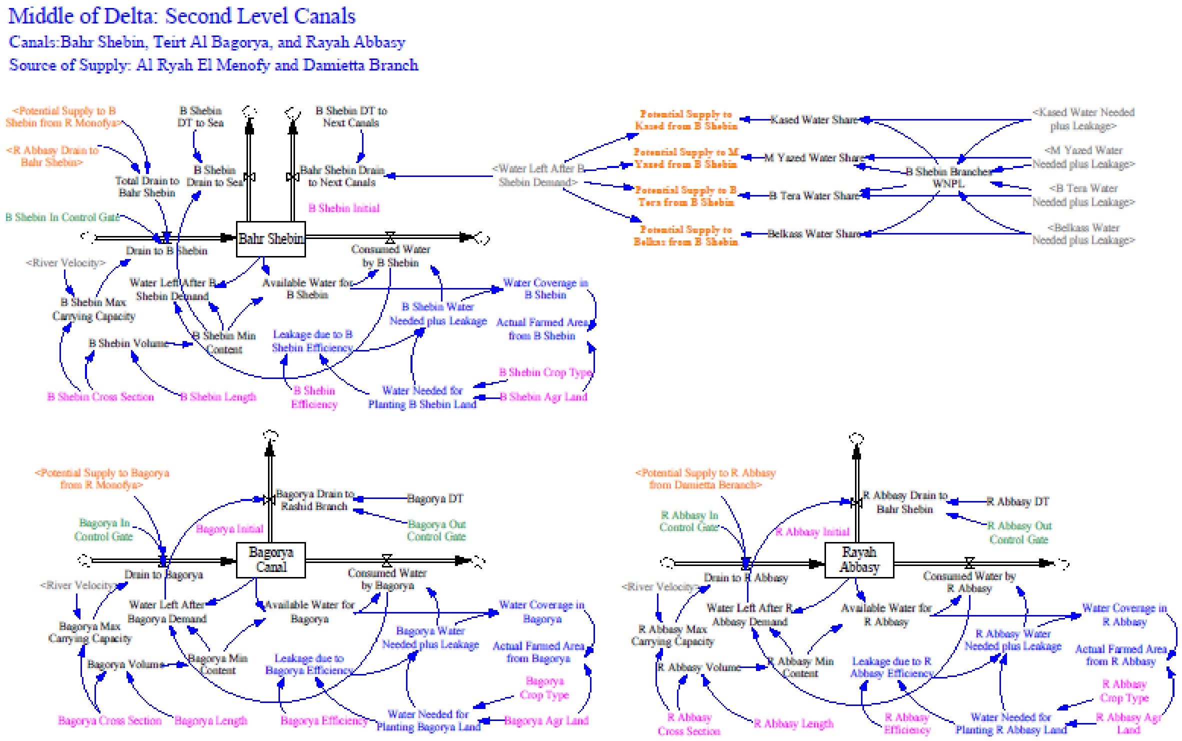

Figure 6-23: The second level canals in the Middle of the Delta.

This view includes the sub-models that represent: Bahr Shebin *(T.L.)*, Bagorya canal *(D.L.)*, and Rayah Abbasy *(D.R.)*.

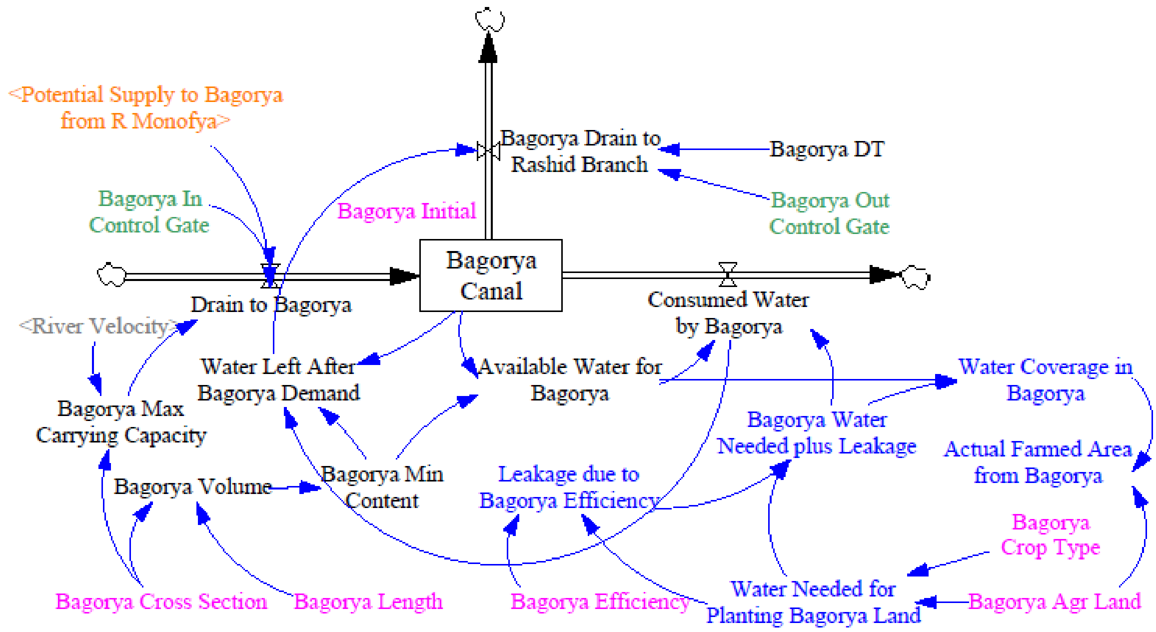

Figure 6-24: The Bagorya canal sub-model.

This canal provides water for large agriculture area in the Middle of Delta and ultimately drains to Rashid branch near to its end before it drains to the Sea.

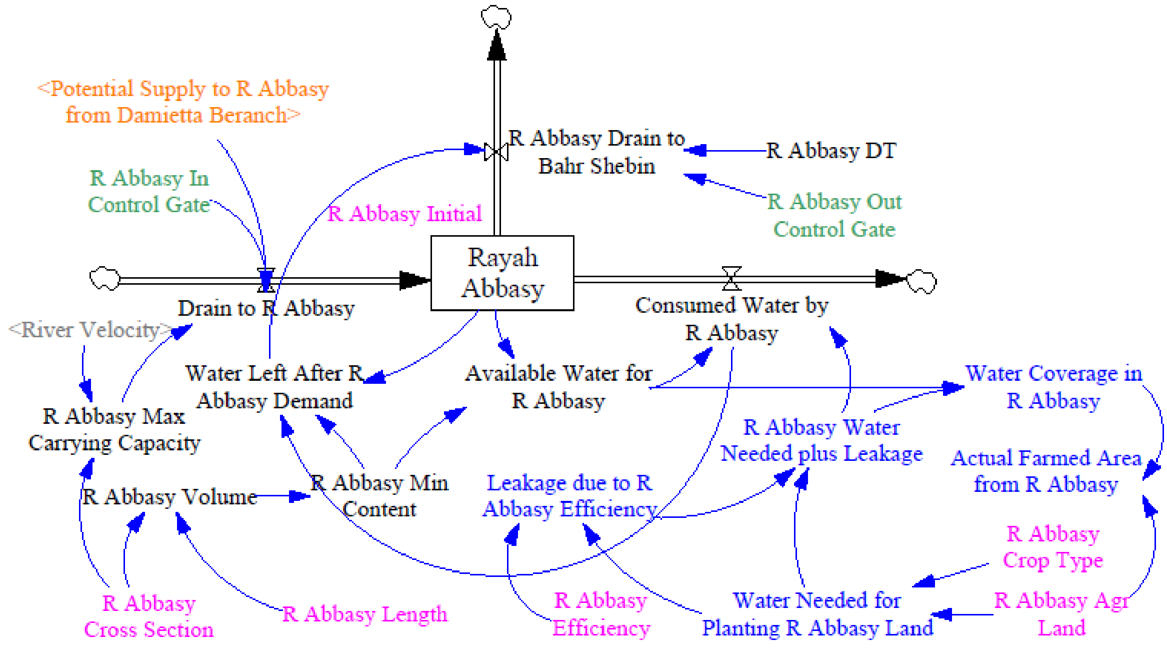

Figure 6-25: The Rayah Abbasy sub-model.

Rayah Abbasy is the only canal at the second level that receives the water from the Damietta branch at East of the Delta. However, it serves the lands in the Middle of the Delta and drains to Bahr Shebin (Figure 6-26). Its supply is critically needed because Bahr Shebin supports almost all the canals at the third level as shown in the Figures 6-27 and 6-28.

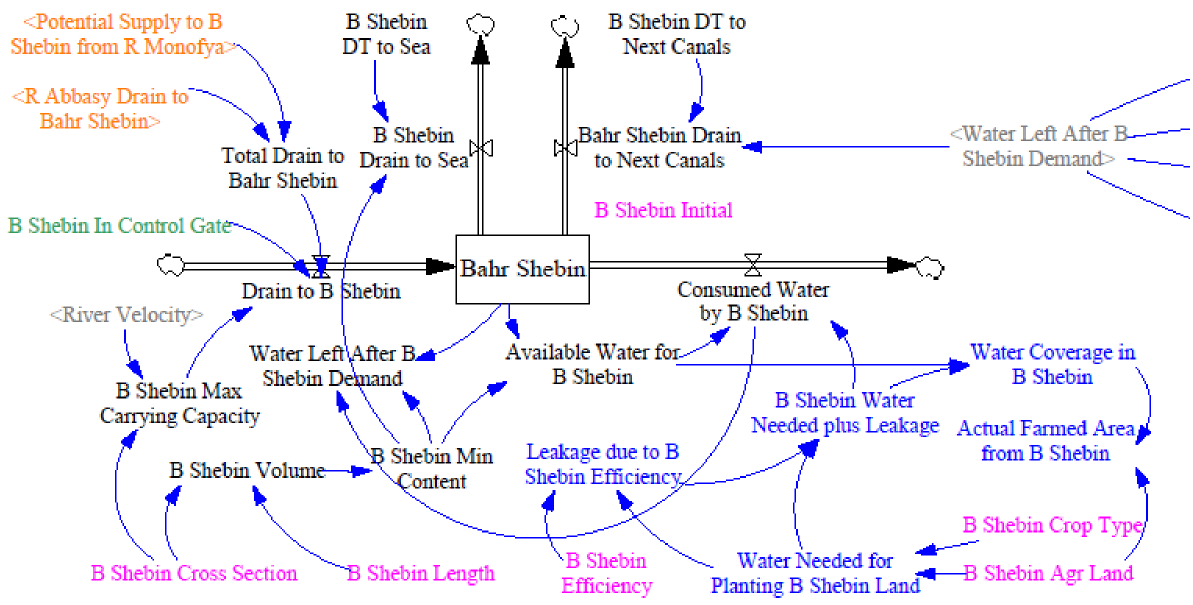

Figure 6-26: The Bahr Shebin sub-model.

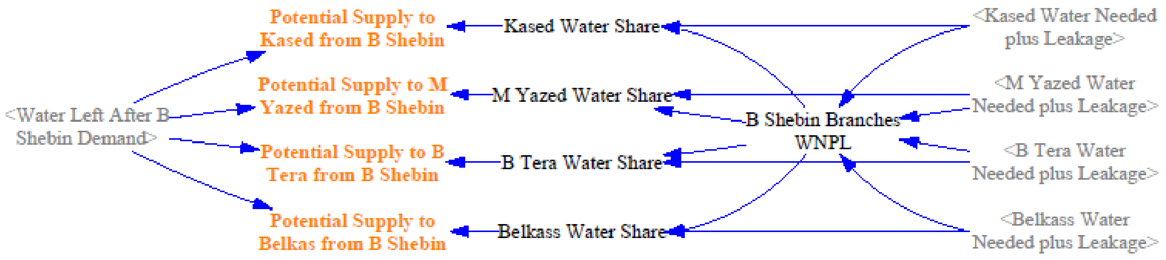

Figure 6-27: The water demand accumulation form the third level canals.

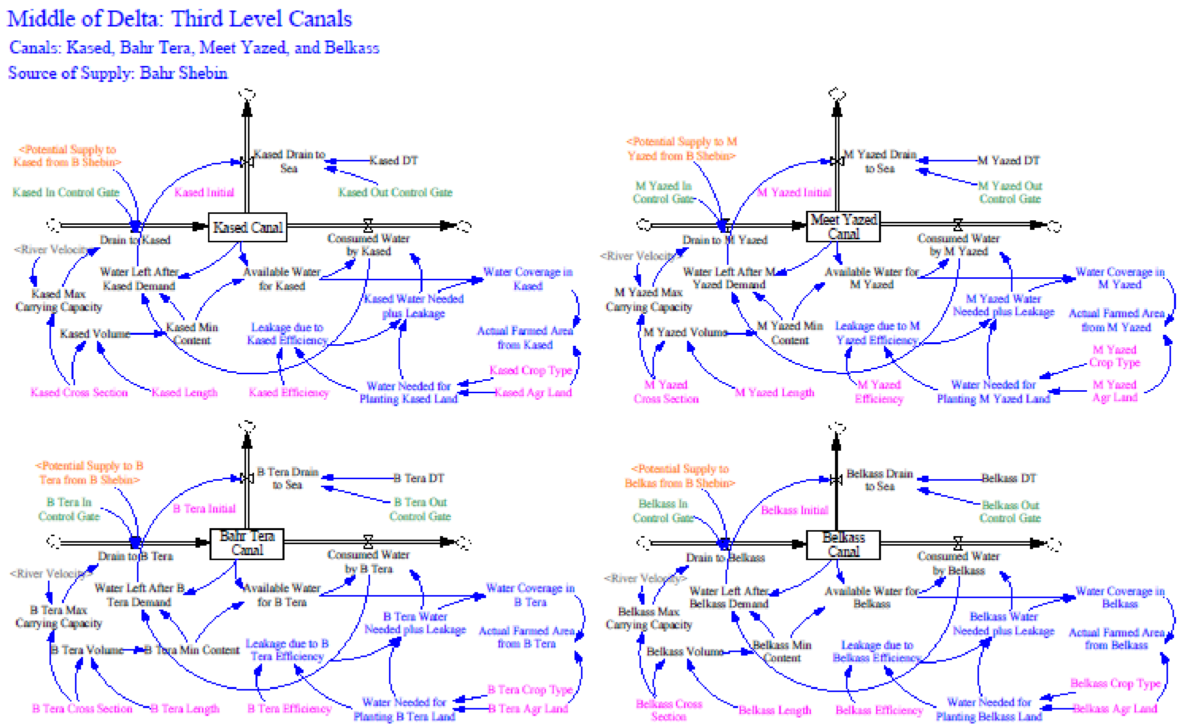

Figure 6-28: The third level canals at Middle of Delta.

This view includes four canals; the Kased canal *(T.L.)*, the Meet Yazed canal *(T.R.)*, the Bahr Tera canal *(D.L.)*, and the Belkass canal *(D.R.)*. These are the canals at the third level at Middle of Delta. The Figures from 6-29 to 6-32 show the sub-models associated with each of these canals.

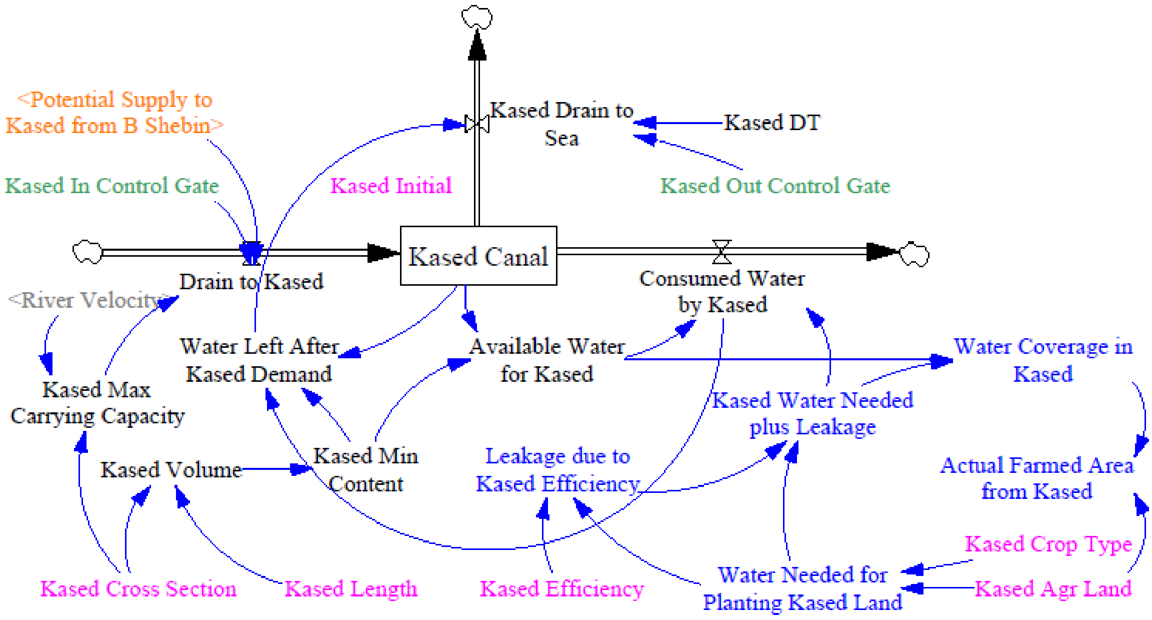

Figure 6-29: The Kased canal sub-model.

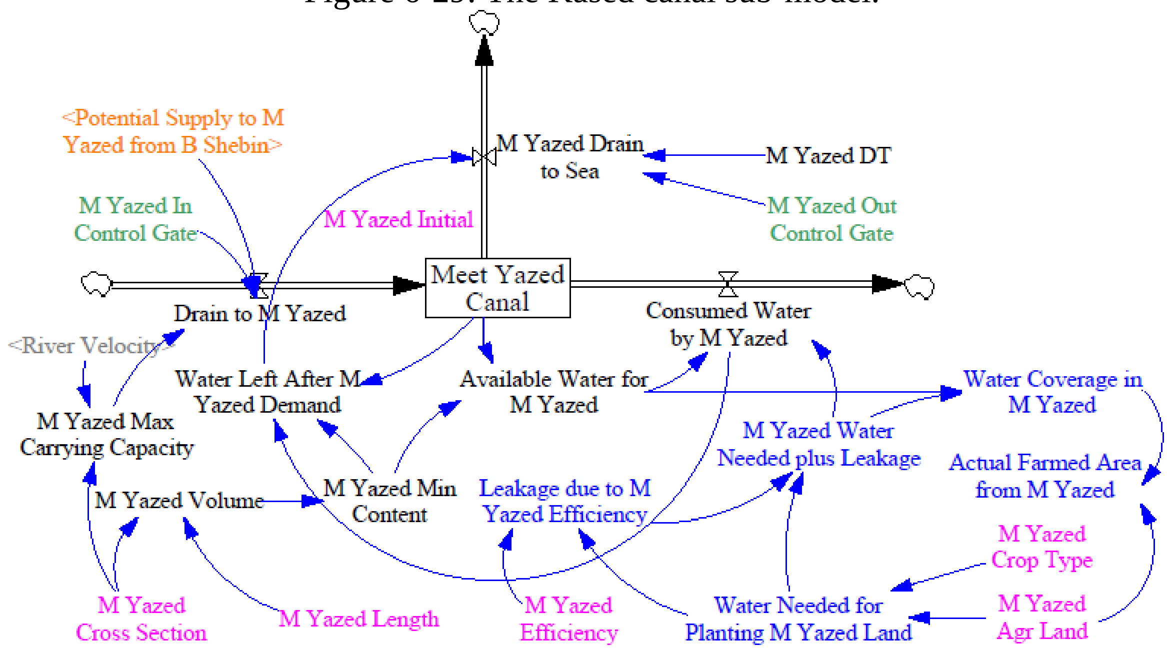

Figure 6-30: The Meet Yazed canal sub-model.

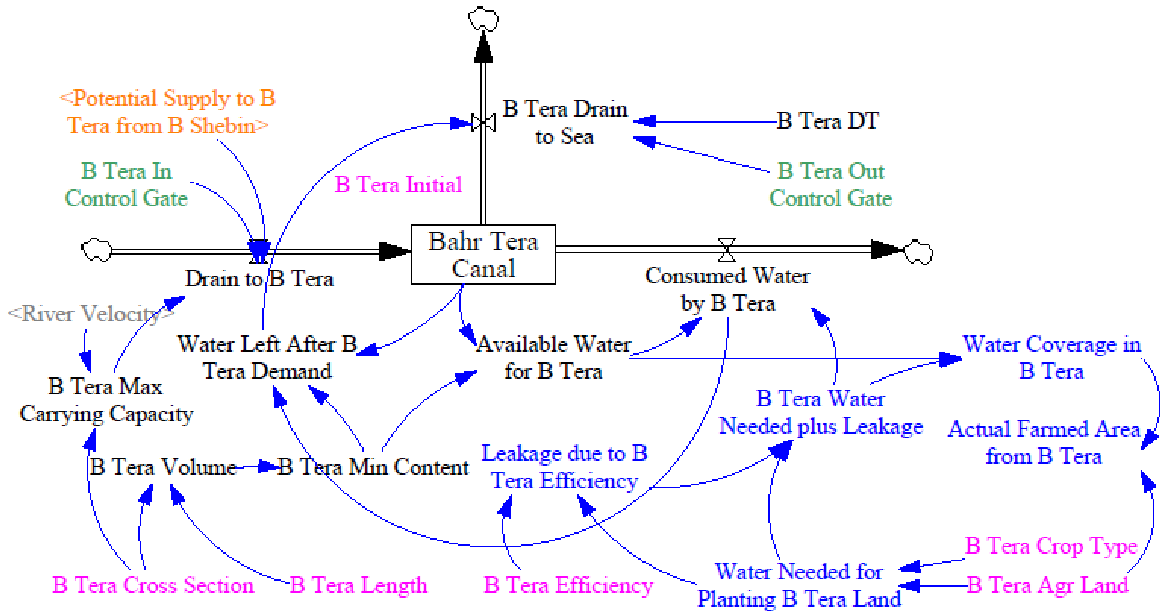

Figure 6-31: The Bahr Tera canal sub-model.

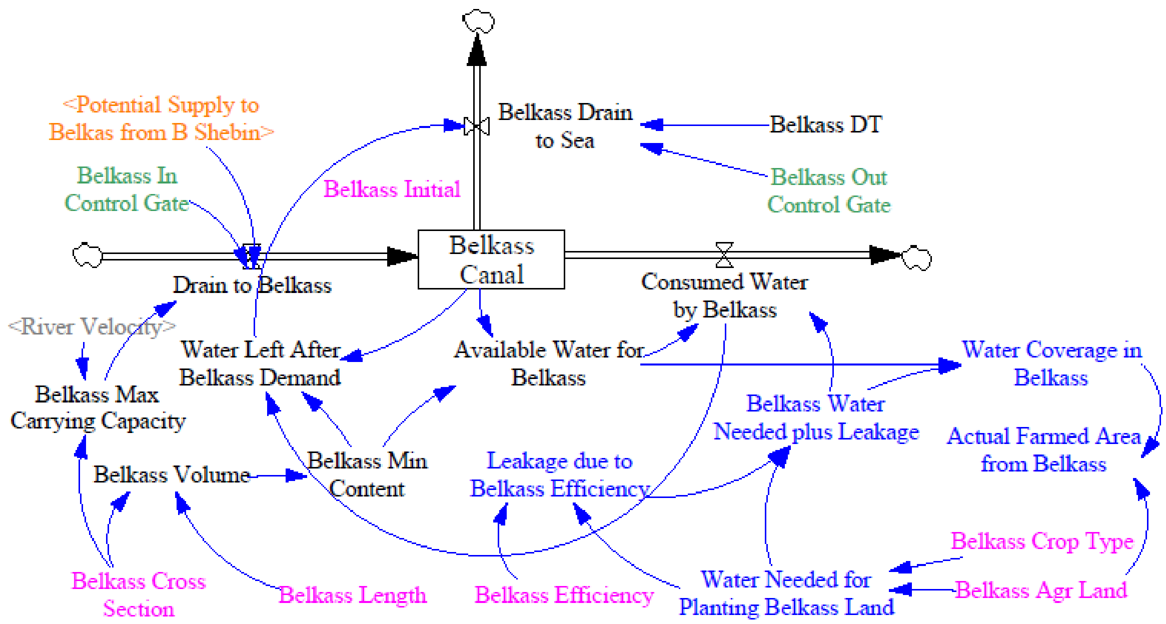

Figure 6-32: The Belkass Canal sub-model.

East of the Delta

This is the area that expands from Damietta branch at the east to *Suez Canal* at the west. The area is irrigated from the Damietta branch, the Sharkawya canal, and the Ismaelya canal at the first level. While the Ismaelya canal drains to the Bitter lake, connected to the Suez Canal, and the Sharkawya canal drains to the Abu Akhder canal at the third level, the Damietta branch supports the flow of water to the second level canals, the Mansorya canal and Rayah Tawfiky, that deliver the water to the third level canals as shown in Figures 6-33 to 6-35.

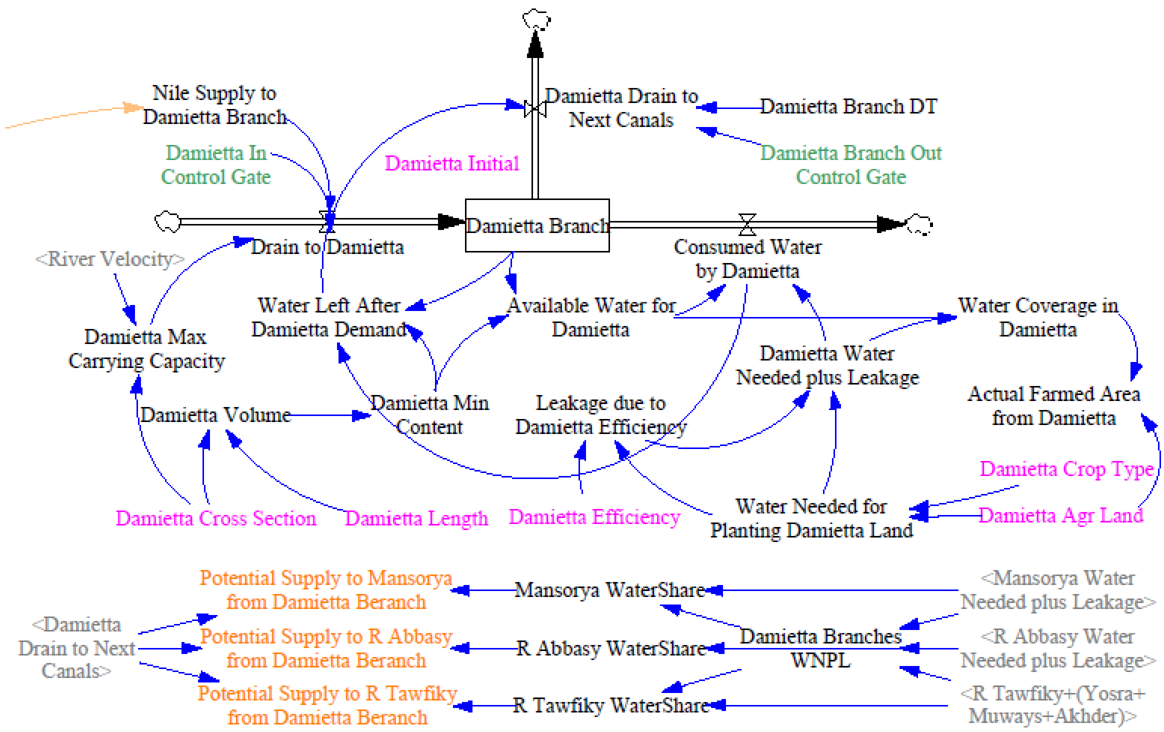

Figure 6-33: The Damietta branch sub-model.

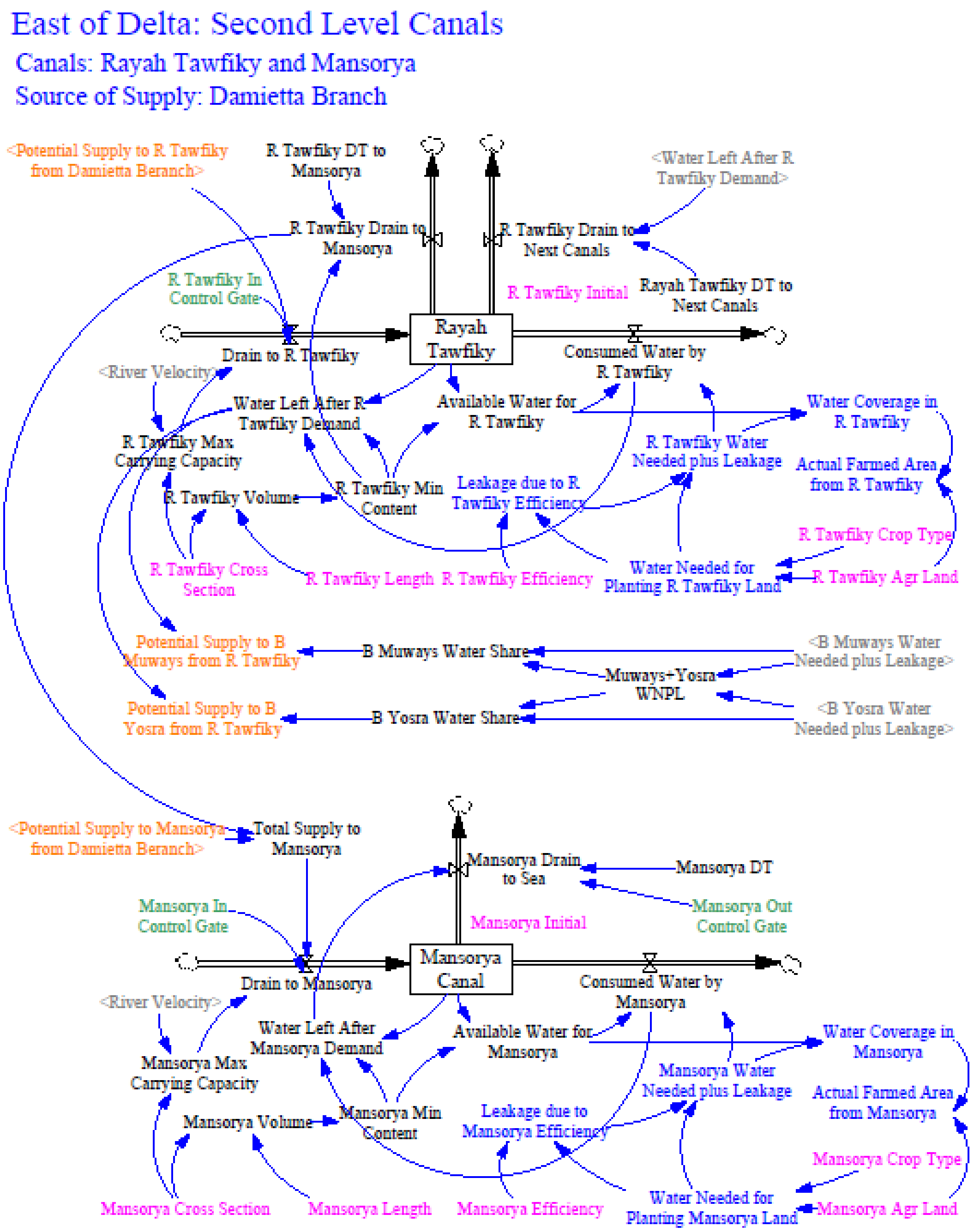

Figure 6-34: The second level canals at East of the Delta.

This view includes the canals at the second level: Rayah Tawfiky *(Top)*, and the Mansorya canal *(Down)*. Noteworthy, Rayah Tawfiky drains to the Mansorya canal which is at the same level but receives the major part of water from the Damietta branch.

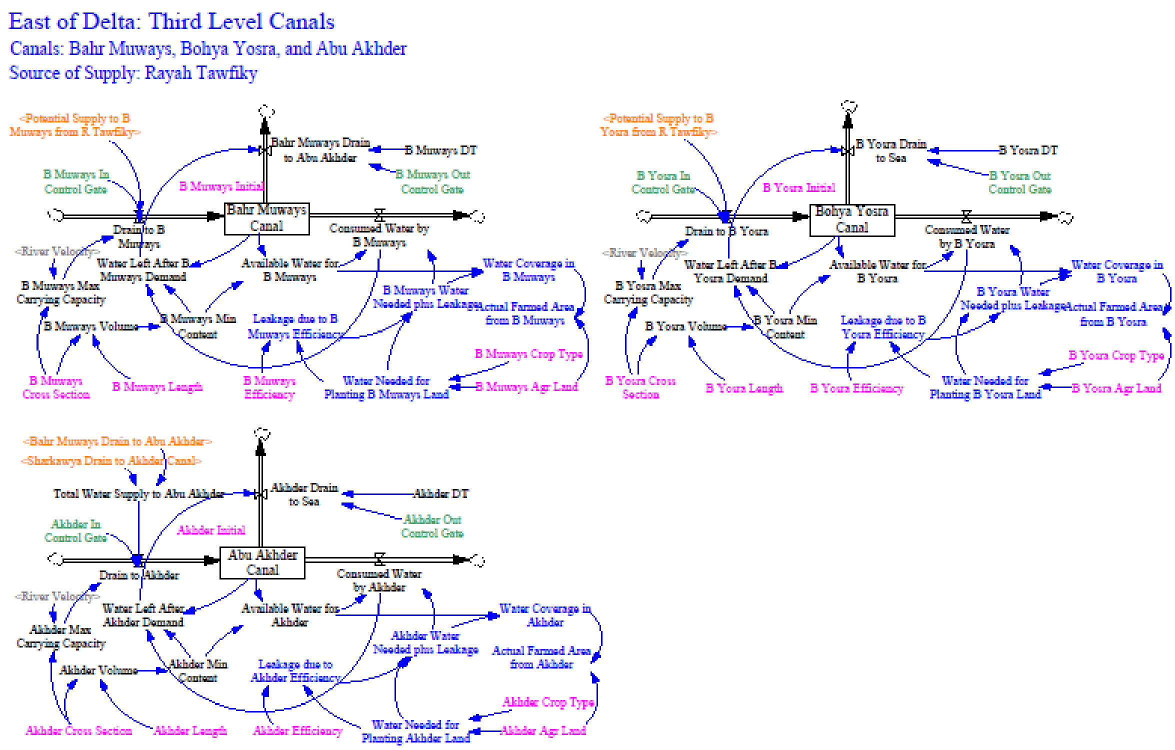

Figure 6-35: The third level canals at East of Delta.

This view includes three canals: Bahr Muways *(T.L.)*, Bohya Yosra canal *(T.R.)*, and Abu Akhder canal *(D.L.)*. Closer shots are shown in Figures 6-36 to 6-38.

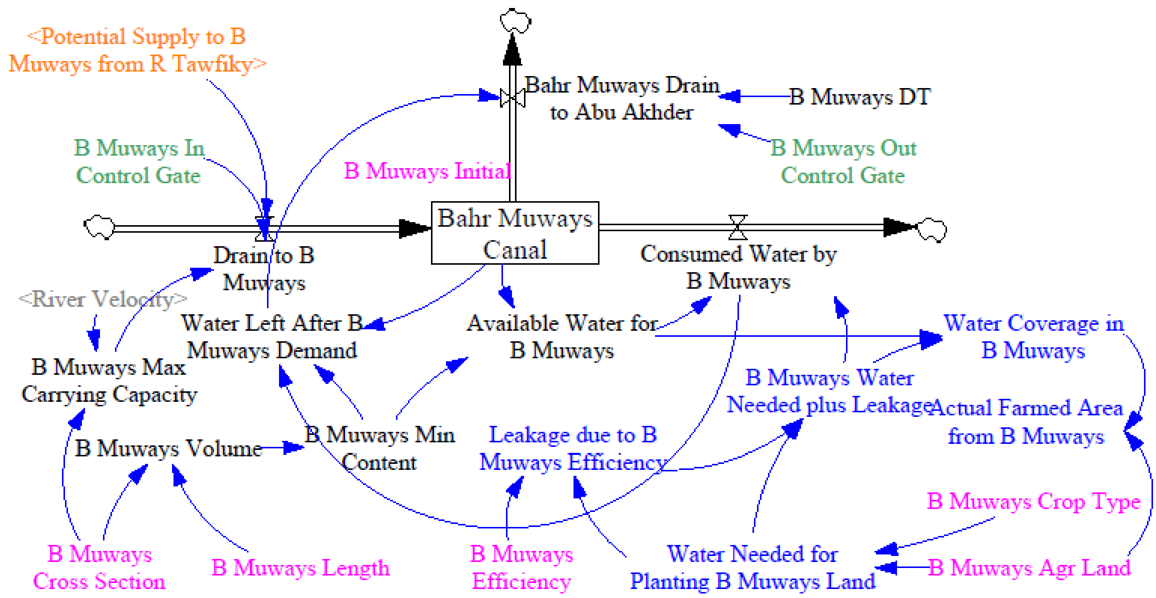

Figure 6-36: The Bahr Muways Canal sub-model.

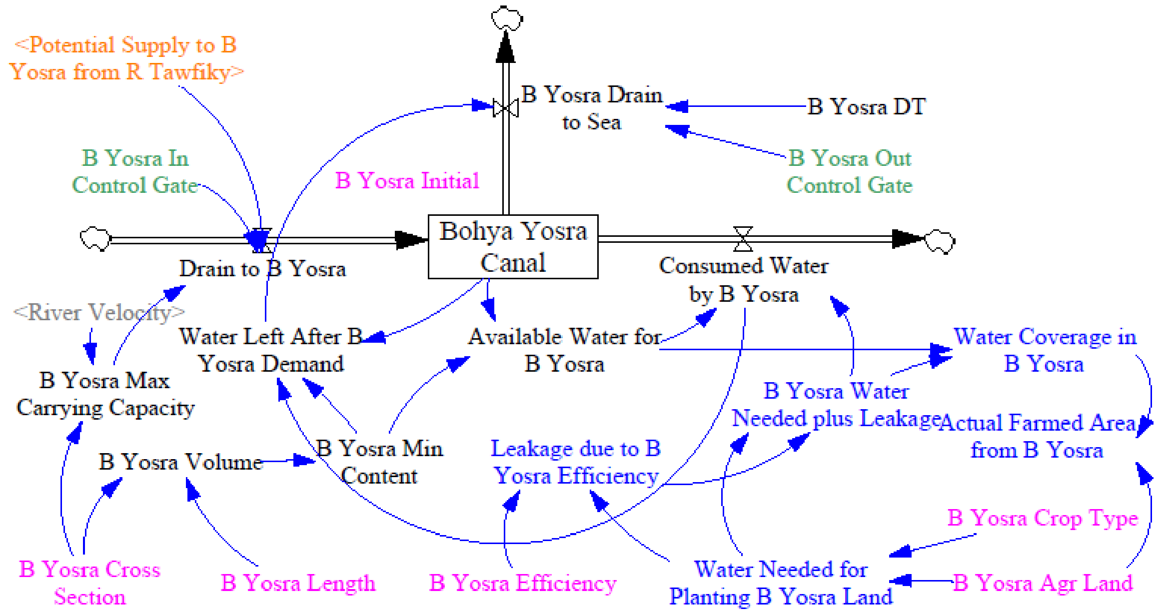

Figure 6-37: The Bohya Yosra Canal sub-model.

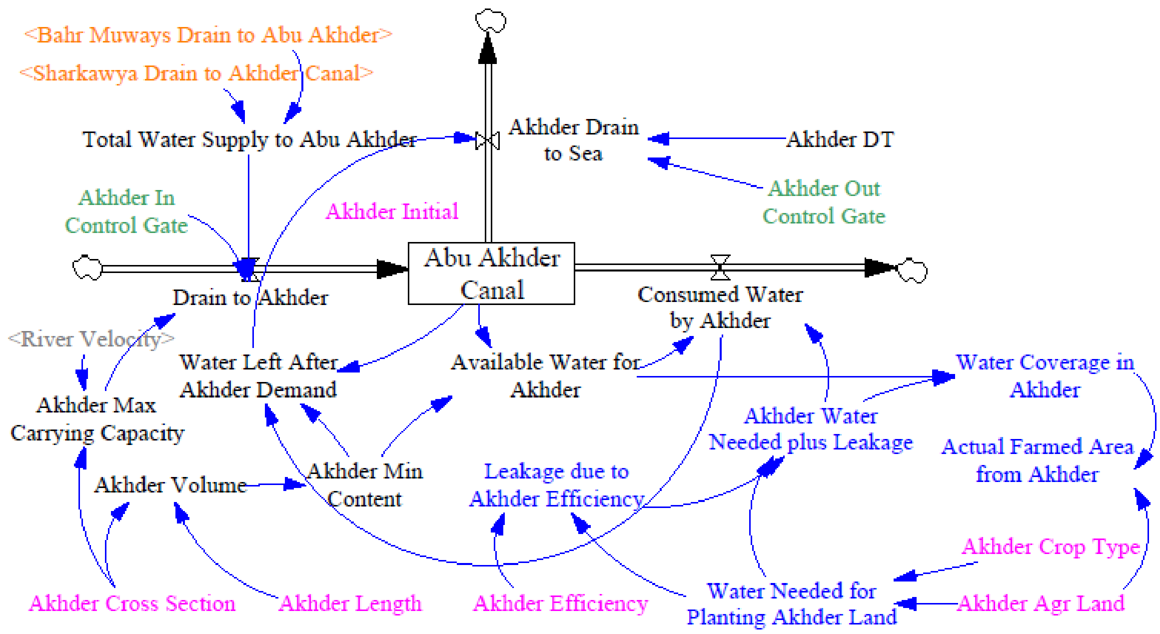

Figure 6-38: The Abu Akhder Canal sub-model.

The Figures 6-39 and 6-40 portrays the sub-model of the first level canals Sharkawya and Ismaelya, respectively.

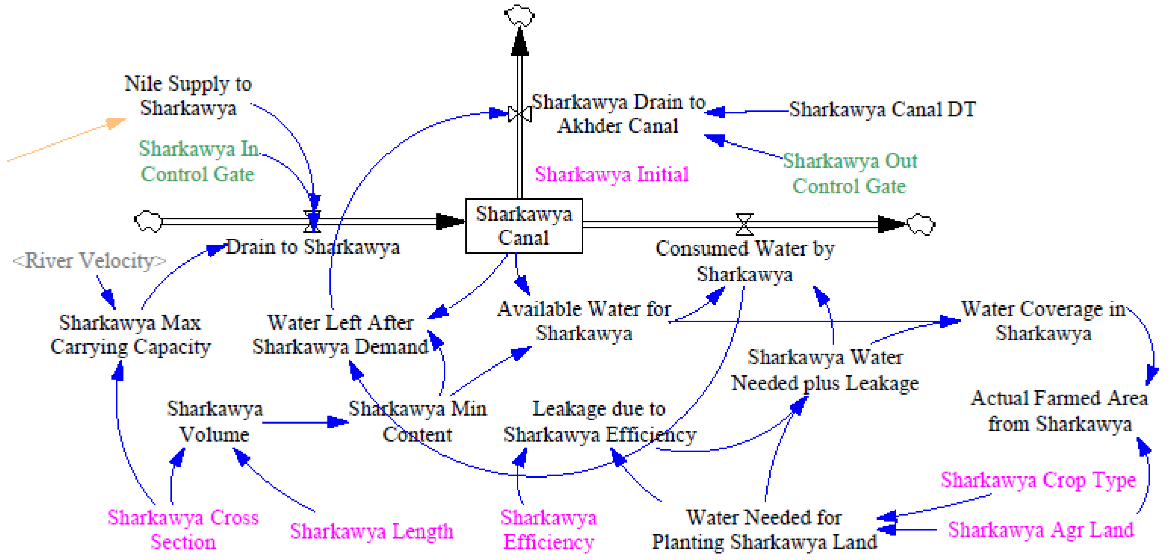

Figure 6-39: The Sharkawya Canal sub-model.

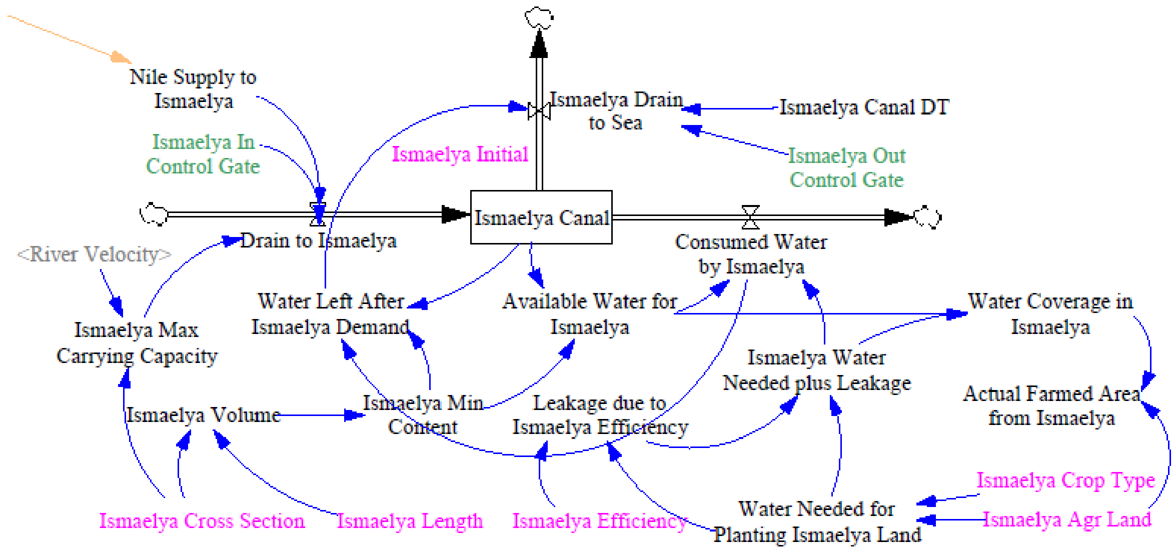

Figure 6-40: The Ismaelya Canal sub-model.

There is one more view worth exhibiting in this section. That is the model initialization view shown in Figure 6-41. The aim of this view is to provide the user with a convenient way to set the initial values for the model decision variables that are distributed across the various model views.

First Level

<Ismaelya Initial>	<Ismaelya Length>	<Ismaelya Cross Section>	<Ismaelya Efficiency>	<Ismaelya Agr Land>	<Ismaelya Crop Type>
<Sharkawya Initial>	<Sharkawya Length>	<Sharkawya Cross Section>	<Sharkawya Efficiency>	<Sharkawya Agr Land>	<Sharkawya Crop Type>
<R Monofya Initial>	<R Monofya Length>	<R Monofya Cross Section>	<R Monofya Efficiency>	<R Monofya Agr Land>	<R Monofya Crop Type>
<Rashid Initial>	<Rashid Length>	<Rashid Cross Section>	<Rashid Efficiency>	<Rashid Agr Land>	<Rashid Crop Type>
<Damietta Initial>	<Damietta Length>	<Damietta Cross Section>	<Damietta Efficiency>	<Damietta Agr Land>	<Damietta Crop Type>

Second Level

Delta West					
<R Nasiry Initial>	<R Nasiry Length>	<R Nasiry Cross Section>	<R Nasiry Efficiency>	<R Nasiry Agr Land>	<R Nasiry Crop Type>
<R Behary Initial>	<R Behary Length>	<R Behary Cross Section>	<R Behary Efficiency>	<R Behary Agr Land>	<R Behary Crop Type>
<Mahmoudya Initial>	<Mahmoudya Length>	<Mahmoudya Cross Section>	<Mahmoudya Efficiency>	<Mahmoudya Agr Land>	<Mahmoudya Crop Type>
Delta Middle					
<B Shebin Initial>	<B Shebin Length>	<B Shebin Cross Section>	<B Shebin Efficiency>	<B Shebin Agr Land>	<B Shebin Crop Type>
<Bagorya Initial>	<Bagorya Length>	<Bagorya Cross Section>	<Bagorya Efficiency>	<Bagorya Agr Land>	<Bagorya Crop Type>
<R Abbasy Initial>	<R Abbasy Length>	<R Abbasy Cross Section>	<R Abbasy Efficiency>	<R Abbasy Agr Land>	<R Abbasy Crop Type>
Delta East					
<R Tawfiky Initial>	<R Tawfiky Length>	<R Tawfiky Cross Section>	<R Tawfiky Efficiency>	<R Tawfiky Agr Land>	<R Tawfiky Crop Type>
<Mansorya Initial>	<Mansorya Length>	<Mansorya Cross Section>	<Mansorya Efficiency>	<Mansorya Agr Land>	<Mansorya Crop Type>

Third Level

Delta West					
<Hager Initial>	<Hager Length>	<Hager Cross Section>	<Hager Efficiency>	<Hager Agr Land>	<Hager Crop Type>
<Noubarya Initial>	<Noubarya Length>	<Noubarya Cross Section>	<Noubarya Efficiency>	<Noubarya Agr Land>	<Noubarya Crop Type>
<Khandak Initial>	<Khandak Length>	<Khandak Cross Section>	<Khandak Efficiency>	<Khandak Agr Land>	<Khandak Crop Type>
<B Gharbya Initial>	<B Gharbya Length>	<B Gharbya Cross Section>	<B Gharbya Efficiency>	<B Gharbya Agr Land>	<B Gharbya Crop Type>
Delta Middle					
<Kased Initial>	<Kased Length>	<Kased Cross Section>	<Kased Efficiency>	<Kased Agr Land>	<Kased Crop Type>
<M Yazed Initial>	<M Yazed Length>	<M Yazed Cross Section>	<M Yazed Efficiency>	<M Yazed Agr Land>	<M Yazed Crop Type>
<B Tera Initial>	<B Tera Length>	<B Tera Cross Section>	<B Tera Efficiency>	<B Tera Agr Land>	<B Tera Crop Type>
<Belkass Initial>	<Belkass Length>	<Belkass Cross Section>	<Belkass Efficiency>	<Belkass Agr Land>	<Belkass Crop Type>
Delta East					
<B Muways Initial>	<B Muways Length>	<B Muways Cross Section>	<B Muways Efficiency>	<B Muways Agr Land>	<B Muways Crop Type>
<B Yosra Initial>	<B Yosra Length>	<B Yosra Cross Section>	<B Yosra Efficiency>	<B Yosra Agr Land>	<B Yosra Crop Type>
<Akhder Initial>	<Akhder Length>	<Akhder Cross Section>	<Akhder Efficiency>	<Akhder Agr Land>	<Akhder Crop Type>

Figure 6-41: The model initialization view

In this section, we have provided an overview of the model structure. More details regarding the model equations and formulas are provided in Appendix C. In the following section, we describe the adaptation of the SDGIS application to the irrigation system in the Nile Delta.

6.3.5 The SDGIS Application Improvements

This is the third version of the SDGIS Application. The application has been improved mainly to host the SD spatial model and the last version of the classified map. In addition to the modifications of the “SD Model” panel and the “GIS Tools” panel, four additional panels were introduced to provide more control over the models and to improve the visualization. These panels are labelled the “More Graphs”, the “Delta Image”, the “Model Initialisation”, and the “Control Gates” panel, respectively.

The "SD Model" Panel

In the first panel, shown in Figure 6-42, a new SSTab control object has been added. It includes 25 Text-Boxes to display the values of the 24 canals and the stock associated with the Nile. The Text-Boxes are organized in three columns with respect to the three geographical zones, and distributed across three tabs corresponding to the three levels of canals within the irrigation system (see Figure 6-43). For example, the Nile River, the two main branches, and the three main canals appear in first tab, while in the second tab the eight canals at the second level are organized in three columns corresponding to their location. The third tab includes the eleven canals at the third level and they are organized in three columns as well. These Text-Boxes show the "Initial values of the canals" (i.e., the initial water volume) resulting from the user loading the simulation model and before the simulation has been started. The Text-Boxes are editable so that the user can set the desired initial value for any canal. During the simulation, the application retrieves the *current water volume* in each canal and displays it in the associated Text-Box. In the code page, the functions *Vensim_get_val* and *FOR*, and a fixed size array have been used to retrieve the values of the canals. Noteworthy, the function *Vensim_get_val* retrieves the values of the canals in an alphabetical order, meaning that the canal named *Abu Akhder* for example will be retrieved before *Rashid Branch* despite its lower level in the irrigation system, its geographical location, or its place in the model (in which view it is located). Consequently, a few lines of code have been added to trace the order of value retrieving, associate the Text-Boxes with the canals, and to reorganize the Text-Boxes on the SSTab.

The frame labelled "The Model Canals" appearing above the new SSTab (see Figure 6-42) contains a List-Box and another frame labelled "Canal Attributes" to display the characteristics of a single canal. Unlike the List-Box in the previous application, this List-Box shows only the stocks in the simulation model, that is the

24 canals and the stock associated with the Nile River[48]. The List-Box has a method added to its properties that enables the user to select an item (a canal) from the List-Box. The attributes of the selected canal are then shown in the frame “Canal Attributes” and the view containing this canal is displayed in the Picture-Box.

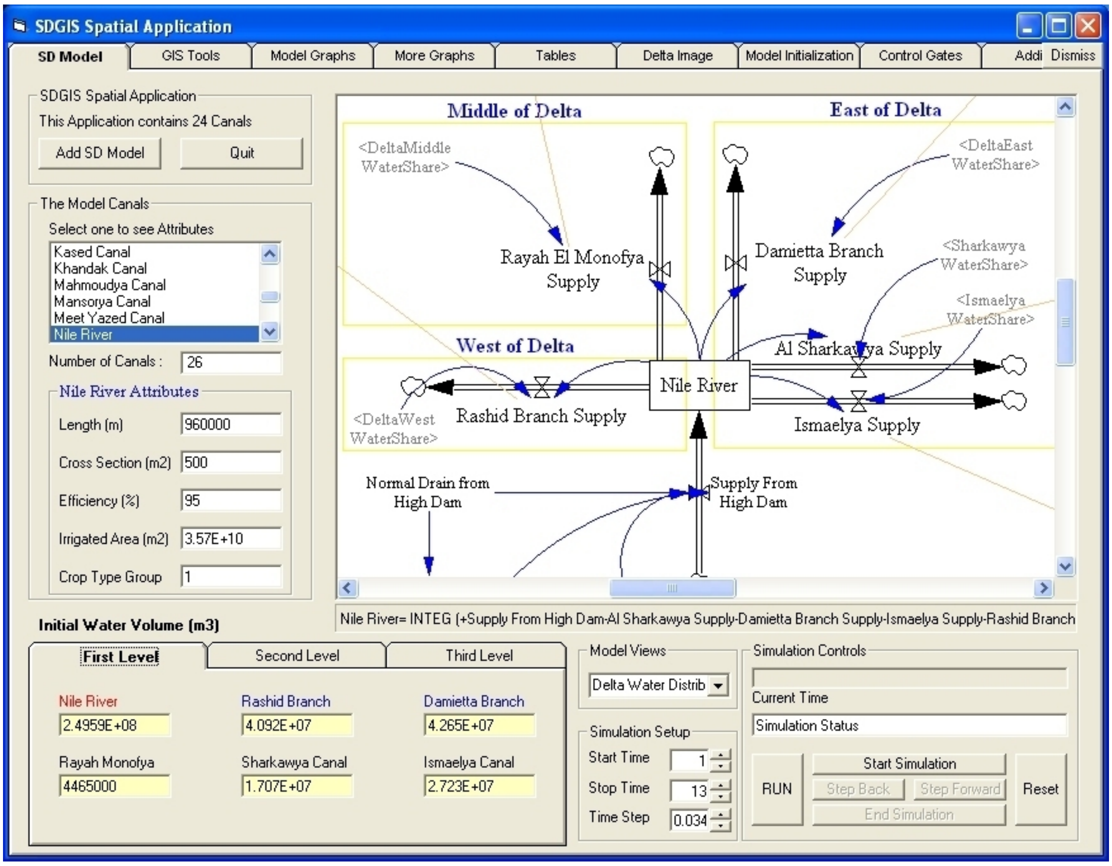

Figure 6-42: The “SD Model” Panel

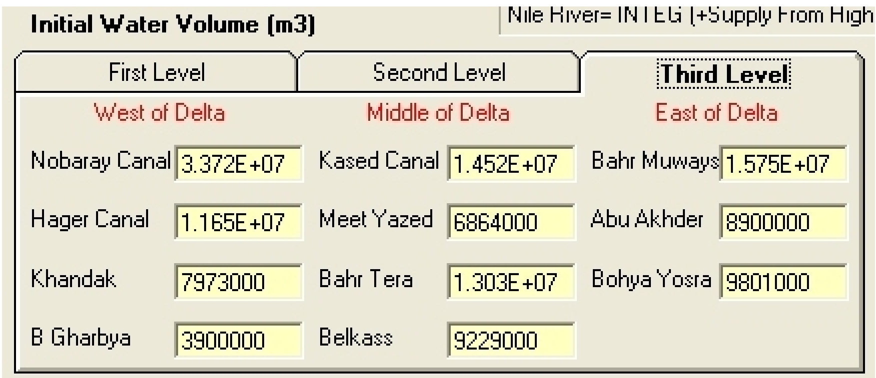

Figure 6-43: The new SSTab.

[48] The List-Box in the previous application shows the model variables. In this spatial model, there are more than seventy variables most of them are shown in other panels. Therefore, there is no need to display all of them in this List-Box.

The "GIS Tools" Panel

In the second panel, shown in Figure 6-44, two frames labelled "Selected Canal Attributes" and "Selected Farm Attributes" have been added to the left side to display the attributes of one single canal and its associated agriculture land. In fact, because of the number of the canals included in the SD spatial model (i.e., 24 canals), the SSTab appearing in the previous application (see Figure 5-48) that encompass only nine canal-classes, has been removed and a new panel labelled "Model Initialisation" has been added to accommodate the attributes of the 24 canals. The "Model Initialisation" panel is described later in this section.

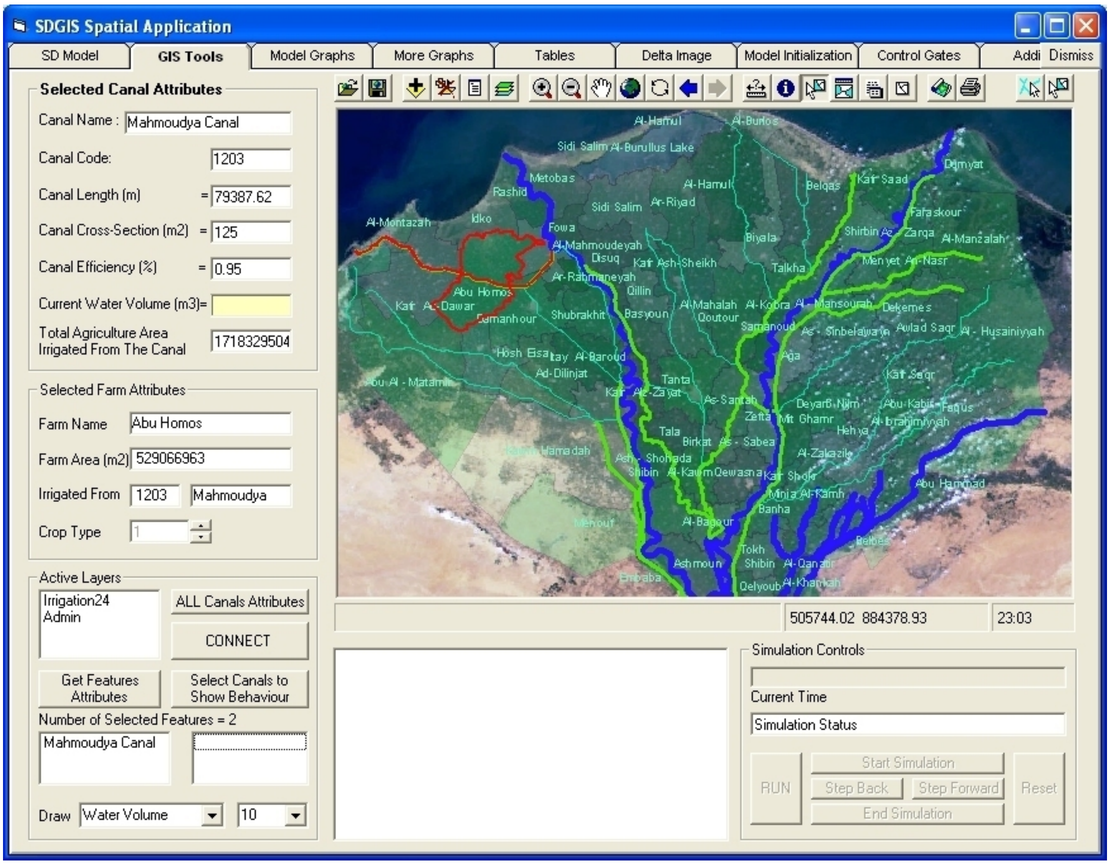

Figure 6-44: The GIS Tools Panel

The Frame, labelled "Active Layers", appearing at the bottom on the left hand side (see Figures 6-44 and 6-45), has been reorganized and the functions associated with the command buttons have been modified[49]. For example, the function

[49] For more information, see the detailed code in Appendix C

associated with the command button "All Canals Attributes" has been modified to access the attribute table of the layer *Canals*, to retrieve the attributes of the 24 canals and the Nile River, and to display these attributes in the "Model Initialization" panel (Figure 6-48).

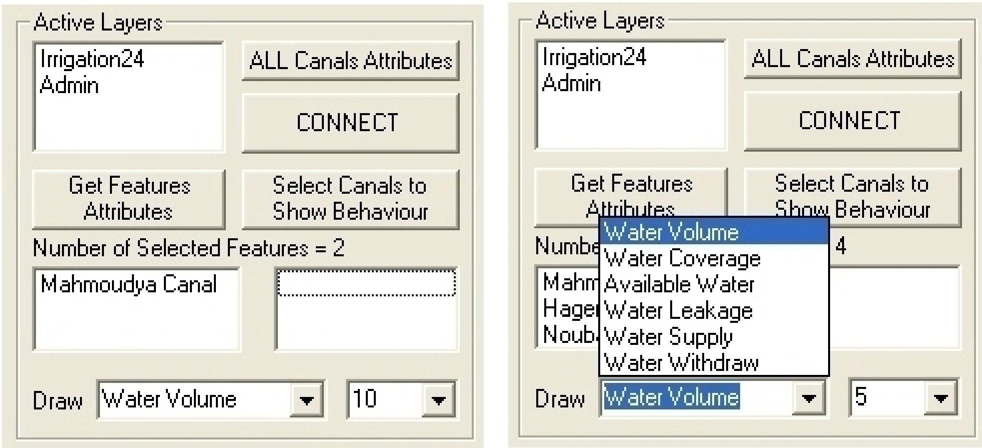

Figure 6-45: The Active Layers Frame

The Additional Panels:

1. "More Graphs" Panel

Because the SD spatial model includes 24 canals, classified in three categories, a larger number of graphs were needed to exhibit the behaviour of the system. Therefore, six graphs have been added in a separate panel labelled "More Graphs" in addition to the previous four graphs in the "Graph" panel. The graphs should be created using the Vensim simulation software and marked as *WIP* graphs. In fact, the six Picture-Boxes that appear in the panel are programmed to display any six graphs named as [Graph1, Graph2…Graph6] from the upper-left to the lower-right corner. The user can create any number of graphs in the Vensim software, and then select the desired graphs to be displayed and their location by way of naming them [Graph1, Graph2…Graph6]. If the user chooses to display less number of graphs, the rest of the Picture-Boxes will appear empty.

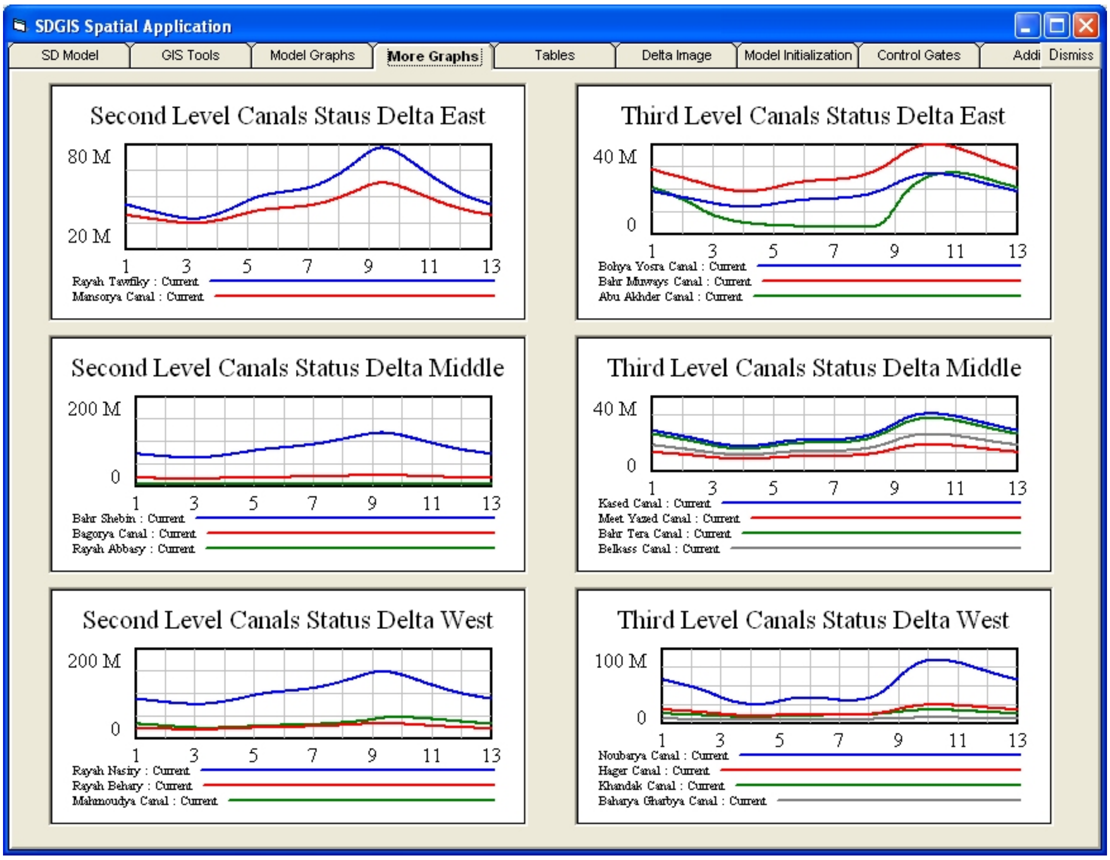

Figure 6-46: The new panels “More Graphs”.

2. The “Delta Image” Panel

This panel contains an image control object to display a *static* image for the irrigation network. The image is a snapshot from the ArcGIS for the irrigation Map. On top of the image, copies of the Text-Boxes associated with the current water volume of the canals have been added and placed over the corresponding canal. During runtime, the values of the canals are displayed at every time step. Thus, the user can observe the changes in all canals’ volumes simultaneously. The four command buttons appear in the lower-left are copies of the simulation control buttons, so that the user can run the simulation from this panel and watch the change in the state of the canals.

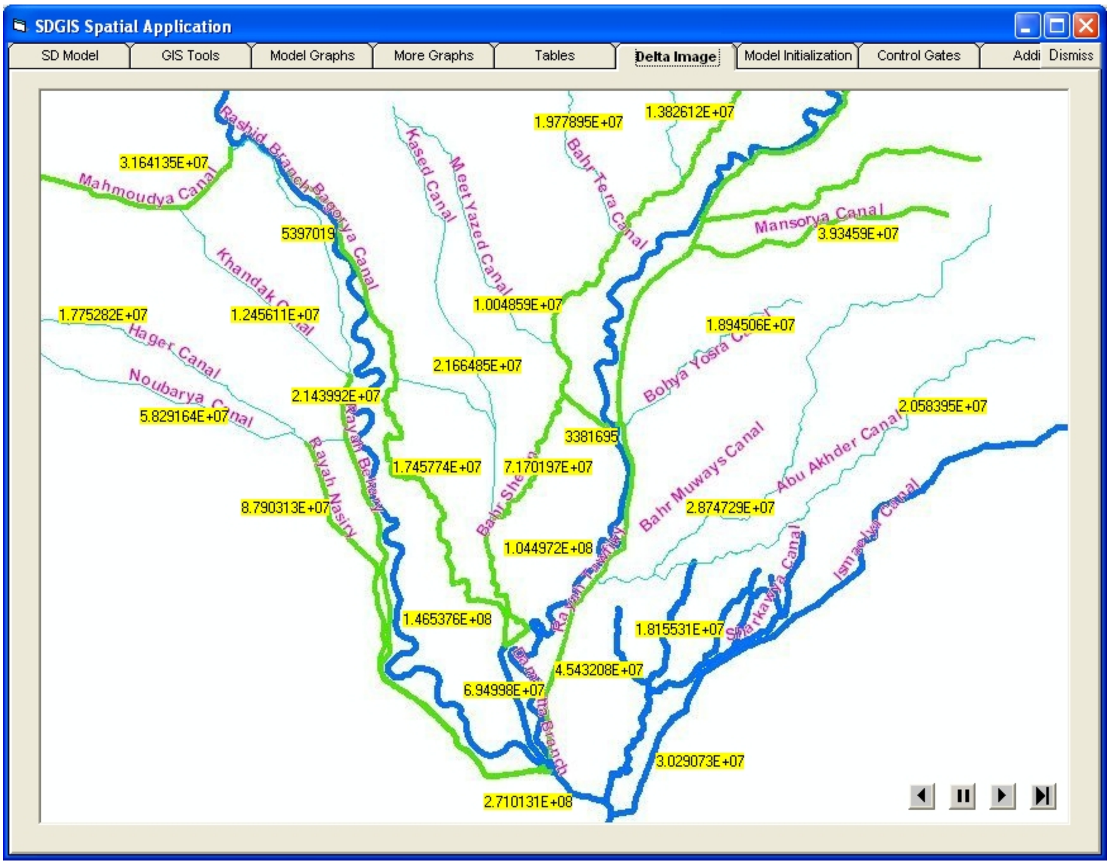

Figure 6-47: The Delta Image Panel

3. The "Model Initialisation" panel

This panel, shown in Figure 6-48, has been created to provide an easy access to the initial values of the 24 canals included in the SD spatial model and the GIS model. This panel is multi purpose panel.

First, it can be used as an input tool to set the initial values to the simulation model. Before the simulation is started, the user can develop a scenario and assign the desired values for the decision variables associated with the canals in the various Text-Boxes. These Text-Boxes are associated with the variables associated with each sub-model of the target canal. The initial values include: the canal length, cross-section, efficiency, crop type, and the area of the agriculture land irrigated from this canal. There are three command buttons at the bottom of the panel: "Fill Panel From Model" to obtain the original values of the variables from the SD spatial model;

“RESET” to evacuate the Text-Boxes; and “Set These Values To Model” to insert the new initial values into the simulation model.

Second, the panel is used as an intermediate platform facilitating the communication between the *Map* and the simulation model. When the user loads the irrigation network map into the application through the “GIS Tools” panel, the application retrieves the attributes of the canals from the attribute table and displays them in the associated Text-Boxes. Then, when the user uses the command button CONNECT in the GIS Tools panel, these values are written into an array and sent, as a vector of data, to the simulation model.

Third, the panel is used as a display screen. When the user selects more than one canal from the map and uses the command button “Get Features Attributes”, and because the GIS Tools panel can display the attributes of only one canal, the rest of the canals’ attributes are displayed on this panel in the associated Text-Boxes. The panel is also used to display the values of all canals when the command button “All Canals Attributes” is used. Finally, the user may need to reset the original values of the canals if these values must been changed to represent various scenarios.

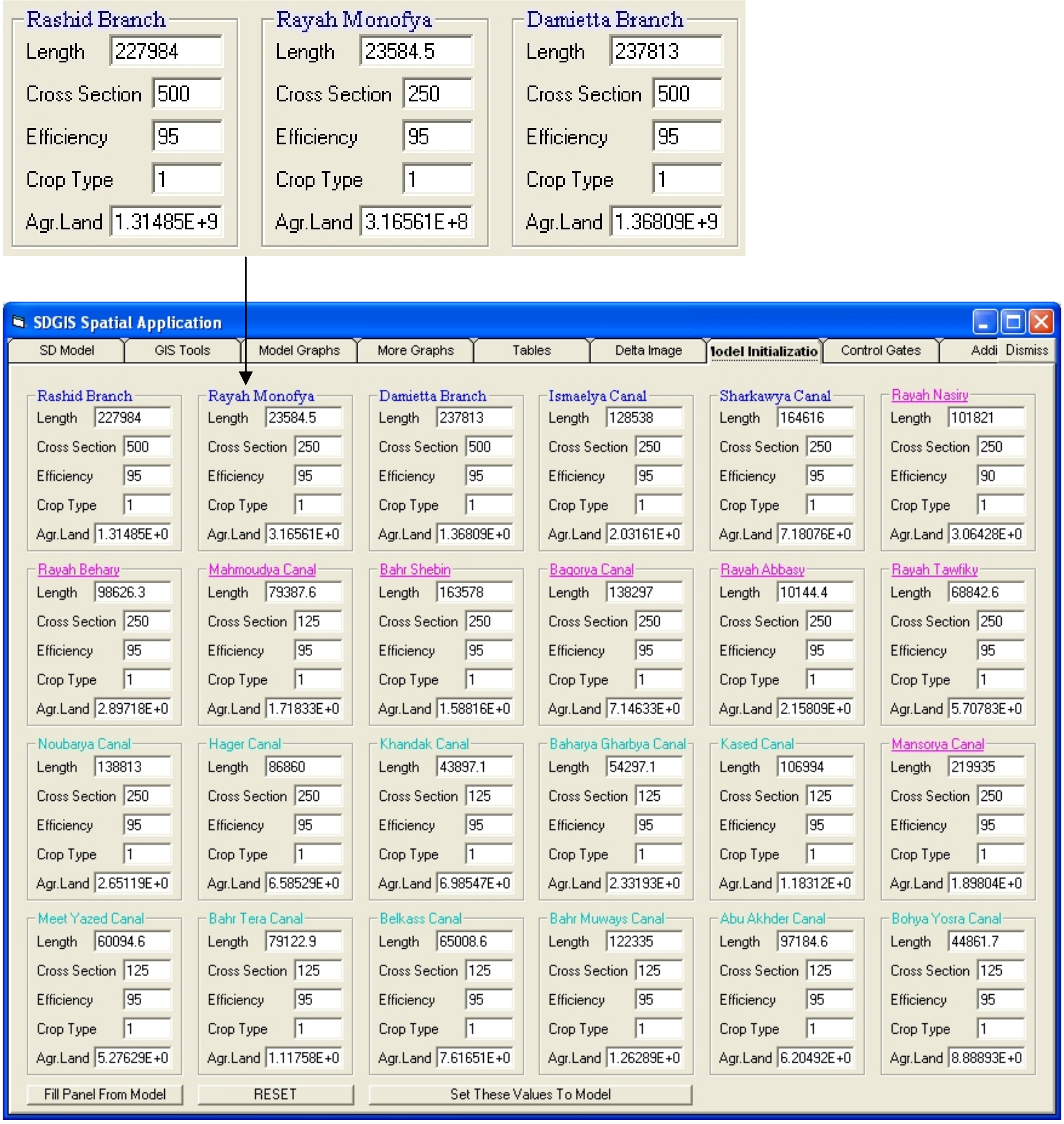

Figure 6-48: The model initialisation Panel

4. The “Control Gates” Panel

This panel has been created to host the control gates included in the irrigation system. During the simulation, the user can change the state of a certain control gate to adjust the flow of water into the canal. This is one of the most significant decisions that the user may take to analyse and study the behaviour of the system or to test a certain policy. In fact, these controls have been extensively used, to steer the water supply and to adjust it to the demand, during the testing of policies for water preservation.

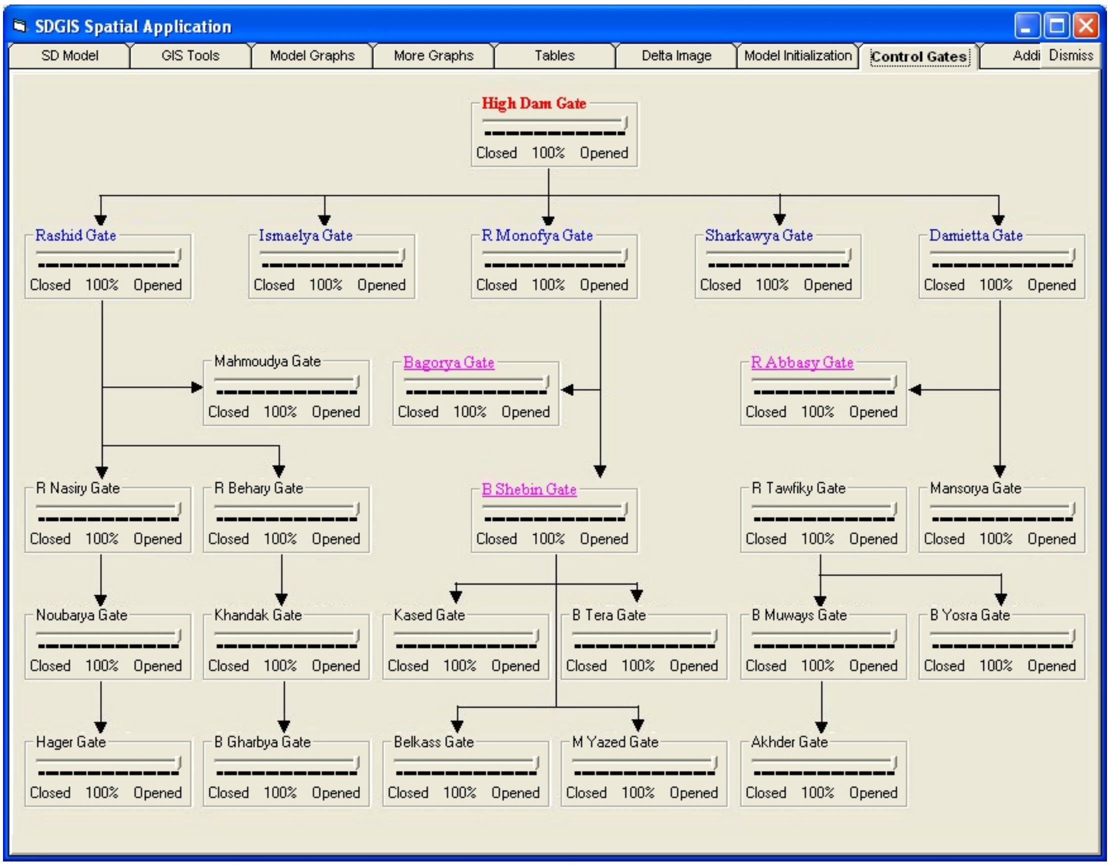

Figure 6-49: The “Control Gates” Panel

The control gates are represented with *Slider* control objects where the user can move the slider in both directions to regulate the volume of the water passing through it. The application converts the value of the slider to a numeric value and assigns it to the target control gate in the simulation model. For example, the value appears on the screen as 100% means full open valve capacity. This value is converted to one and multiplied by the volume of the water inflow. The sliders are organized in the order of the water flow directions within the irrigation network starting from the High Dam gates, that is the main source of water, and through the main branches and canals ending up to the canals at the tail of the system that drain to the sea.

6.4 Running the SDGIS Application

The SD spatial model and the new classified map is being loaded and connected through the SDGIS application using the SD Model panel and GIS Tools panel. The simulation model is calibrated with the initial values that are reported in Table 6-4. The application retrieves the Canals' attributes such as *Name, Length, Cross Section*, and the *Area of the agriculture lands* associated with each canal, from the attribute table of the new classified map. In this run, *The Base Run*, an assumption has been made concerning the cropping patterns. That is, all the agriculture areas have the same cropping pattern (i.e., group one of crop rotation that includes clover, cotton, and rice have been used in all Delta zones). The conveyance efficiency is calibrated according to the empirical data available obtained during the fieldwork (i.e., 90%, 80%, and 70% for the canals at the 1st, 2nd, and 3rd levels respectively).

Table 6-4: The initial values used in the first simulation

Ncode	Canal Name	Length (m)	Cross Section(m^2)	Efficiency	Agr. Land Area (m^2)	Crop Type
1100	Nile River**	47833.62	500	90%	963874714	1
1101	Rashid Branch	227984.08	500	90%	1314847737	1
1102	Rayah Monofya	23584.46	250	90%	316560763	1
1103	Damietta Branch	237812.77	500	90%	1368092441	1
1104	Sharkawya Canal	164615.89	250	90%	718076315	1
1105	Ismaelya Canal	128537.99	250	90%	2031608848	1
1201	Rayah Nasiry	101820.53	250	80%	2774561112	1
1202	Rayah Behary	98626.29	250	80%	289718344	1
1203	Mahmoudya Canal	79387.62	125	80%	1718329504	1
1204	Bahr Shebin	163578.18	250	80%	1588156544	1
1205	Bagorya Canal	138296.99	250	80%	714632483	1
1206	Rayah Abbasy	10144.36	250	80%	215808681	1
1207	Rayah Tawfiky	68842.60	250	80%	570782696	1
1208	Mansorya Canal	219934.64	250	80%	1898035125	1
1301	Hager Canal	86860.03	250	70%	658528785	1
1302	Noubarya Canal	138812.64	250	70%	2651194589	1
1303	Khandak Canal	43897.08	125	70%	698547274	1
1304	Baharya Gharbya	54297.11	125	70%	233193442	1
1305	Kased Canal	106993.73	125	70%	1183120292	1
1306	Meet Yazed Canal	60094.57	125	70%	527628910	1
1307	Bahr Tera Canal	79122.94	125	70%	1117583594	1
1308	Belkass Canal	65008.57	125	70%	761650788	1
1309	Bohya Yosra Canal	44861.65	125	70%	888892874	1
1310	Bahr Muways Canal	122335.39	125	70%	1262890810	1
1311	Abu Akhder Canal	97184.58	125	70%	620491648	1

**The length of the Nile indicated in this table is the length of that part of the Nile appears in the map and the associated agriculture area.

The model is simulated for one year using DT equal to one day where the model's time corresponds to one month. The output map was saved at every time step and after the simulation has produced the maps displayed sequentially in Figure 6-50.

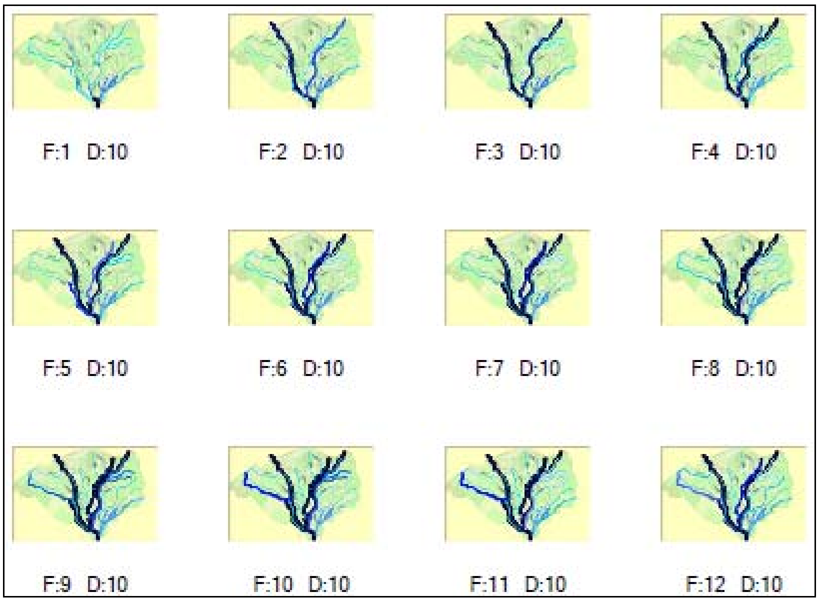

Figure 6-50: The output maps of the simulations[50]

Close-up snapshots taken during the simulation runtime are shown in Figures 6-52 to 6-57. Figure 6-52 shows the state of the canals at the beginning of the simulation. The canals are represented by a blue colour ramp corresponding to their initial values of water volume (notice that the initial value of the canal is calculated as a percentage of its carrying capacity, e.g., 30% of the carrying capacity). The dark colours indicate large volumes and visa versa. The lighter the colour the less are the volumes. The canals are labelled with their *Ncodes* for the purpose of easy identification[51]. A part from the Nile River appears at the bottom of the map in dark blue as it carries the largest volume of water being the source of the water supply. Then, the Rashid branch appears with a blue colour as the second largest volume, and then the rest of the canals with different range of blue colour ramp. As the simulation advances, the canals, particularly those at the first level, start to receive an additional supply as shown in Figure 6-53.

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[50] F is the frame number and D is the time (in seconds) the frame is displayed on the screen in a slideshow presentation.

[51] A guide map for the canals' names is shown in Figure 6-52. Reader can use it to follow description

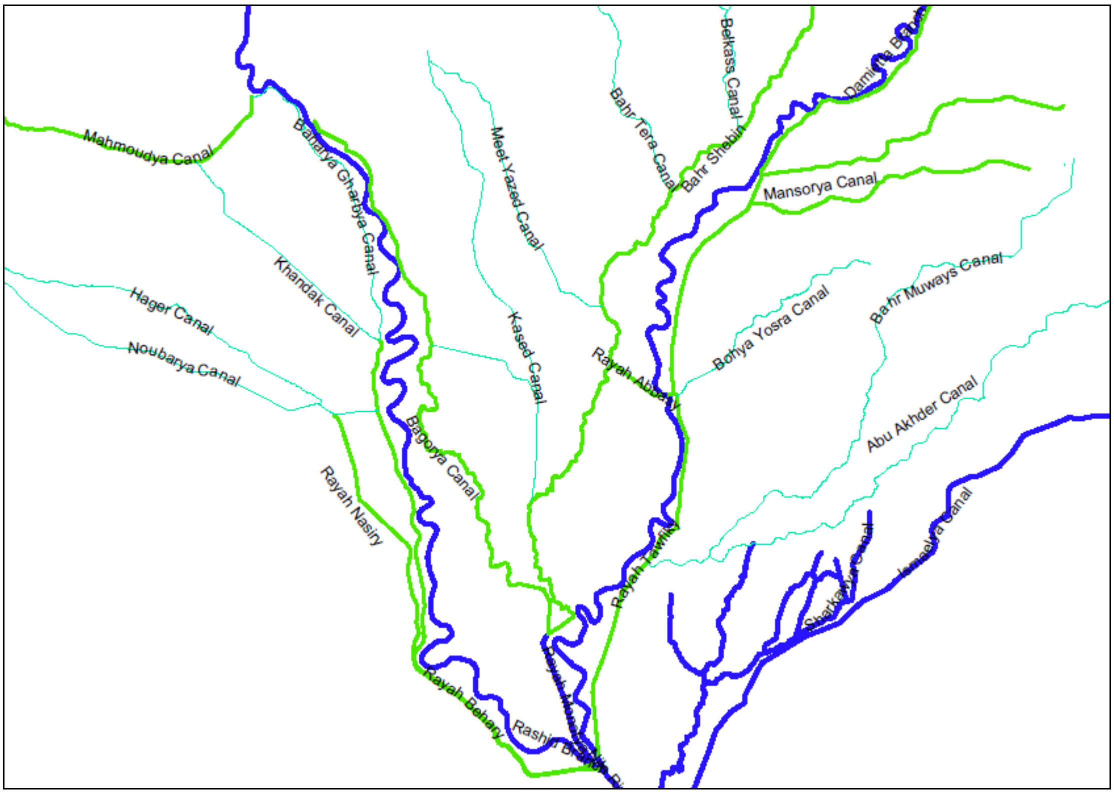


Figure 6-51: A guide map for the canals' names

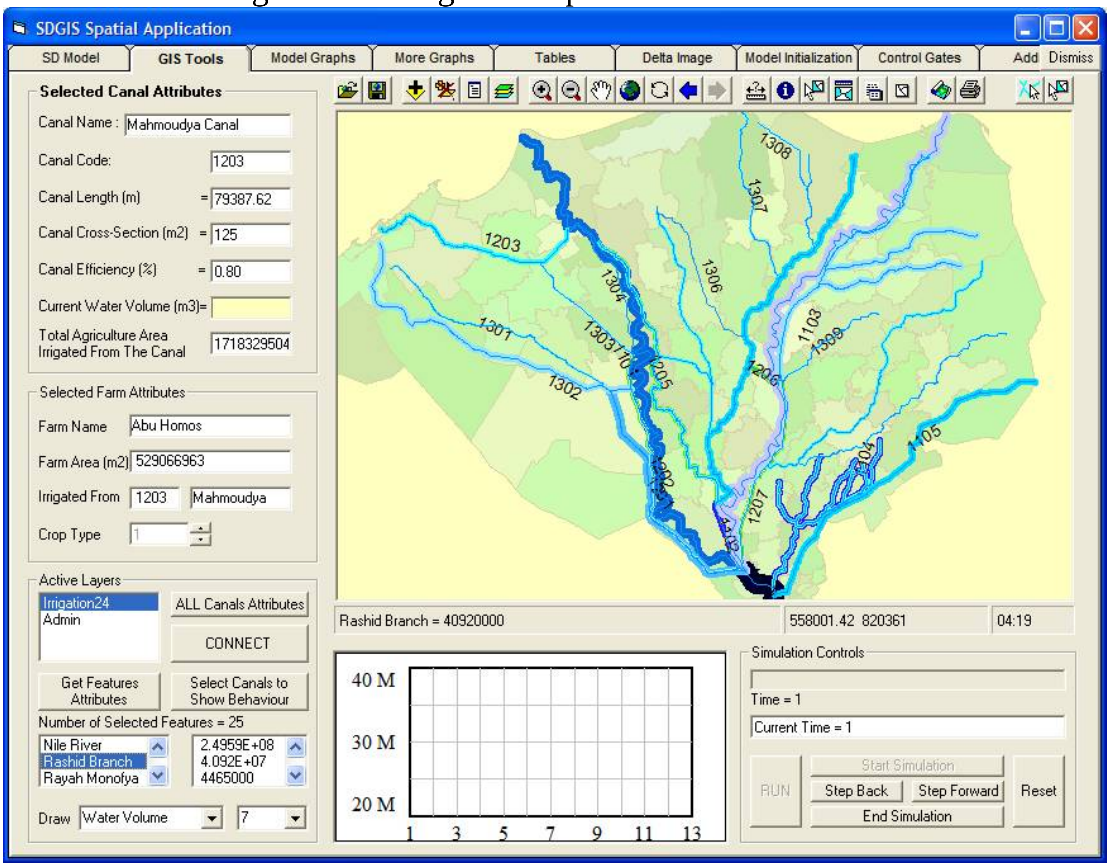


Figure 6-52: The state of the Canals at simulation Time = 1.

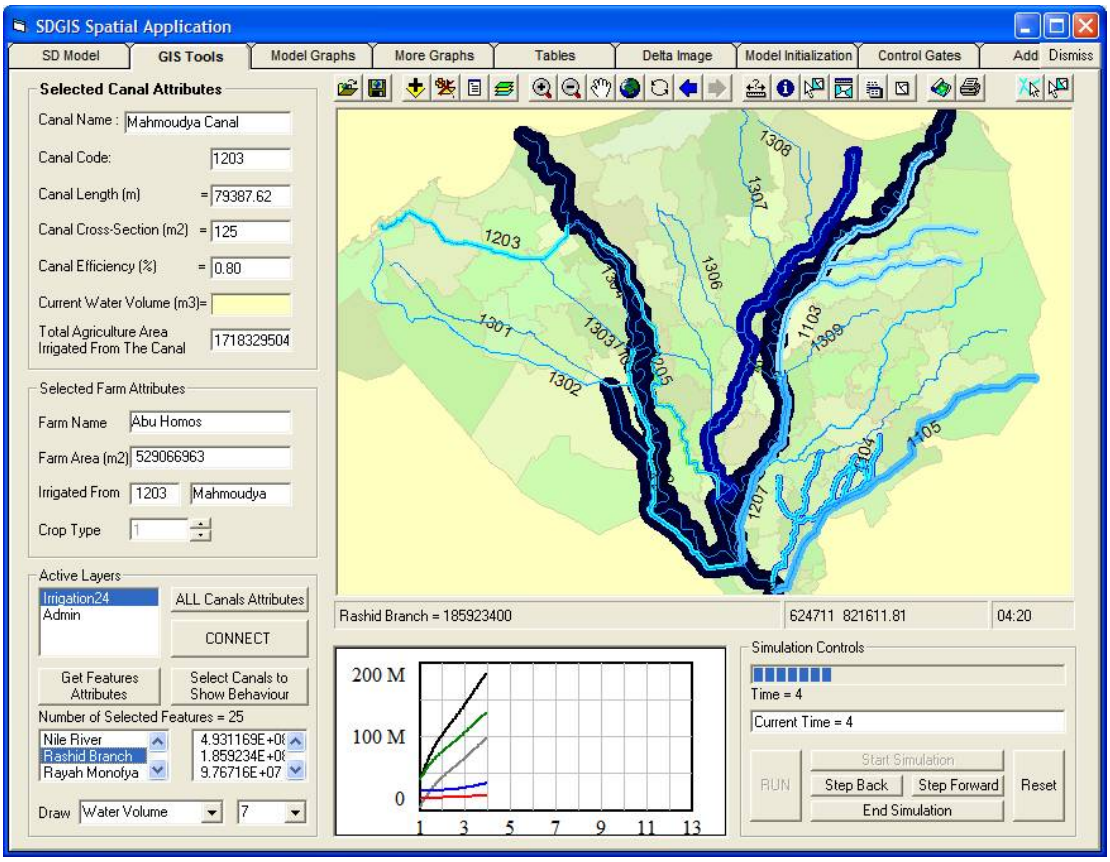
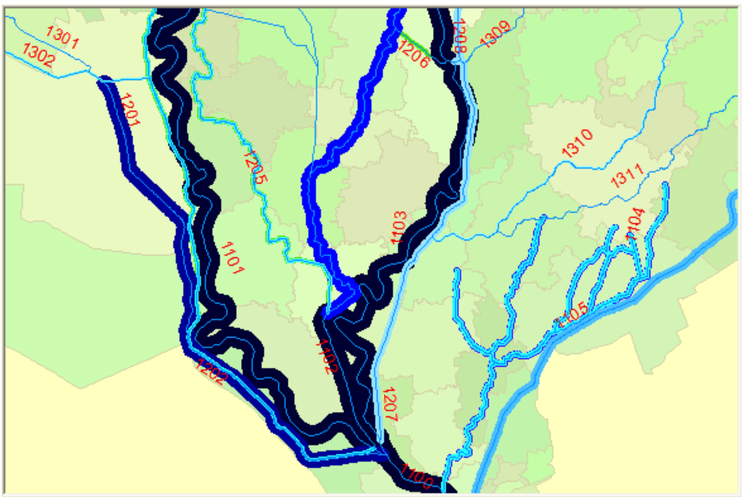


Figure 6-53: The state of the Canals at simulation Time = 4.

Using the *zoom-in* tool, a closer view of the map is shown in the figure below. The view reveals, for example, that: at West of the Delta, Rayah Nasiry *1201* became dark blue, while Rayah Behary *1202* appears in light blue. At the Middle of the Delta, Bahr Shebin *1204* became blue. At East of Delta, the Damietta branch *1103* has turned to dark blue while Rayah Tawfiky *1207* became light blue.



As the simulation continues, the state of the canals is changing as shown in the Figures 6-54 to 6-57.

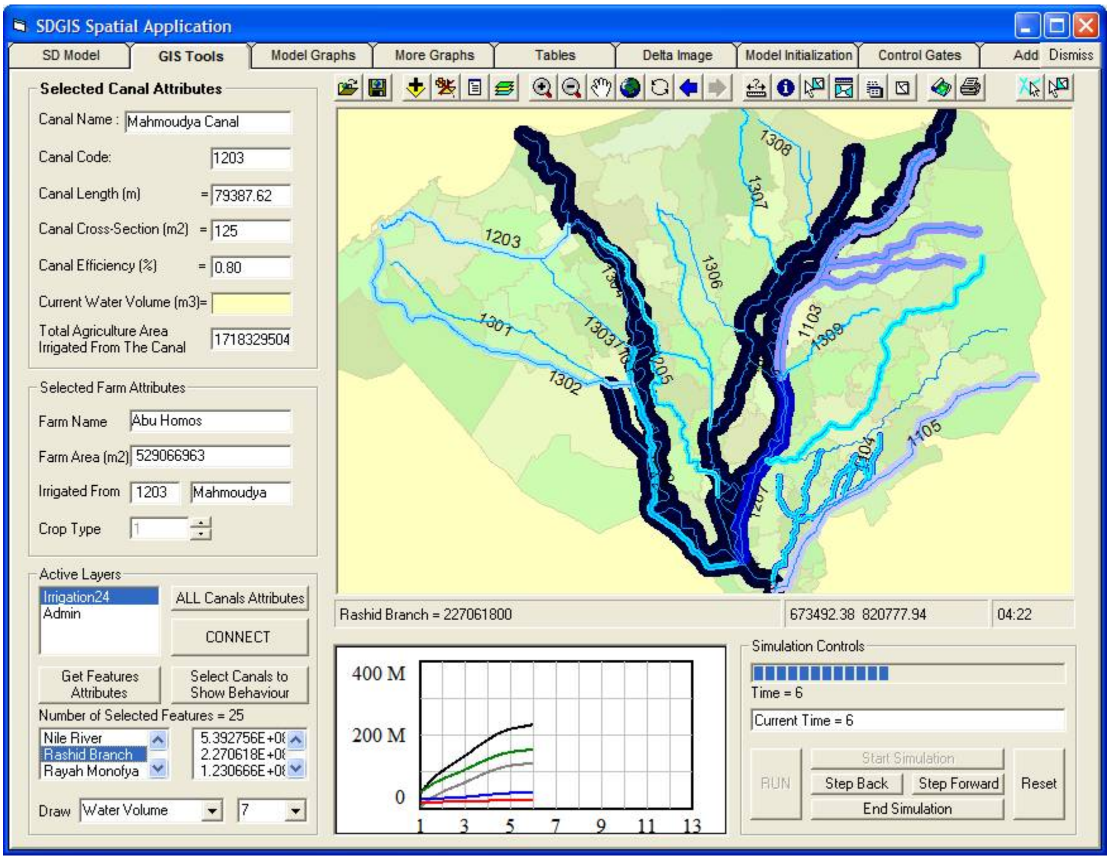


Figure 6-54: The state of the Canals at simulation Time = 6.

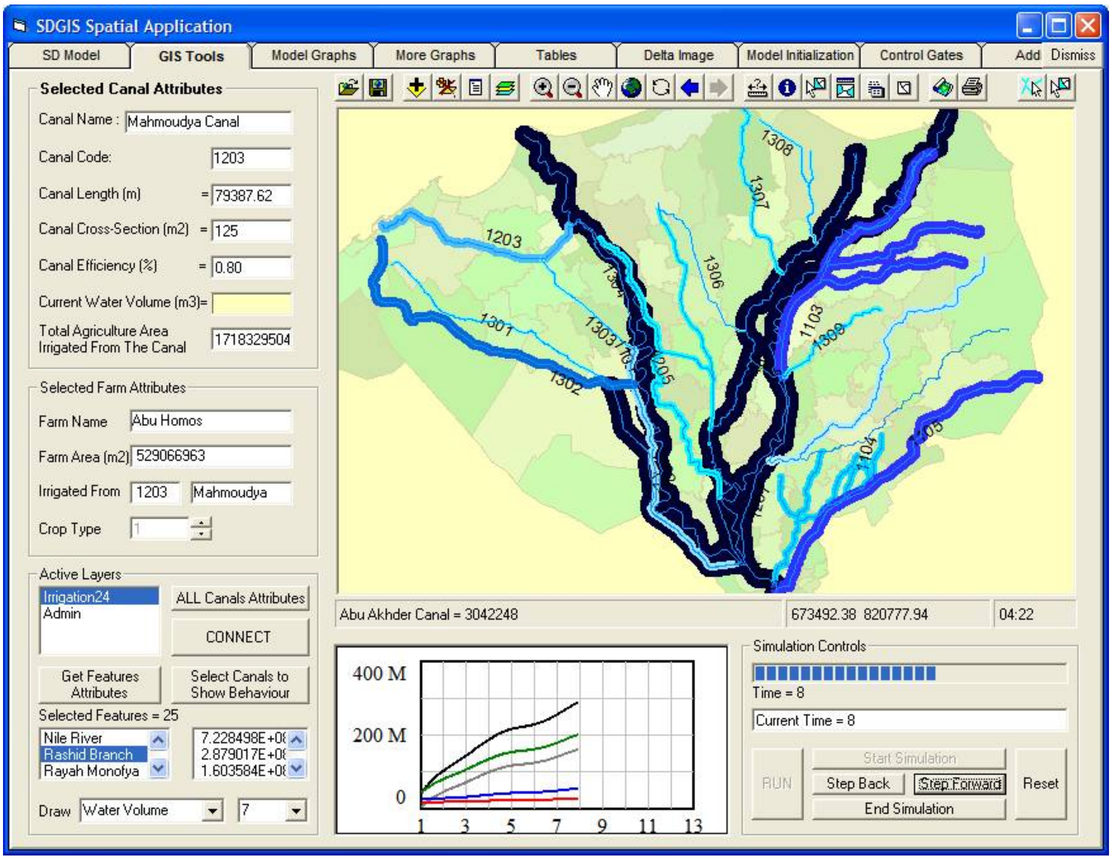


Figure 6-55: The state of the Canals at simulation Time = 8.

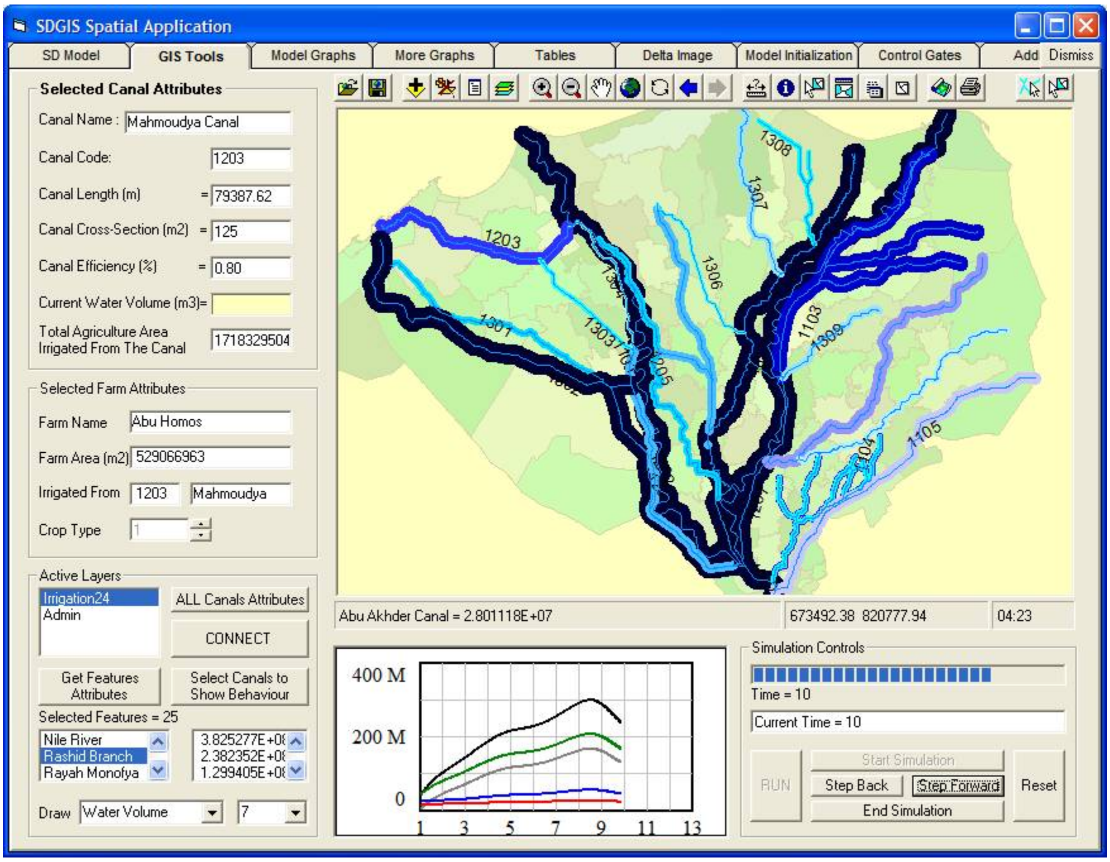


Figure 6-56: The state of the Canals at simulation Time = 10.

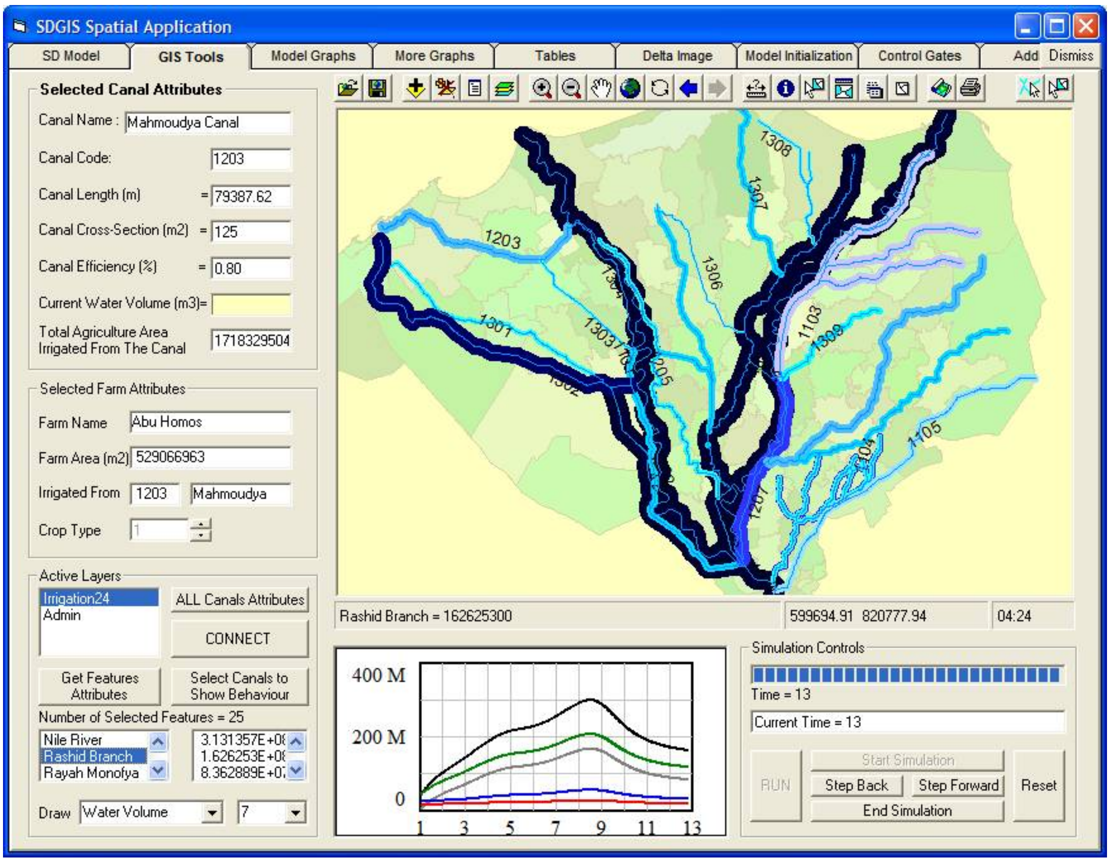


Figure 6-57: The state of the Canals at simulation Time = 12

The model has been simulated for 24 months and then for 36 months using the same initial values we listed in the Table 6-4. Two snapshots for the two runs, at the beginning of the second year and the beginning of the third year, are shown in Figures 6-58 and 6-59 respectively. By comparing these two figures, we found that they are identical. Notice the graph in the Picture-Box placed below the MapControl Viewer, in Figure 6-58, the graph shows one year simulation while in Figure 6-59 the graph shows the simulation for two years. Noticeably, the behaviour of the model exhibits identical cycles repeated over a period of time equals to one year. This means that the model behaviour is stabile (steady state behaviour). However, both figures are dissimilar to the state of the canals at the beginning of the first year shown in the Figure 6-52 (above). To test the model sensitivity to the initial conditions, we recorded the initial values of the canals and run the model for one year (we called this run the *Original Initial*) then we saved the values of the canals at the end of the simulation (end values) as shown in Table 6-5.

Table 6-5: The *Initial* and the *End* values of the water volume in the canals

Time (Month)	Initial Value (MCM)	End Value (MCM)
Nile River	249.59	291.39
Rashid Branch	40.92	166.43
Rayah Monofya	4.465	67.38
Damietta Branch	42.65	113.03
Ismaelya Canal	27.23	30.49
Sharkawya Canal	17.07	18.22
Rayah Behary	8.901	25.58
Rayah Nasiry	35.32	105.75
Mahmoudya Canal	18.71	37.26
Noubarya Canal	33.72	70.61
Hager Canal	11.65	20.81
Khandak Canal	7.973	15.39
Baharya Gharbya Canal	3.900	6.379
Bahr Shebin	25.23	69.38
Bagorya Canal	15.39	16.64
Rayah Abbasy	2.673	3.524
Kased Canal	14.52	22.13
Meet Yazed Canal	6.864	10.25
Bahr Tera Canal	13.03	20.21
Belkass Canal	9.229	14.12
Rayah Tawfiky	9.696	60.10
Mansorya Canal	31.68	45.57
Bahr Muways Canal	15.75	42.43
Bohya Yosra Canal	9.801	28.58
Abu Akhder Canal	8.900	35.97

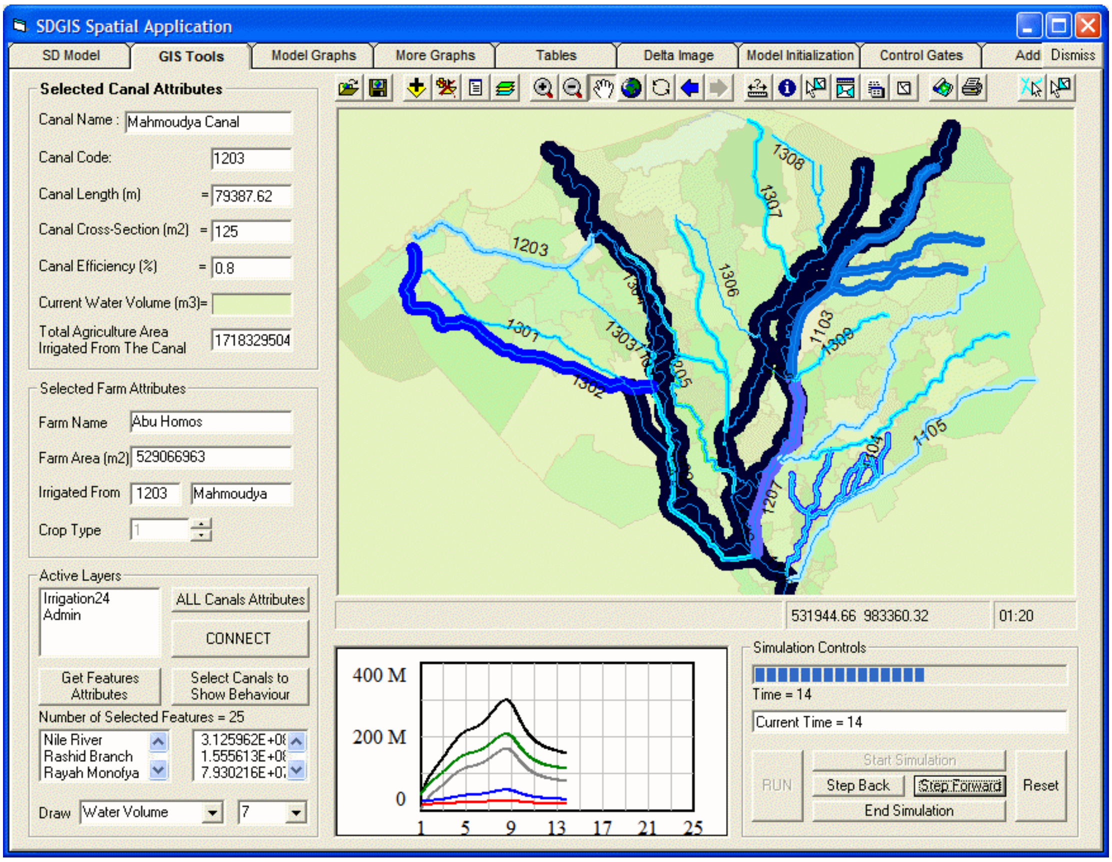


Figure 6-58: The state of the canals at the beginning of the second year

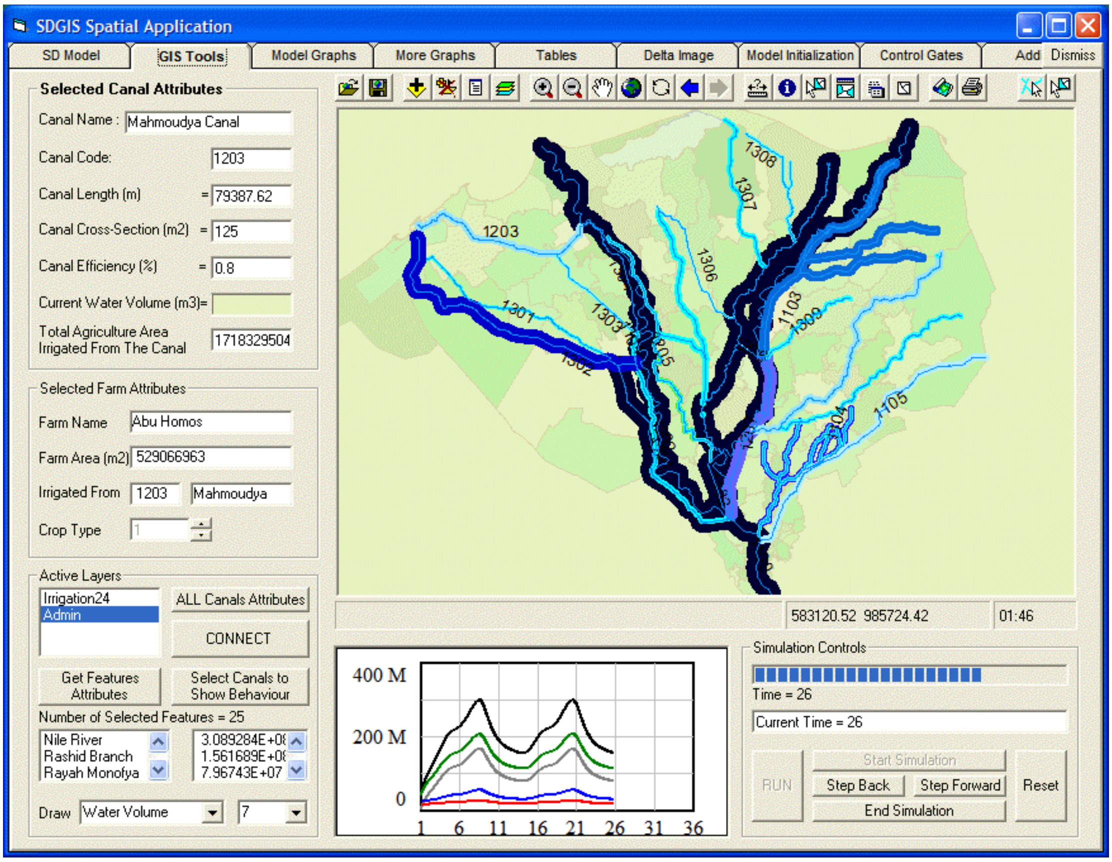


Figure 6-59: The state of the canals at the beginning of the third year

Then, we used the end values of the canals to initialize the model, and run it for three years (we called this run the *Modified Initial*). Remarkably, the model exhibited the same pattern of behaviour (i.e., the repeated cycles) after a very short period of time from the simulation starting point (transient state) as illustrated in Figures 6-60 to 6-64. Figure 6-60 shows that the behaviour of the Nile River, for example, has not been affected by changing the initial value except in the first two months. Moreover, the behaviour of the two main branches, Rashid and Damietta shown in Figures 6-61, 6-62, and 6-63 respectively, has also been stabilized shortly after the simulation has started (about four months after the simulation starting point). To gain more confident in the behaviour of the model, we run also this sensitivity analysis using the Vensim software. Figure 6-62 illustrates an example for the sensitivity graphs produced by Vensim. This graph shows the sensitivity of the Rashid Branch to the initial condition.

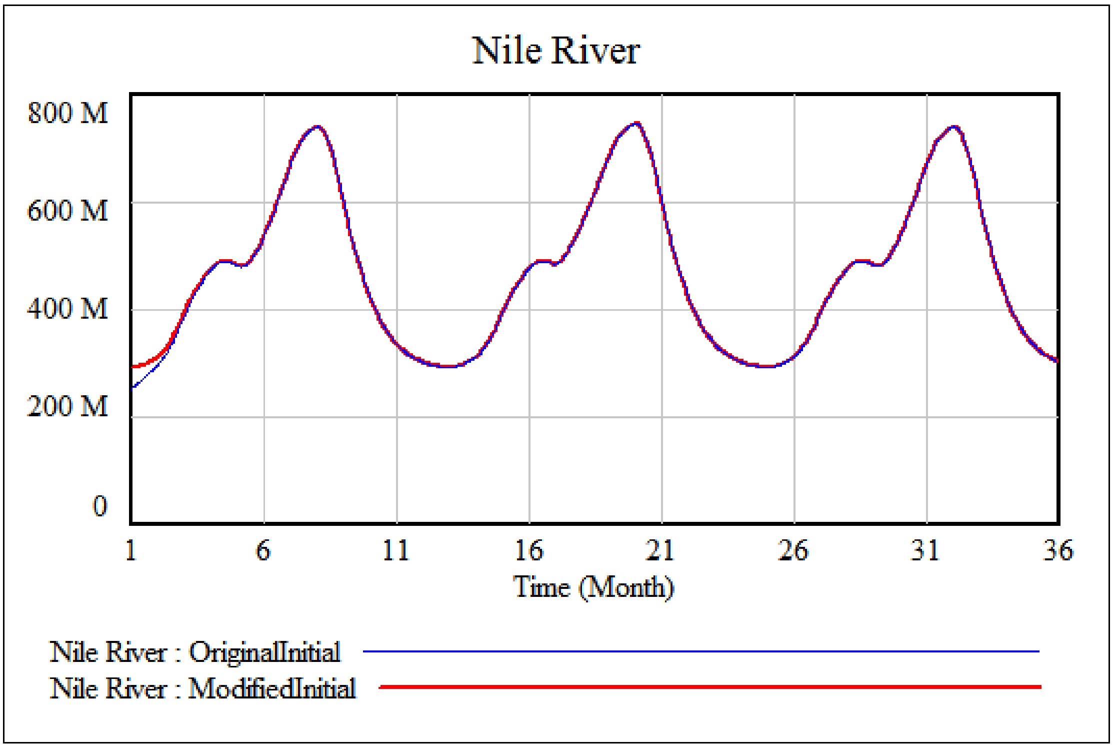


Figure 6-60: The behaviour of the Nile with two different initial values.

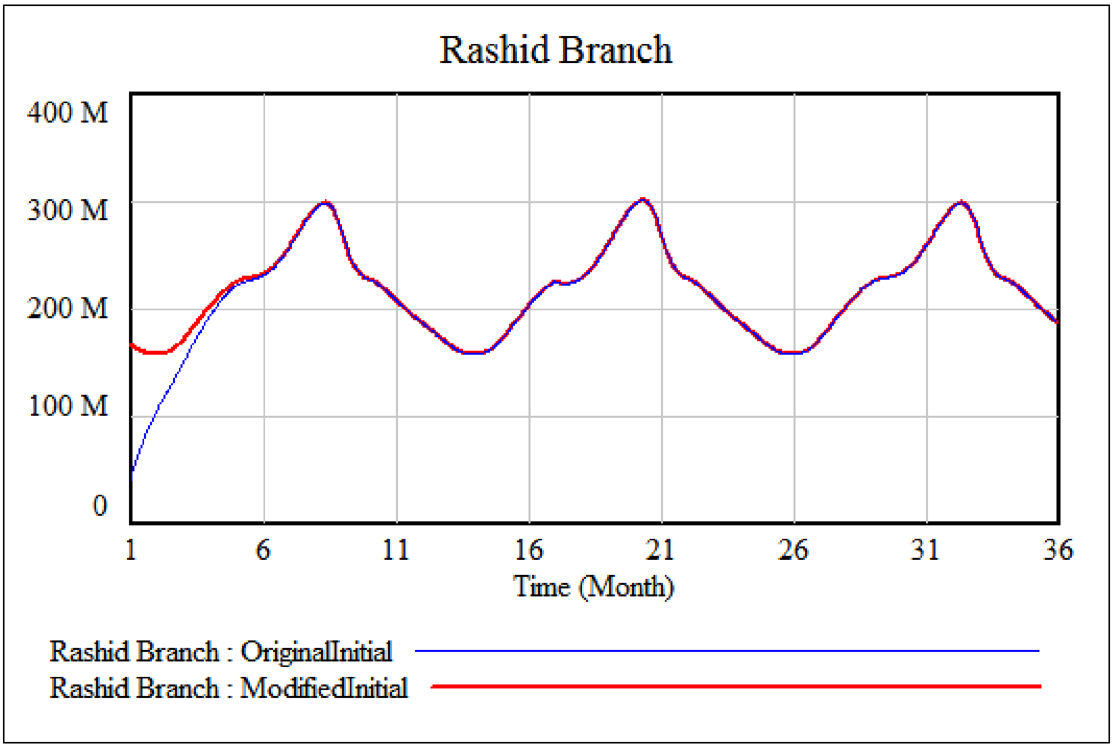


Figure 6-61: The behaviour of the Rashid Branch.

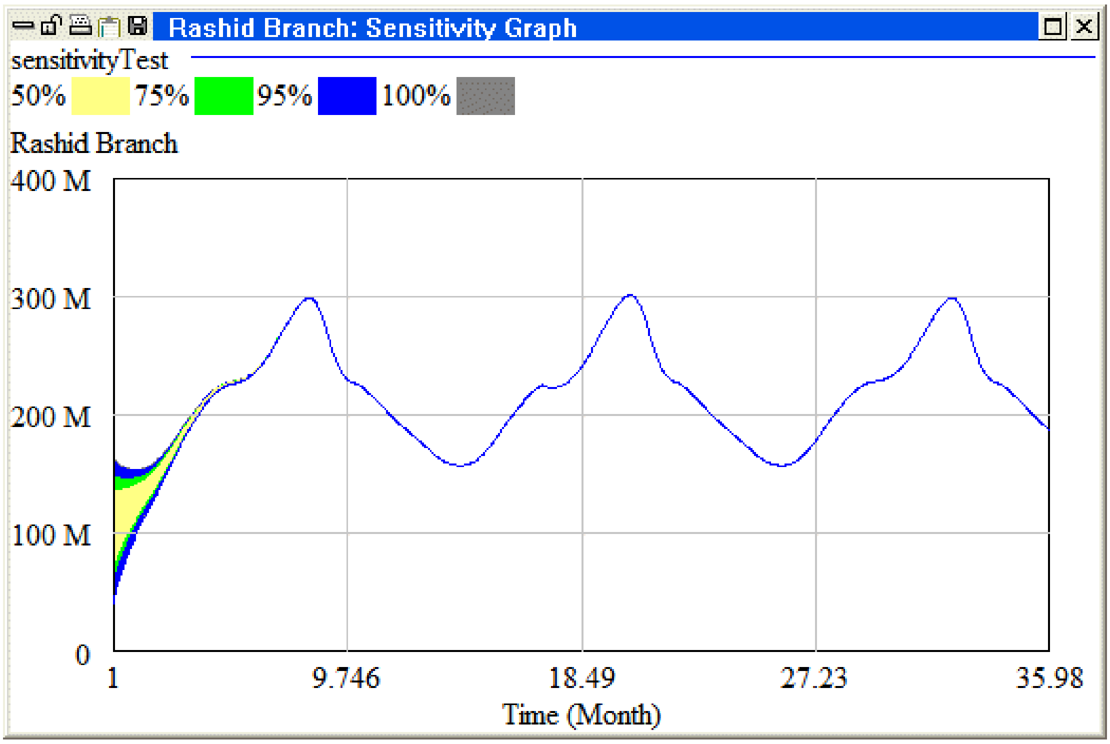


Figure 6-62: The sensitivity graph for the Rashid Branch

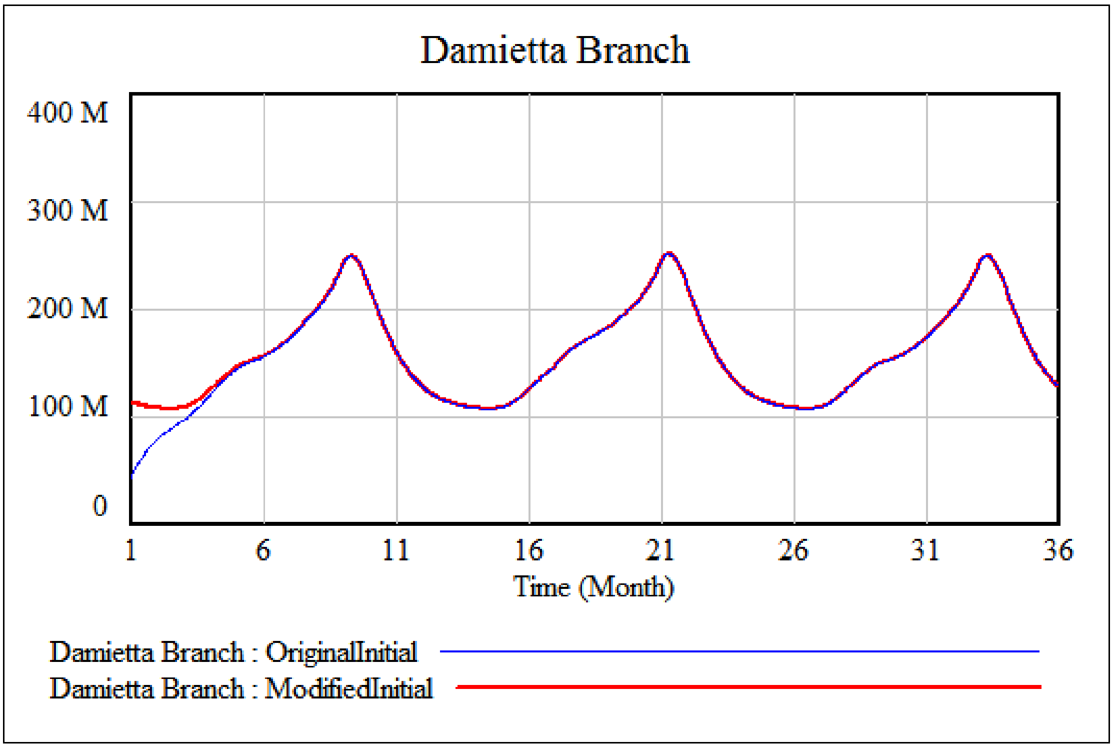
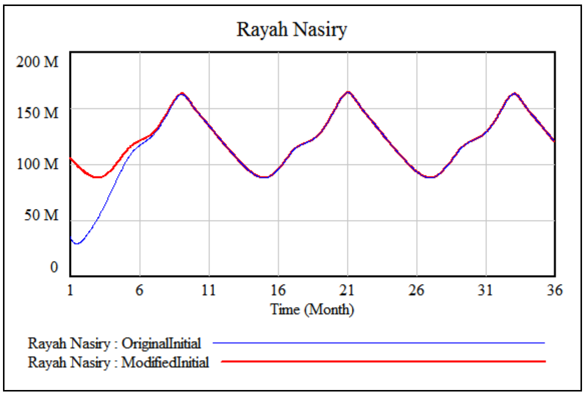
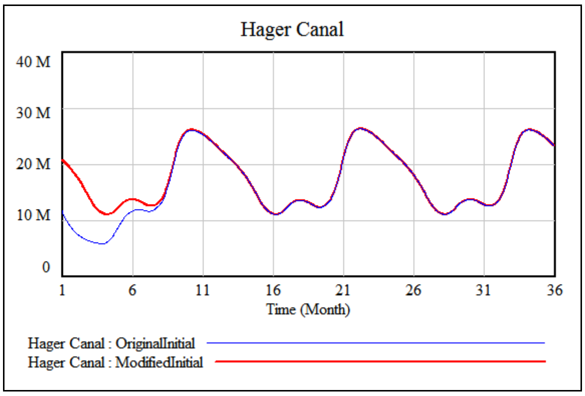


Figure 6-63: The behaviour of the Damietta Branch.

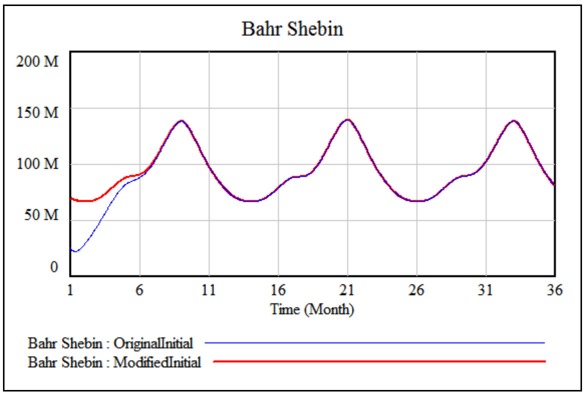
The rest of the canals in the model have shown a similar behaviour. Figure 6-64 shows some selected graphs illustrating the behaviour of some canals at the second and the third level at the three Delta zones. For example, graphs (a) and (b) show the Rayah Nasiry at the second level and the Hager Canal at the third level at the West of the Delta, respectively. Graphs (c) and (d) show the Bahr Shebin at the second level and the Kased Canal at the third level at the Middle of the Delta respectively, while graphs (e) and (f) show the Mansorya Canal and Bahr Muways at the second and the third level at the East of the Delta. As a general observation, changing the initial values have affected the behaviour of the canals at the second level only during the first seven months (transient state) and then the behaviour stabilized, while in the third level canals the behaviour have been affected during the first eight months and after that the behaviour of the canals has stabilized. We concluded that the model is *insensitive* to the initial conditions (i.e., the initial values of the water volume in the canals). In fact, this is very significant because it indicates the quality of the model. In other words, the model is robust and has successfully reflected the real structure of the irrigation system accurately. The behaviour of the model repeats the same cycles after one year, which is relatively a short period of time. Indeed, Egypt with nearly 5000 years of agriculture and irrigation practices, it was expected that the behaviour of the irrigation system is very stable and is not vulnerable to sever disturbance as a result of fluctuation in water flows.



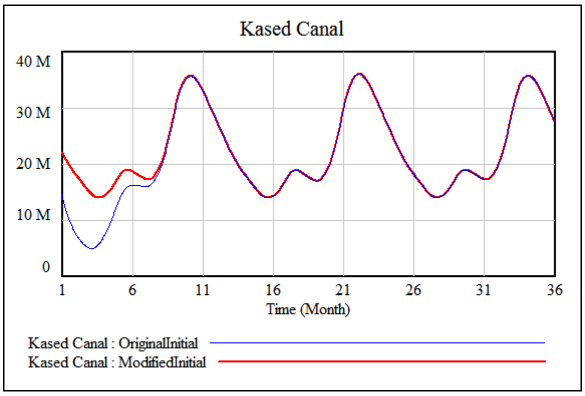
(a) The Rayah Nasiry at the 2nd level, WoD.



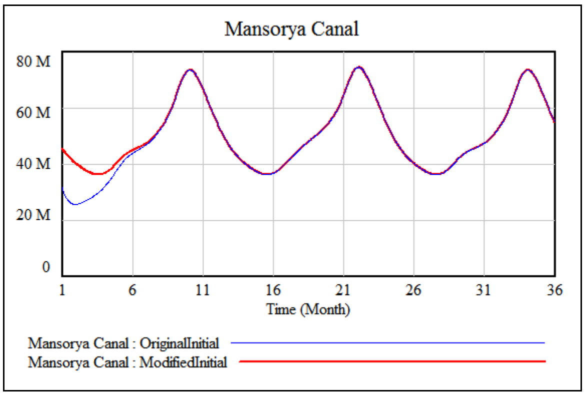
(b) The Hager Canal at 3rd level, WoD



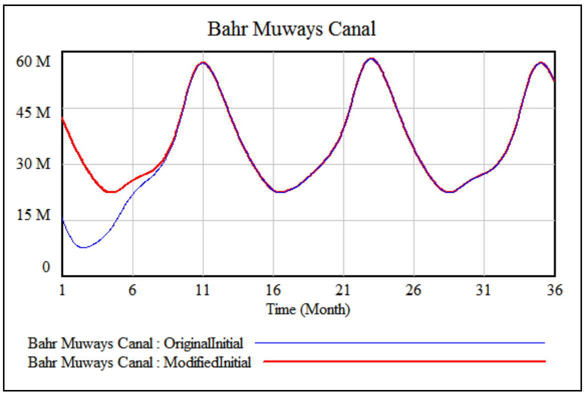
(c) The Bahr Shebin at the 2nd level, MoD



(d) The Kased Canal at 3rd level, MoD



(e) The Mansorya Canal at 2nd level, EoD



(f) The Bahr Muways at 3rd level, EoD

Figure 6-64: The behaviour of the canals at 2nd and 3rd levels in the three Delta zones.

6.4.1 Testing the control gates sliders

In this run, we chose to start the simulation by closing the main gate of the High Dam. The aim is to test the performance of the application and to observe the behaviour of the system under this extreme condition. As we anticipated, the water supply dropped dramatically and most of the canals ran dry in a very short period of time. Figure 6-65 shows the canals' status at the beginning of the simulation. Obviously, there are many canals that appear with green colour indicating the low level of the water volumes in these canals.

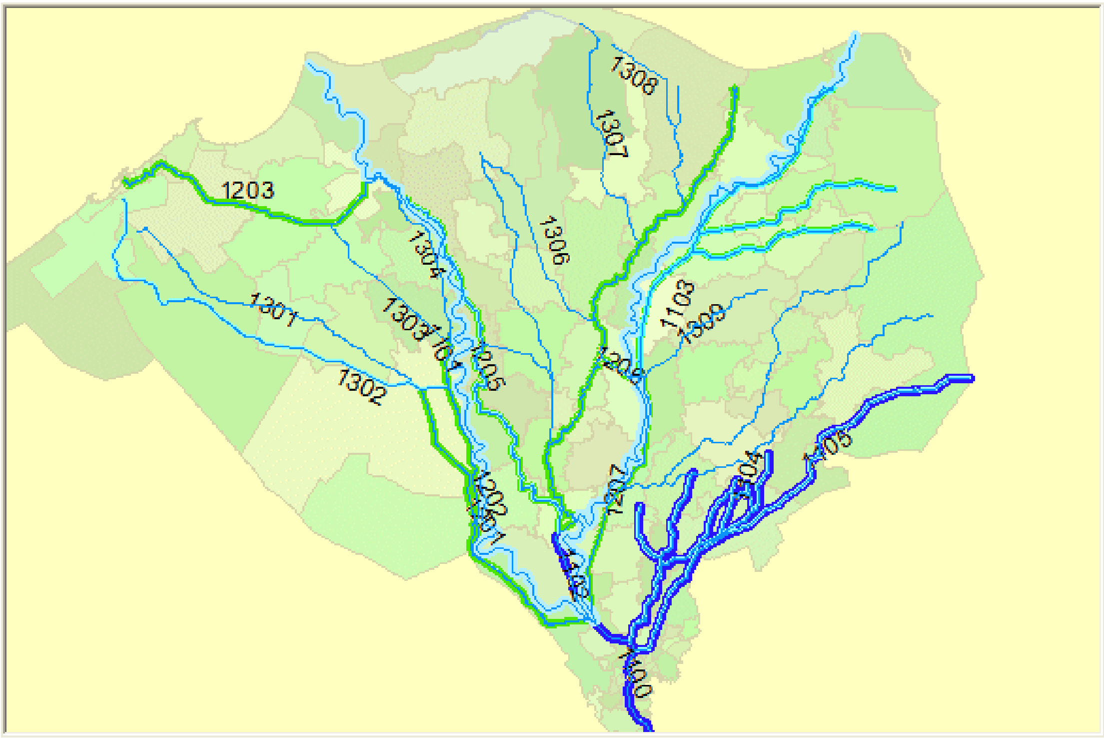
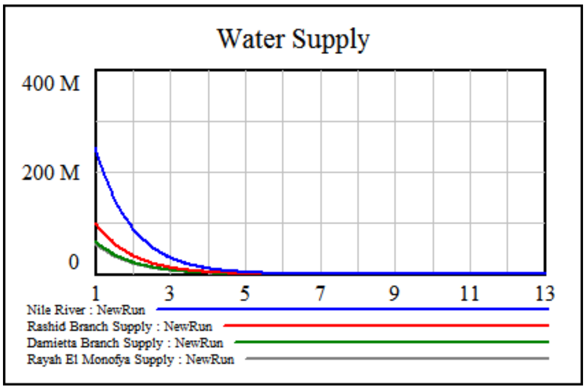
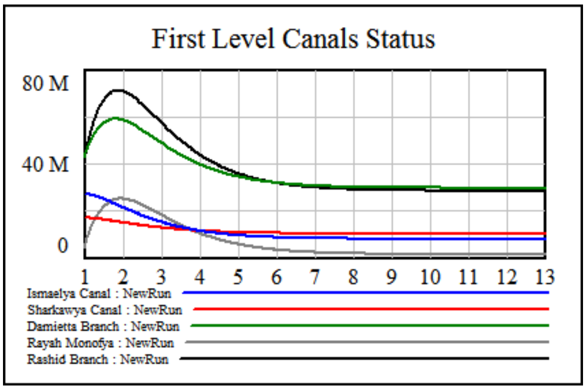


Figure 6-65: the state of the canals with main control gate closed.

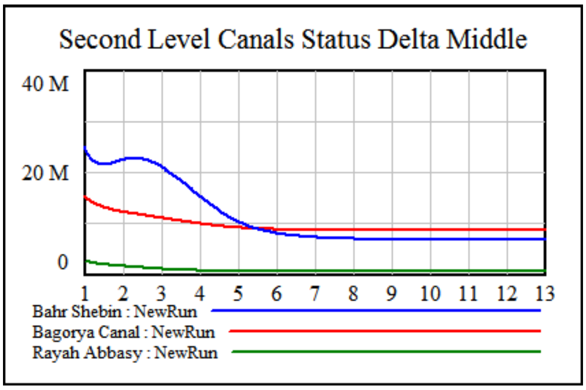
Figure 6-66 shows that: (a) the water supply from the Nile continued to run for five months before it drops to zero. This is because the Nile initially had a large volume of water that continued to drain to the first level canal. (b) The first level canals, in particular the Rashid and Damietta branches, continued to supply the second level canals and, for this reason, the second level canals appeared to receive water during the period from the mid of the first month to the end of the second month (as shown in c), while the third level canals, that drain to the sea, drop dramatically and almost run out of water by the end of the third month as shown in d. This example has demonstrated the effect that closing the main control gate has on the behaviour of the system. Obviously, there are unlimited number of scenarios that can be developed using the 25 gates for the purposes of the adjustment of water supply with the demand and the water conservation at large.



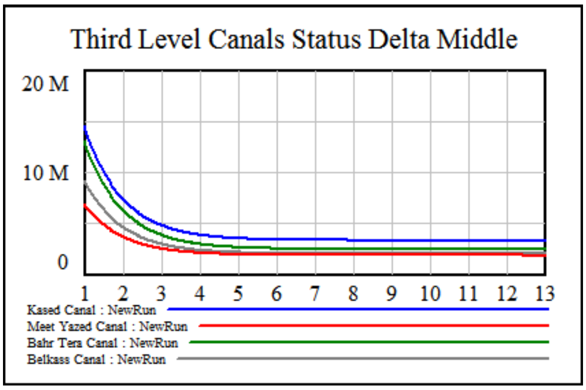
(a) The water supply



(b) The state of the first level canals



(c) The state of the second level canals



(d) The state of the third level canals

Figure 6-66: The results of the simulation with the main control gate closed.

6.4.2 The effect of changing the efficiency

In this run, the conveyance efficiency in the second level canals and the third level canals has been upgraded to 90% instead of 80% and 70%. To demonstrate the effect of improving the conveyance efficiency on the behaviour of the system, two Figures, 6-67 and 6-68, are provided to compare the results of this run with the results of the *Base Run*.

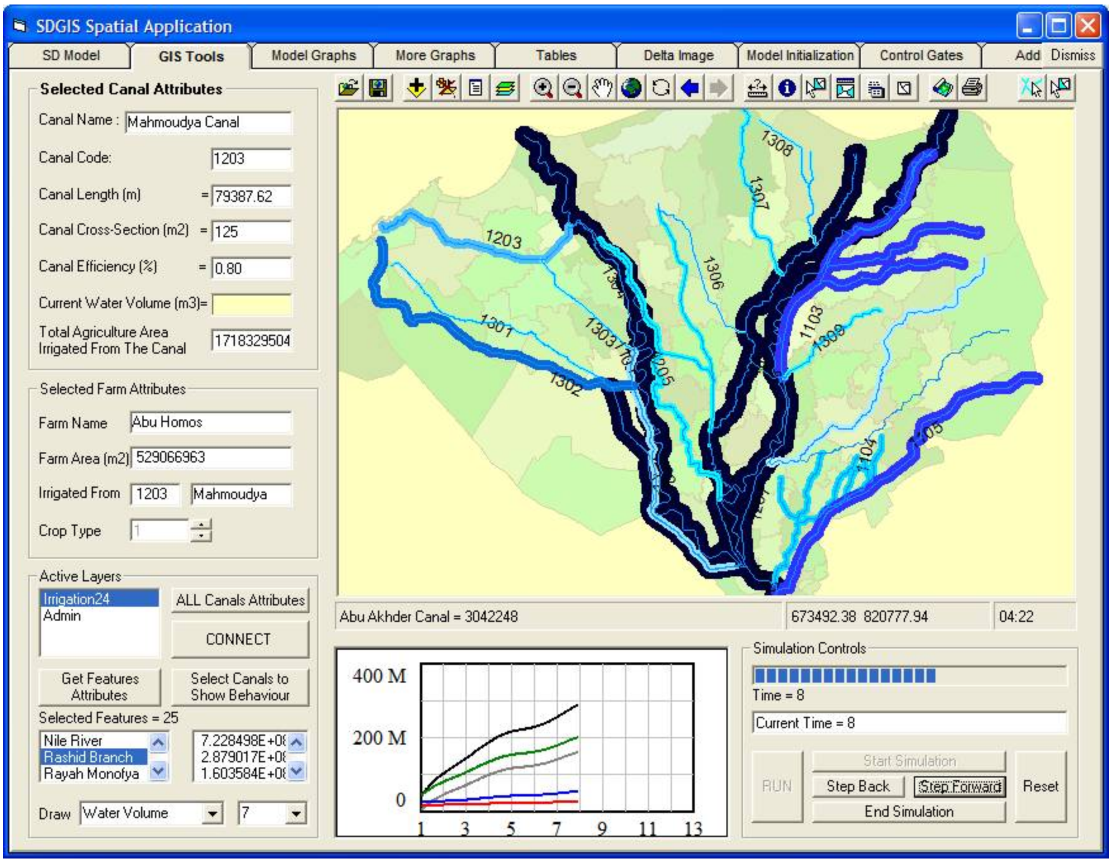


Figure 6-67: The behaviour of the system without applying efficiency improvements

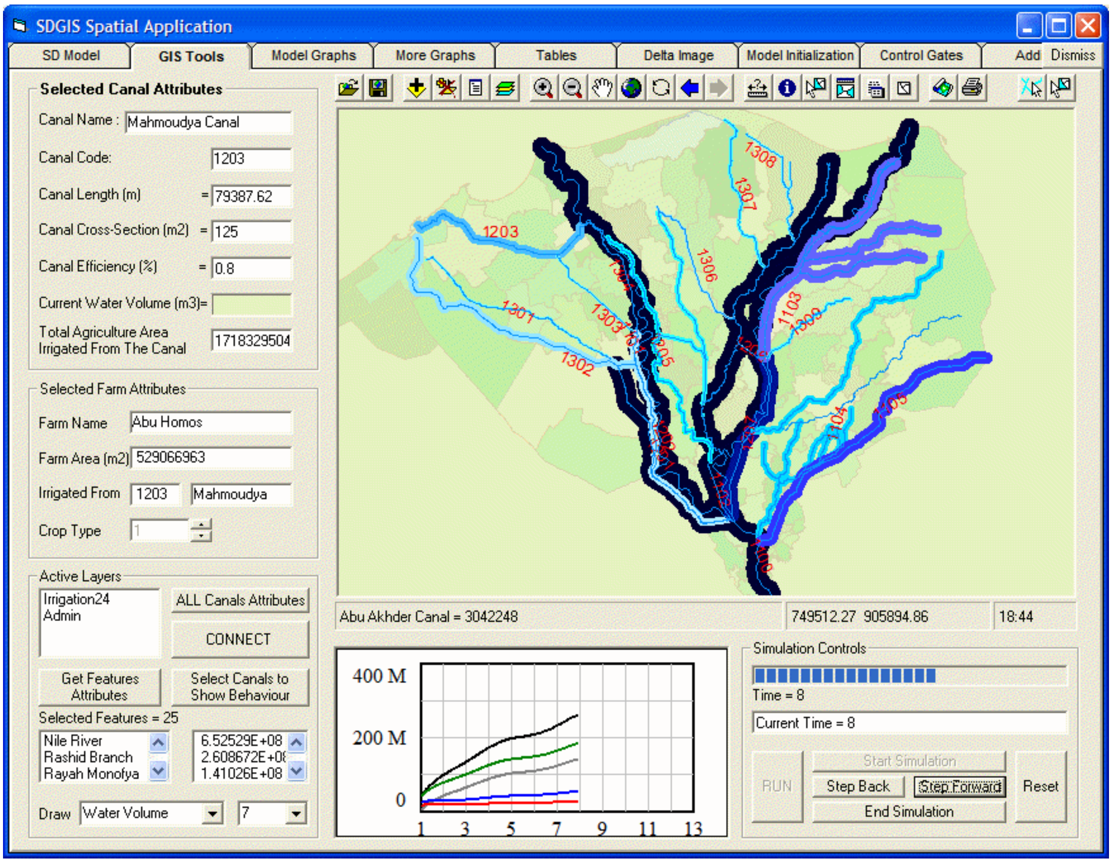
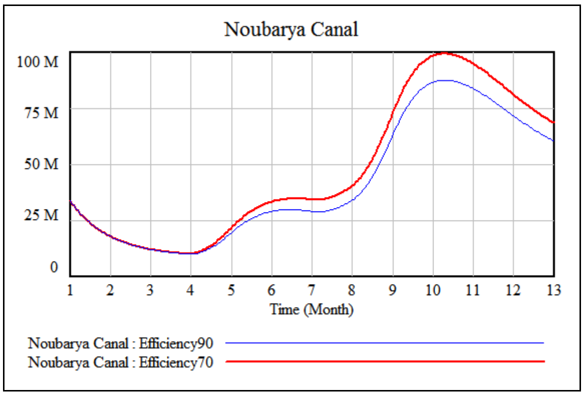
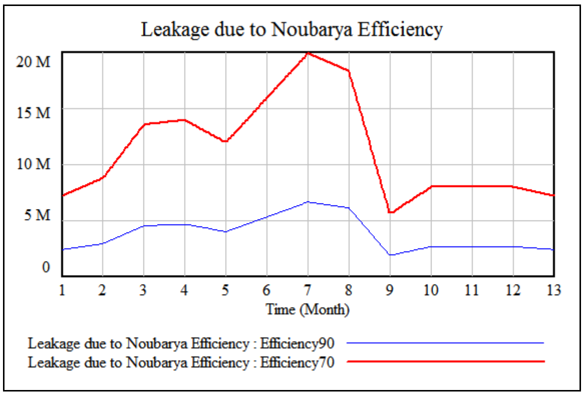


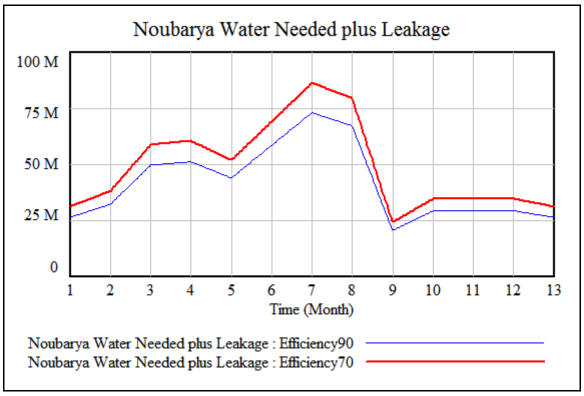
Figure 6-68: The behaviour of the system with applying Efficiency improvements.



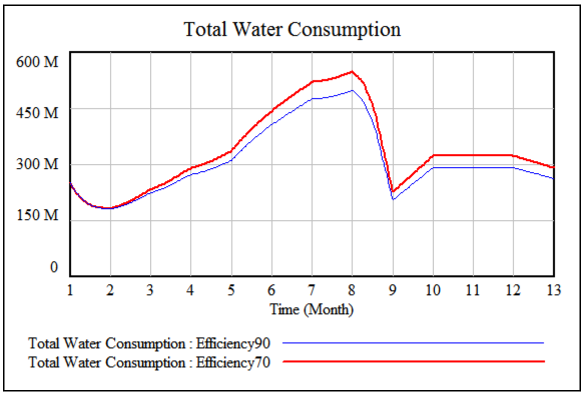
(a) The change in Noubarya canal status



(b) The difference in the canal leakage



(c) The difference in the water demand



(d) The difference in water consumption

Figure 6-69: A selected graphs to demonstrate the effect of the efficiency upgrading.

In the above figure, the Noubarya canal at the third level at West of the Delta has been selected to demonstrate the change in the behaviour of the system by improving the conveyance efficiency. Noteworthy, the water volume in the canal has decreased. This is because the leakage from the canal has been reduced and the water needed in the field is now delivered as required. The water saved by improving the efficiency decreases the gross demand which includes the water for irrigation and the water lost during conveyance. Consequently, the overall water consumption in the system has been reduced by improving the second and third level canals.

6.4.3 The effect of changing the Cropping Pattern

In the Base Run, one cropping pattern has been applied to all agriculture lands in the three Delta zones. In this run, we chose to change the cropping pattern in the Middle of the Delta to group two of crop rotation (that includes wheat, rice, and corn), and East of the Delta to group three of crop rotation (that includes beans, corn, potato, and tomato). The cropping pattern in West of the Delta remained unchanged (the group one of crop rotation). The aim is to demonstrate the effect of changing the cropping pattern on the behaviour of the system. Note that there are 25 agriculture areas associated with the canals in the model. The application enables the user to assign various cropping patterns for each agriculture land. However, for the purpose of this test, in this example we simply changed the cropping patterns at the level of the three geographical zones and did not proceed to a more detailed level.

Figure 6-70 shows the behaviour of the system in the *Base Run* (i.e., at Time = 10, with one cropping pattern assigned for all zones) while Figure 6-71 shows the behaviour of the system in this run (at Time = 10, with the newly assigned cropping pattern). The difference in the canals' status can be seen in the Middle and East of Delta, and particularly, in the second and third level canals. Figure 6-72 includes a series of graphs that demonstrate the change in the state of some selected canals between the two runs. For example: (a) the water volume in Rayah Monofya *1102* at the first level at the Middle of the Delta, has generally decreased, particularly in the last quarter of the year, indicating that cropping pattern group 2 consumes less water. (b) On the contrary, the water volume in the Damietta branch at the first level at the East of the Delta has increased during the last quarter of the year. (c) A similar development took place in the second and third level canals (graphs c and d). This indicates that the cropping pattern group 3 consumes more water. As a general observation, the total water demand (shown in graph e) has remained the same during the two runs. This is also true for the total water consumption (shown in graph f). However, there is a shift in the timing of the peak and drop points which is very significant considering the water availability at these times.

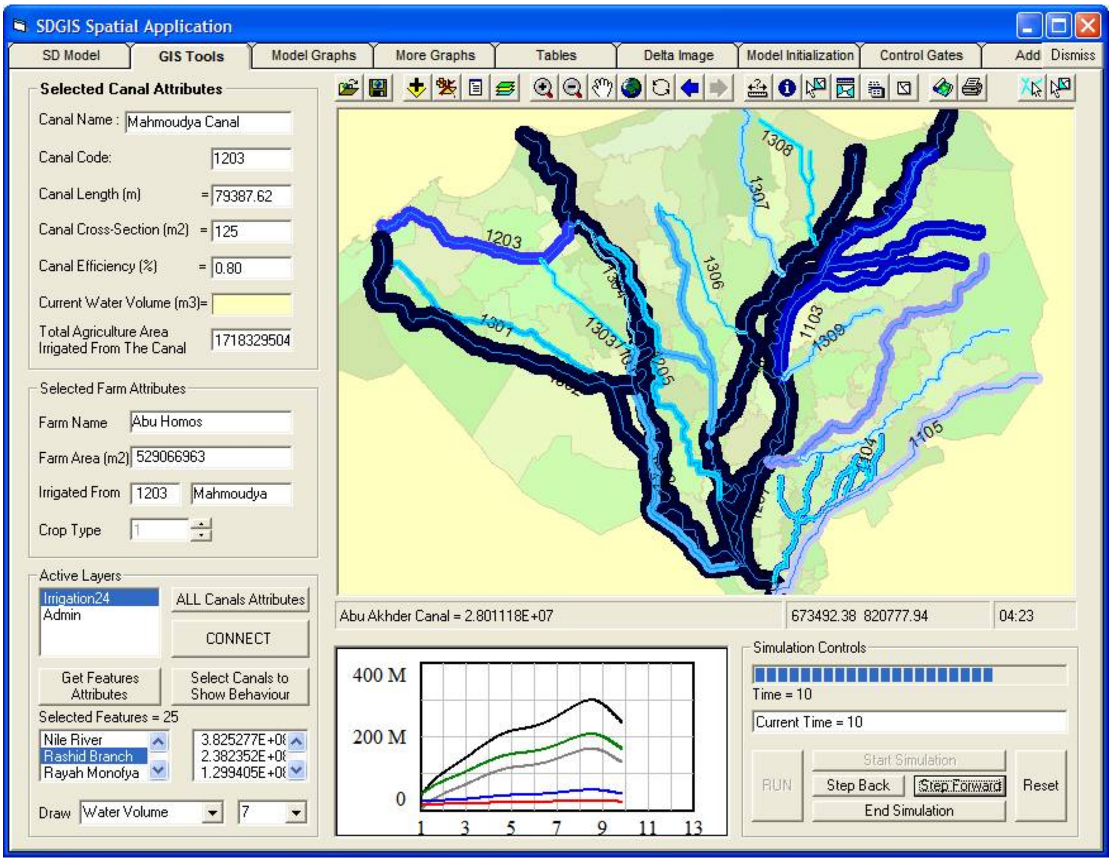


Figure 6-70: Same cropping pattern one in all areas.

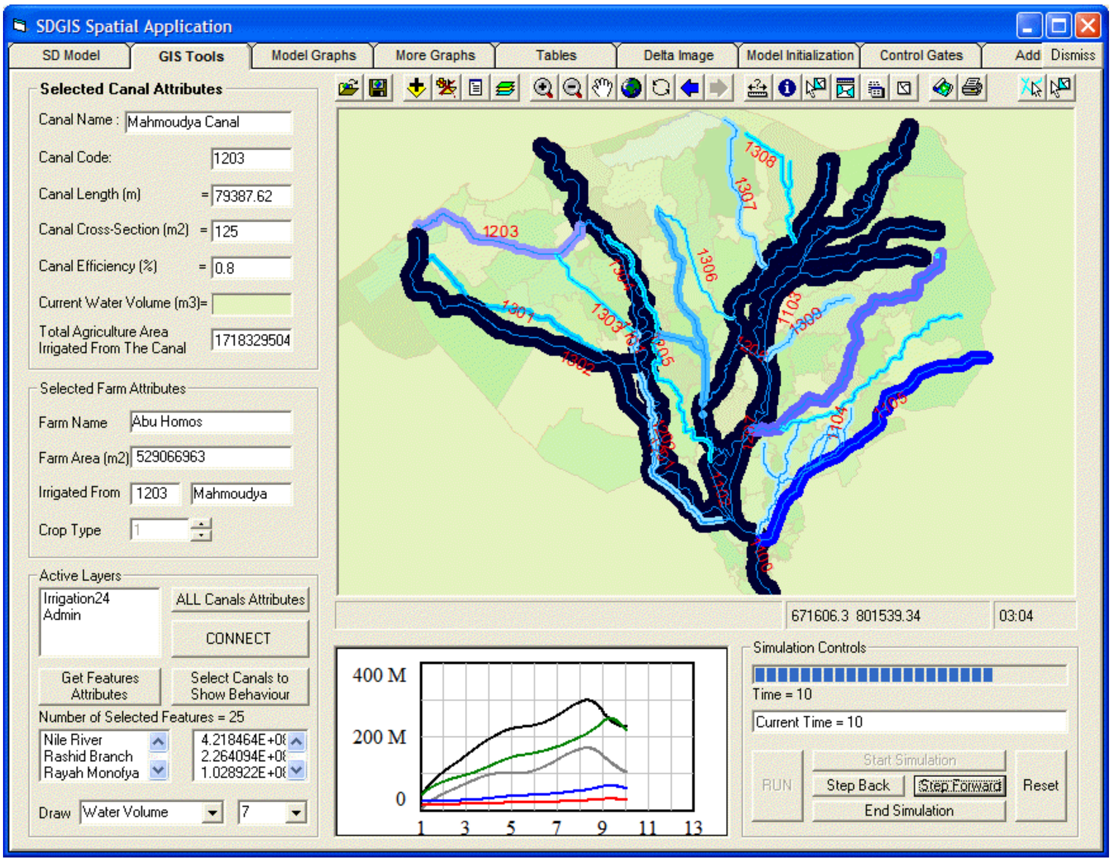
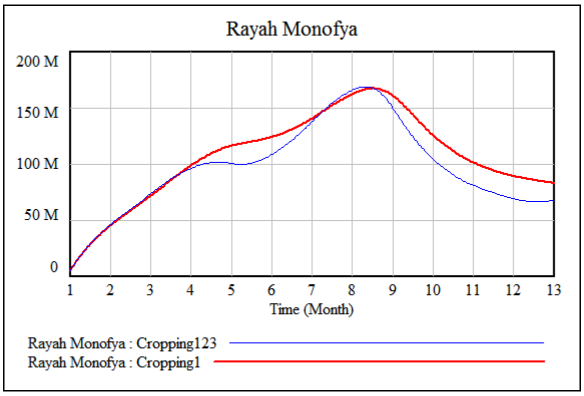
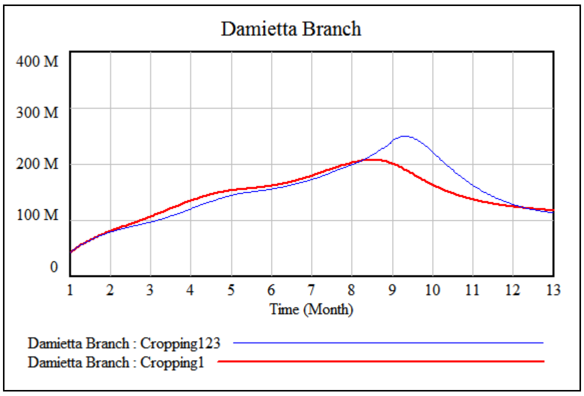


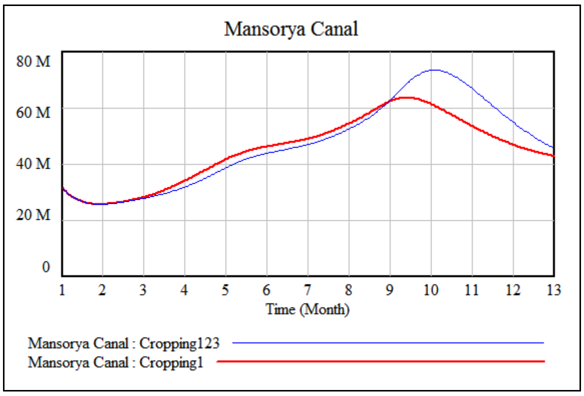
Figure 6-71: Cropping pattern 1 in the west, 2 in the middle, and 3 in the east.



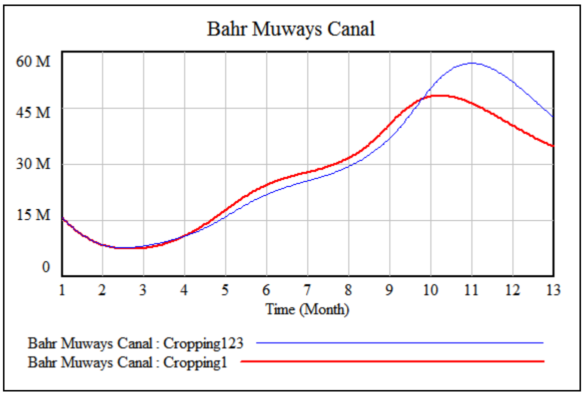
(a) First level canal at Middle of Delta



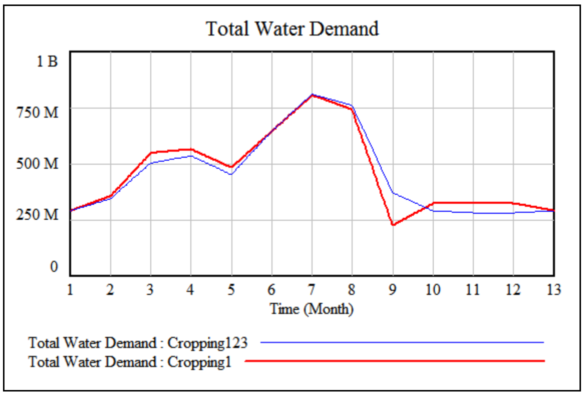
(b) First level canal at East of Delta



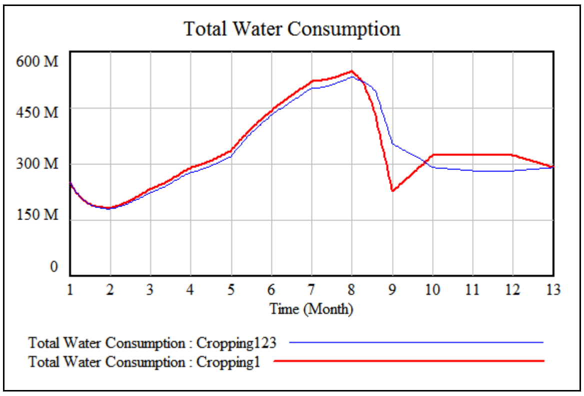
(c) Second level canal at East of Delta



(d) Third level canal at East of Delta



(e) Total water demand in Delta zones.



(f) Water consumption in Delta zones.

Figure 6-72: Changing the cropping pattern in Middle and East of Delta.

6.5 Conclusion

Water is a finite resource and is essential for agriculture, industry, and human existence. In arid and semi-arid countries, such as Egypt, the water resources are quite limited. The challenges for achieving the highest possible water use efficiency are particularly significant. It is important to save and conserve water while providing necessary quantities to satisfy irrigation as well as domestic and industry requirements. However, due to the increase in population and associated rise in the standards of living and human social and economic activities, the demands on water are significantly intensifying.

The water resources in Egypt are for all practical purposes limited to the Nile River. The average annual yield of the Nile is estimated at 84 BCM at Aswan. The discharge of the Nile is subject to wide seasonal variation. Egypt's annual share of the river water is determined as 55.5 BCM. Egypt's water requirements is increasing over time due to the increasing population and the associated food security issues, as well as the government policy to reclaim new lands and expand the agriculture areas that accommodate half of the population and absorbs the 50% of the labour force. The cultivated and cropped areas have been increasing over the past few years and will continue to increase due to the increase in food demands. The irrigation system and its performance has been the focal point in tackling the water scarcity problem. The Egyptian irrigation system is tremendous in size and complexity. Throughout this system, about 59 BCM of water are distributed annually, not only for cultivated land, but also for municipal and industrial use, and for the navigation purposes. In the future, irrigation water, which is the absolutely crucial part of Egypt's agriculture, has to satisfy demands of even larger population. Given the water determined quota, water saving and conservation is the only option available to confront the potential water shortages.

The system dynamics approach and the spatial analysis capabilities associated with GIS have been used to illustrate the dynamic interactions between the irrigation system components and the driving forces that tend to intensify and possibly escalate the water scarcity problem. The SDGIS application developed in this research has been adapted to the irrigation system in the Nile Delta region. The associated simulation model and the GIS model have been developed and integrated into this application. The GUI of the application has been designed in a friendly way to enable the user to interact with the models and obtain better understanding to the dynamics and complexity associated with the irrigation system operation.

Several runs have been carried out to test the behaviour of the system, the operability and the performance of the application using various scenarios. The SDGIS application enables the user to emulate the irrigation system operations. The user can alter the conveyance efficiency of any distributor canal, assign different cropping patterns to various agriculture lands, and alter the control gates to regulate the water flow or redirect the flows in the network. Thus, experiments with new scenarios or planned policies to the irrigation system can be assessed using the application.

In the next chapter, we demonstrate the capabilities of the SDGIS application through illustrative examples for employing the SDGIS as: (i) an interactive learning environment for the educational purpose of explaining the complex irrigation system behaviour and management to non-technical individuals; (ii) an optimization tool for the irrigation network and the agriculture lands to attain the ultimate utilization of water and land resources; (iii) a spatial decision support system (SDSS) for supply, demand, and water allocation management; and as a policy assessment tool for water preservation measures.

Chapter 7

The Application of the SDGIS

Demonstrating the SDGIS Capabilities

7.1 Introduction

The aim of this chapter is to demonstrate the capabilities of the SDGIS application through illustrative examples for employing the SDGIS as: (i) an interactive learning environment for the educational purpose of explaining the complex irrigation system behaviour and management to non-technical individuals; (ii) an optimization tool for the irrigation network and the agriculture lands to attain the ultimate utilization of water and land resources; (iii) a spatial decision support system (SDSS) for supply, demand, and water allocation management, and as a policy assessment tool for water preservation measures.

This chapter includes three sections. In the first section, we provide a brief discussion concerning the SD based interactive learning environment (ILE); and an example for using the SDGIS application as an ILE. In the second section, we provide an example for a canal-performance optimization. This highlights the potentials of using the SDGIS application to perform various optimization processes regarding the irrigation system components. Although the optimization has mainly been implemented using the Vensim software (which is one of the three components that form the application), the spatial component in the SDGIS application has played a vital role in defining the target variables in the system to be optimized. In the third section, we first define the Decision Support Systems (DSS) and the Spatial DSS that is a special case of the DSS. SDSS consider the location and the spatial relationships between objects in their analysis. We highlight the relationship between the GIS and the DSS and discuss the arguments claim that GIS is a DSS. This greatly helps in evaluating the SDGIS application as a true SDSS. Second, we illustrate some examples for using the SDGIS application in decision making process and the assessment of water preservation policies. The section also includes a valuable dissection regarding the water scarcity problem, the water preservation policies recognized worldwide, and the suitability and feasibility of applying such policies in case of Egypt. Four water preservation policies have been chosen to be evaluated using the SDGIS application. These policies are:

1. Improving the conveyance efficiency of the irrigation network to reduce the quantity of water lost in canals during the delivery process that currently amounted for 10 BCM annually as stated by [Imam, 2003 cited by Malashkhia, 2003] and in particular, between the main canals and the outlets and between the outlets and the fields.

2. Adjusting the water supply and demand to closely match each other (i.e. to deliver the right quantity of water at the right time and save water in harvest seasons with less water demand).

3. To apply cropping pattern optimisation to maximise the benefits of water utilisation (e.g., to minimize planting of water thirsty crops and maximise the areas of high value crops that magnifies the agriculture share in GDP).

4. To apply water pricing policies, if necessary, to avoid sending a wrong massage to the farmers and consumers by affording free water, and use these charges to maintain and improve the operation of the irrigation system.

It is worth noticing that in most cases applying a single policy is not enough to successfully achieve the ultimate goal. We typically need to combine two or more policies to achieve our goals. For example, upgrading the efficiency may be coupled with a cropping pattern optimization policy for more efficient water saving achievements. The chapter is closed with a brief discussion regarding the potential benefits of utilizing the SDGIS application in water resources planning and management.

7.2 Utilizing the SDGIS as a learning tool

Computer-based simulations are important tools to support learning. In the literature, several terms have been used to describe these computer-based simulations that support learning processes. Maier and Größler (2000) analyzed some of these terms and proposed a taxonomy for computer-based simulations. They distinguished between modelling- and gaming-oriented tools. According to their taxonomy, the modelling-oriented tools included two types of models: (1) the models that are built using Vensim, Powersim, Ithink or DYNAMO. These models are classified under feedback-oriented continuous simulations; (2) the models that are created with Taylor or Simple++, and they are classified as discrete, process-oriented simulations. Maier and Größler stated that "The main goals of feedback-oriented continuous simulations are learning, problem solving and gaining insights. Their usefulness and their efficacy in achieving these goals are virtually undoubted within the system dynamics community. In contrast, the aim of process-oriented discrete simulation environments is mainly to optimize process layouts and visualize the behaviour of the system processes under consideration. Their main real world domain is business, especially manufacturing and logistic processes". Obviously, the first type of models mentioned above is system dynamics models. Davidsen (1996) offers a summary of important educational features of system dynamics.

In the system dynamics community, one term that is used to describe such simulators designed for learning purposes is "Interactive Learning Environment" (ILE). Maier and Größler argued that this term usually contains more than a pure computer simulation model. One or more simulation models are embedded into the learning environment, which may also include background information, source material and working instructions integrated into a single computer application (See for example [Paich and Sterman, 1993]). The term "system dynamics based interactive learning environment" makes clear that the simulation model is a central part of such learning tools (see [Davidsen and Spector, 1997]). Maier and Größler concluded that an interactive learning environment is a computer-based simulation with additional components. These components are assumed to be necessary for its effectiveness [Spector and Davidsen, 1997]. A summary of Maier and Größler's taxonomy is portrayed in Figure 7-1.

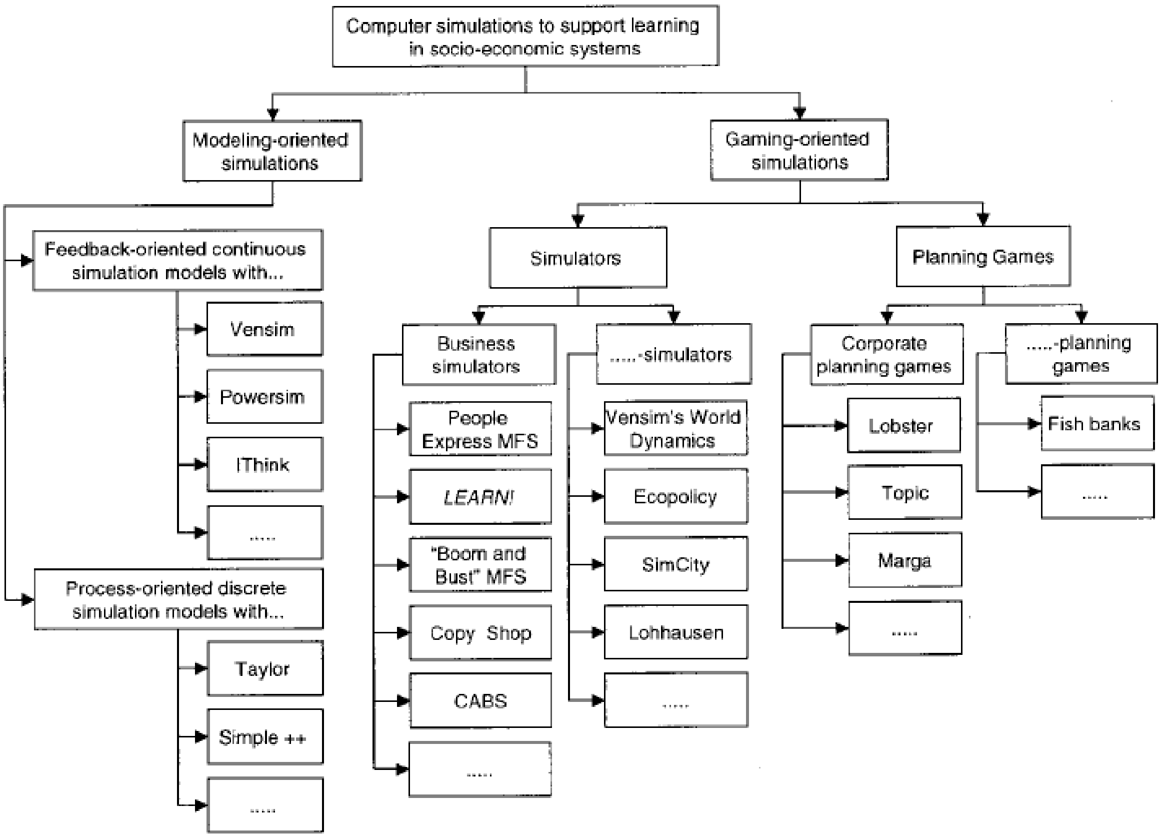


Figure 7-1: Taxonomy of computer simulations to support learning processes in socioeconomic systems.
Source: Maier and Größler (2000).

Davidsen (2000) further explained the kind of learning that occurs by using these ILEs. He distinguished between two kinds of purposes for using ILEs: learning and research validation. Davidsen stated that "learning is to influence the formation of mental models governing human decision making and action in complex, dynamic domains. The learning takes place in the form of the dissemination of the insight originally gained by the researchers or in the form of the development of new knowledge". While "the purpose of ILE based research and validation is to identify the mental models governing human decision making and action in complex, dynamic domains". Davidsen concluded that "we are using ILEs to find out what kind of information is being used and how that information is being applied when people make decisions and take action. Having done so, we may form hypotheses as to why people fail to succeed when operating in such domains”.

In this context, the SDGIS application can be described as an ILE. The SDGIS application consists of three main components; the SD simulation model, the GIS model, and the modules that include functions facilitating the integration between the two models in addition to the GUI. The SD simulation model has been built using the Vensim software (classified under software that facilitates feedback-oriented continuous simulations, see [Maier and Größler, 2000]) in a way that allows the managers and the operators of the irrigation system to test and evaluate alternative management policies. The GIS model provides information regarding the structure of the irrigation network, the spatial location of the irrigation system components and their attributes, required to undertake this management task. The modules of the SDGIS application and the GUI facilitate the connection between the SD model and the GIS model, provide several features (i.e., control objects) to receive the user’s inputs and to execute the simulation under the user’s control, and provide significant supplementary information such as the cropping patterns, the crop-water demand, the pattern of water releases, etc.,. Therefore, we can say, with confidence, that the SDGIS application is an Interactive Learning Environment that comprises background and supplementary information, source materials (e.g., maps, canal attributes), and working instructions (e.g., how to connect the models and display the results using different colour ramps and line thicknesses) integrated into a single computer application.

The SDGIS application, as an ILE, provides the potentials for teaching and training the irrigation system operators and managers to understand the dynamics of the system, e.g. including the delays, and how the performance of their portion of the system is affected by or affect other portions of the system. For example, let us consider the situation where we have three teams representing the operators in the three Delta zones (East, Middle, and West of the Delta). The operators in the East and the Middle of the Delta have chosen to close the control gates in their portions of the system at the beginning of the simulation. Naturally, the water flow will divert towards the canals at the West part of the Delta. The operators in this portion will face a situation where an extra flow of water is approaching. They may become aware of such a situation in the early stages if the facilitator chooses to inform them about it or allowed for communication between the operators. But if the facilitator, for example, chooses not to allow for such a coordination and decided that the three teams must work separately, they may not realize the situation arising from the water redistribution before the simulation has reached Time = 5. Whether informed or not, the managers of the irrigation system at the West part of the Delta must develop plans to confront the overflow and increase the benefits from the extra water they receive by allocating this water in areas that suffer from water shortages.

The scenario described here has been simulated and the output maps and graphs have been compared with the Base-Run. Figures 7-2 (a) and (b) show the state of the canals at West of the Delta at the Time = 4 with closed control gates at East and Middle of the Delta, and in the Base-Run respectively. Both figures, to some extend, look similar although the Noubarya canal *1302* appears with thicker line which indicates that it contains a larger volume of water. In Figures 7-3 (a) and (b), as the time advances (i.e., Time = 8) canals such as the Mahmoudya *1203* and the Noubarya *1302* appear to approach to their maximum capacity, while the water volumes in canals such as the Hager canal *1301* and the Khandak canal *1303* have significantly increased compared with their status in the Base-Run.

The difference in the states of the canals becomes clear in Figures 7-4 (a) and (b) at Time = 12. The canals at the West of the Delta in the Base-Run (Figure 7-4 b) appear with lighter colours and thinner lines, while the same canals appear in Figure 7-4 (a) with darker colours and thicker lines (notice in particular the Mahmoudya canal 1203, the Hager canal 1301, and the Khandak canal 1303). This indicates the large volumes of water delivered to these canals as a result of diverting the water flow from East and Middle of the Delta to the West.

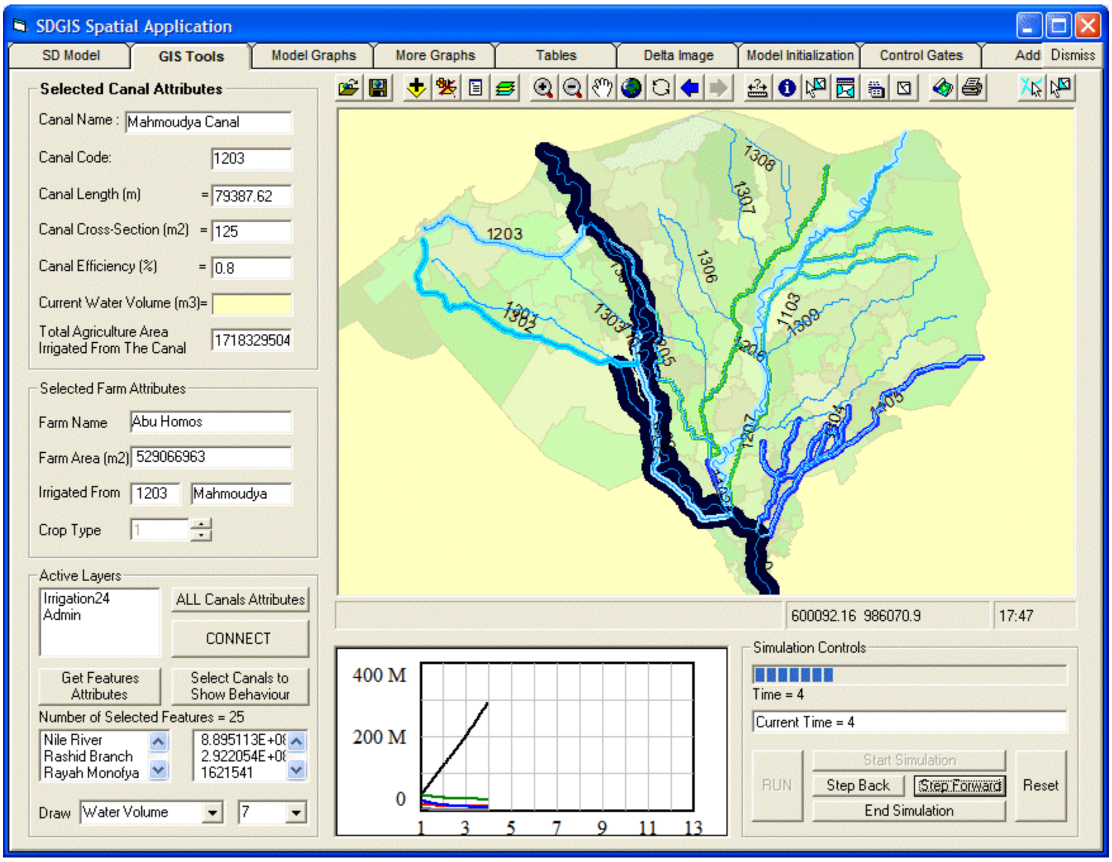


Figure 7-2 (a): The state of the canals at *WoD* at Time = 4

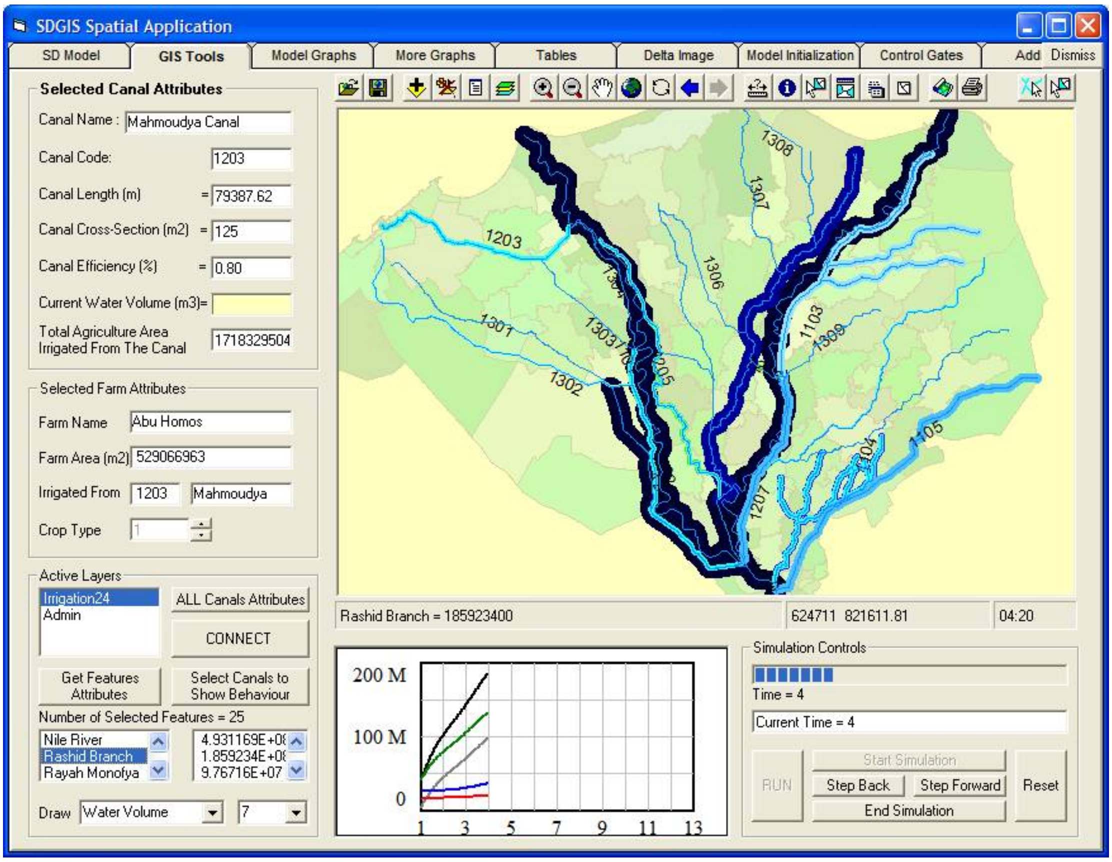


Figure 7-2 (b): The state of the canals in the Base Run at Time = 4.

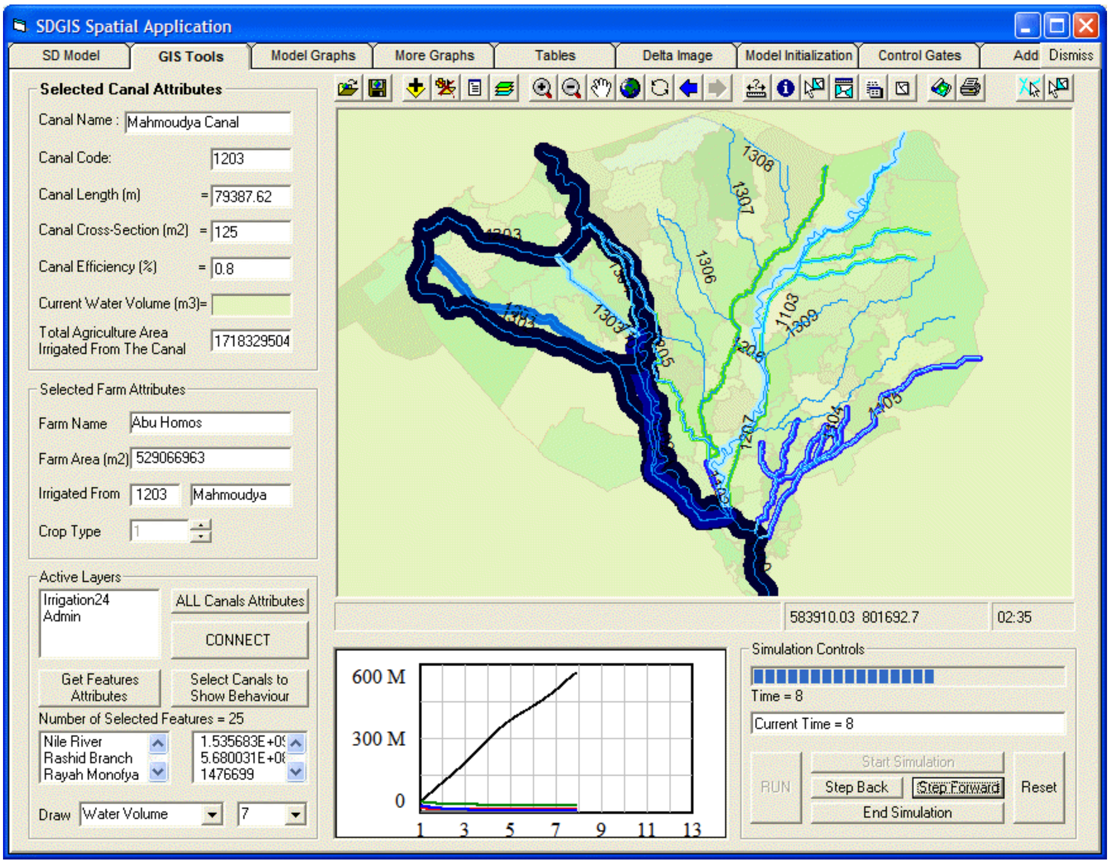


Figure 7-3 (a): The state of the canals at *WoD* at Time = 8.

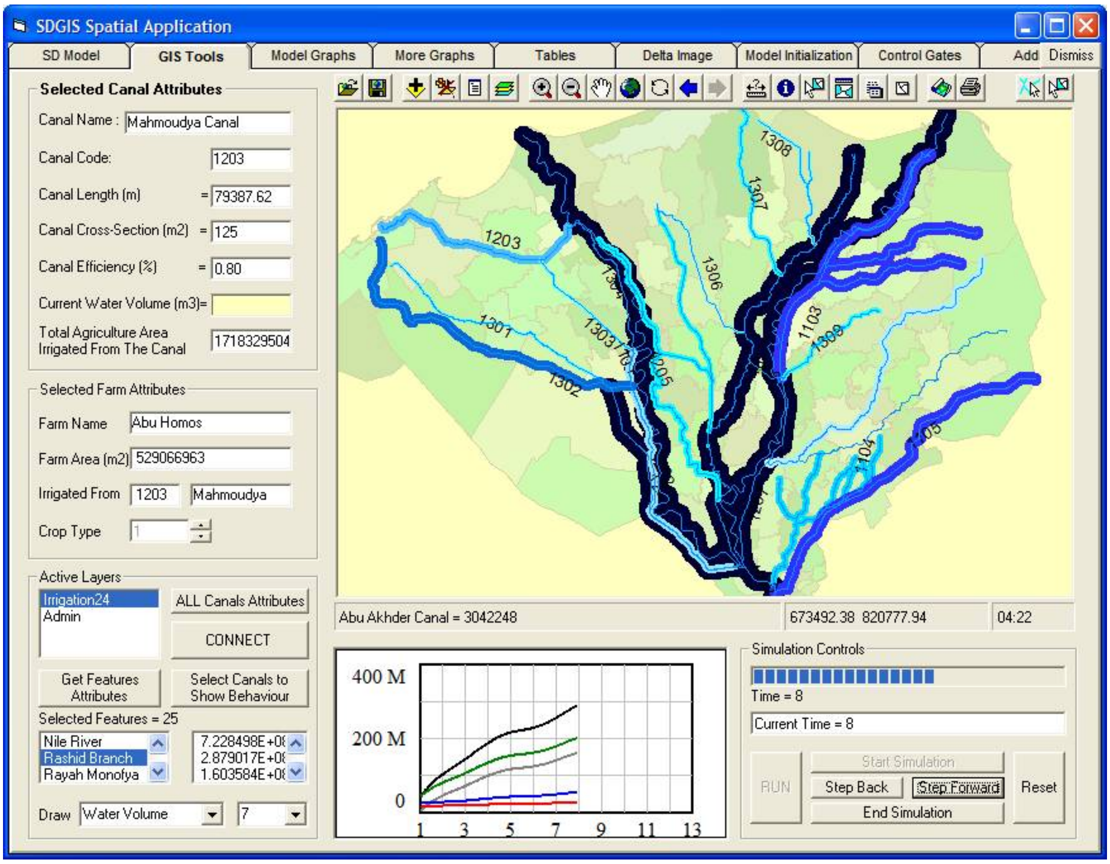


Figure 7-3 (b): The state of the canals in the Base Run at Time = 8.

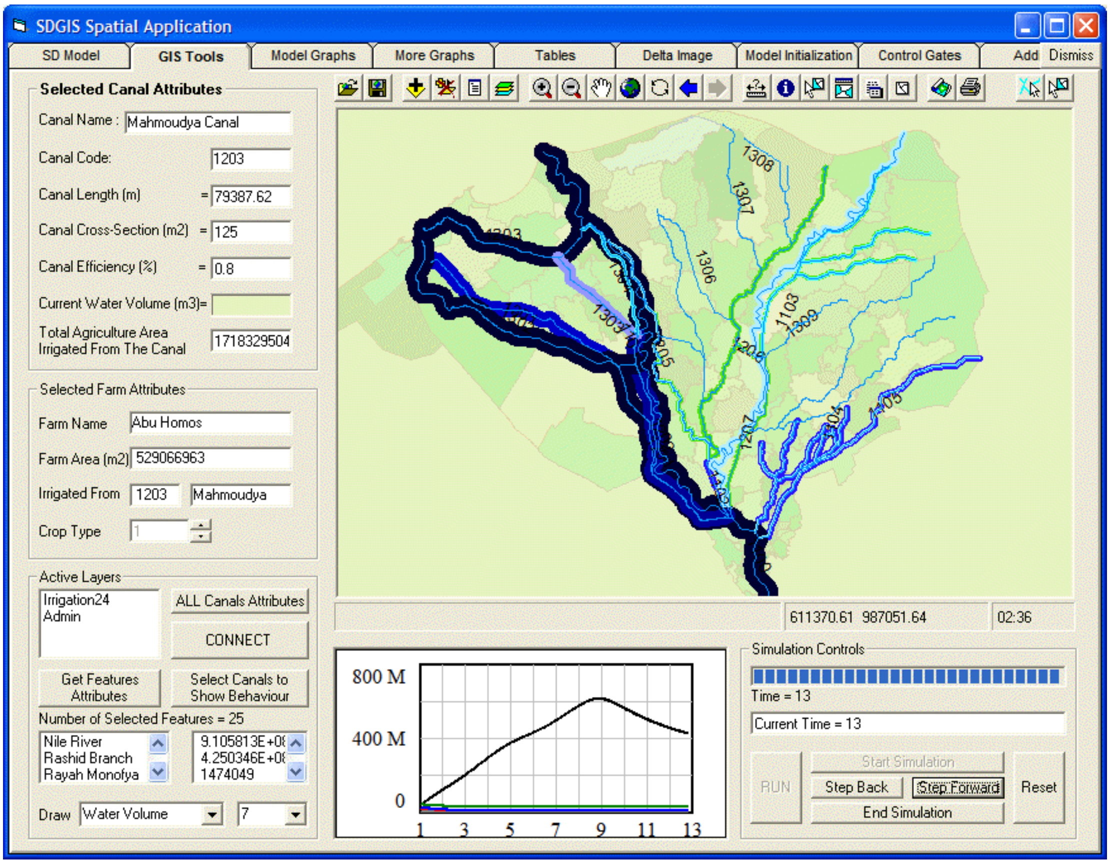


Figure 7-4 (a): The state of the canals at *WoD* at Time = 12.

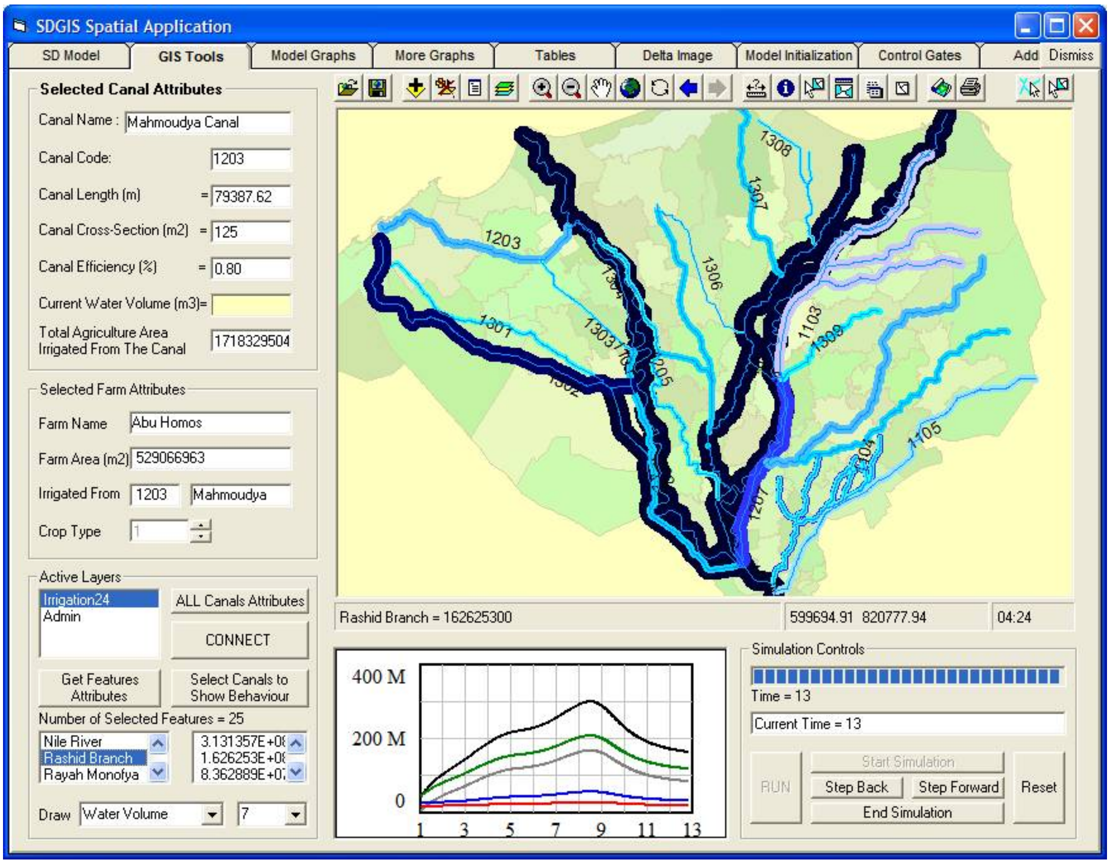
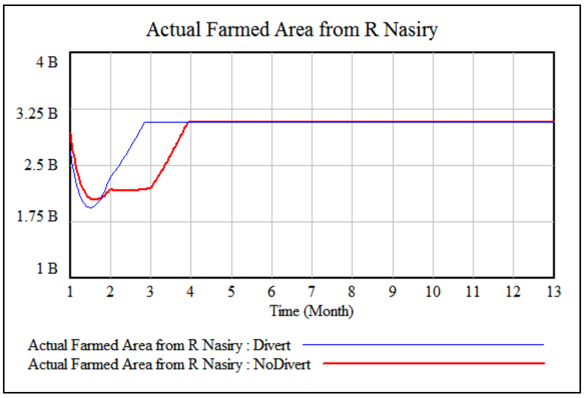


Figure 7-4 (b): The state of the canals in the Base Run at Time = 12.

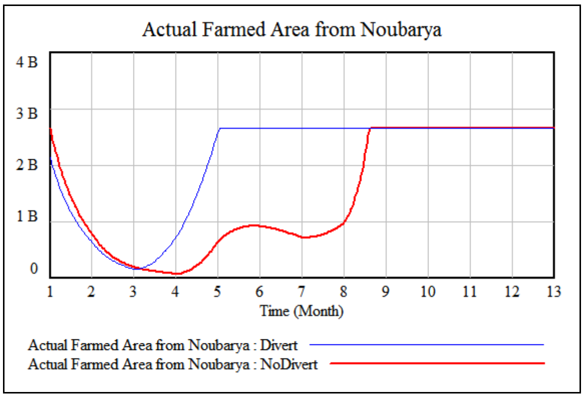
Figure 7-5 includes some selected graphs that were produced using the Vensim software to illustrate the effect of diverting water to the agriculture areas. For example, graph (a) shows the *Actual Farmed Areas* irrigated from the *Rayah Nasiry* (a second level canal at West of the Delta). In the Base-Run (appearing with red line) the land suffered some losses as a result of water shortages. These losses were eliminated by the end of the third month. However, in the Divert-Run (appearing with blue line) these losses were eliminated one month earlier (by the end of the second month). The diversion of water assisted these lands to recover faster, but has no effect after the first three months.

Graph (b) shows the *Actual Farmed Areas* irrigated from the successor canal at the third level (i.e., the Noubarya Canal). Obviously, The diversion of the water has a more significant effect on the agriculture areas irrigated from the canals at this level (the third level) than it has on those areas irrigated from the canals at the second level. The losses in the *Actual Farmed Areas* were eliminated by 3.5 months earlier. The effect of water diversion is more influential in these agriculture lands.

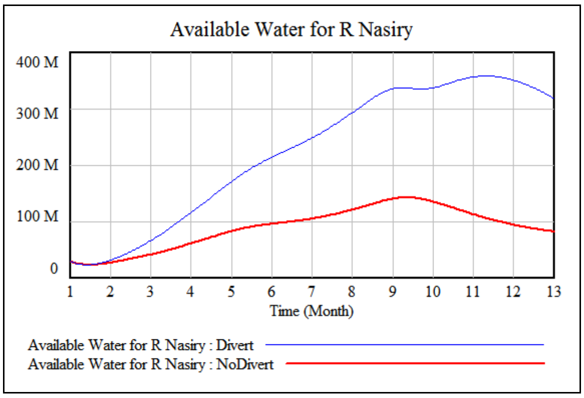
Graphs (c) and (d) show the water availability in *Rayah Nasiry* and *Noubarya Canal* respectively. The water availability reflects the situation of water diversion. In graph (c), the change in the water availability in *Rayah Nasiry*, in the Divert-Run compared with the Base-Run, started at Time = 2 and had an immediate effect on the agriculture land that has fully recovered at Time = 3 (see graph (a)). This effect has diminished after that time although the water availability continued to increase. However, this effect has extended to the successor canal (i.e., Noubarya Canal). The change in the water availability in the *Noubarya Canal* started at Time = 3 (after the agriculture lands in the second level have fully recovered) and had a more significant effect on the agriculture lands (irrigated from Noubarya Canal) that have fully recovered at Time = 5 (see graph (b)).



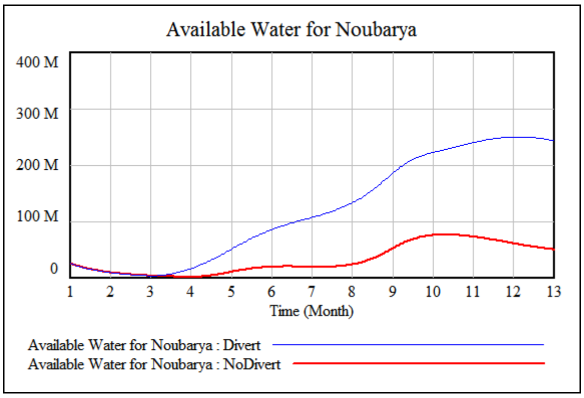
(a) - A second level canal at *WoD*



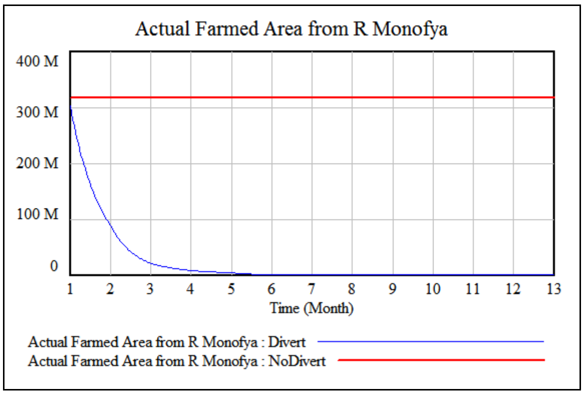
(b) - A third level canal at *WoD*.



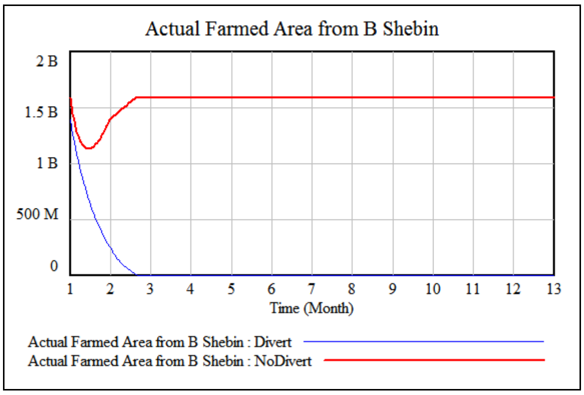
(c) - A second level canal at *WoD*.



(d) - A third level canal at *WoD*.



(e) - The first level canal at *MoD*.



(f) - The second level canal at *MoD*.

Figure 7-5: The effect of diverting water from the East and the Middle of the Delta to the West of the Delta on the agriculture lands.

Graphs (e) and (f) show the *Actual Farmed Areas* irrigated from the second and the third level canals in Middle of the Delta where the water supply has been curtailed. Not surprising, the *Actual Farmed Areas* have dropped dramatically to zero in just five months in the first level and 2.5 months in the second level.

The behaviour of the rest of the canals at the second and third levels at the West of the Delta (e.g., *Rayah Behary*, *Mahmoudya Canal*, etc.) can be studied as well. The team of operators who control all canals at the West of the Delta can collaborate to achieve the best utilization of delivered water. This can be seen as learning/support at the micro-level. On the macro-level, however, they may collaborate with the other teams of operators who control other portions of the system (i.e., the canals at the Middle and East of the Delta) and all-together can achieve the best strategy for water utilization.

This example demonstrates the potential benefits of using the SDGIS application as an ILE to support learning and training for the operators and the managers of the irrigation system to understand their part of the system in the context of the system as a whole, - through providing a virtual world and the capability to test alternative management scenarios in an inexpensive and risk free context.

7.3 Utilizing the SDGIS as an optimization tool

The reader may have noticed that, in Figure 7-5 (a, b, and f), the *Actual Farmed Areas* irrigated from some canals at the second and the third level have suffered some losses in the beginning of the simulation. Similar losses have been observed in the *Total Farmed Area* (from the entire Delta zones) even when the model has been simulated for long periods, as shown in Figure 7-6 (a) and (b), so that the possibility of interpreting this behaviour as a result of the model being sensitive to the initial conditions is excluded. To understand the cause behind such behaviour, we performed the steps described in the following paragraphs.

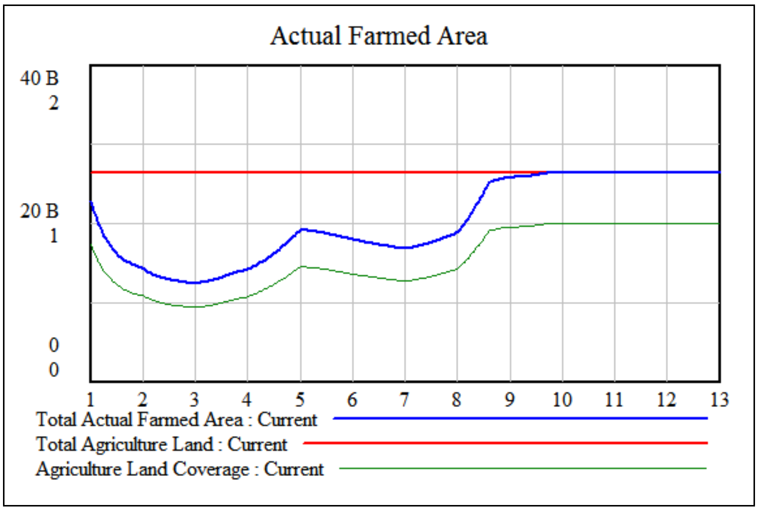


Figure 7-6 (a): The Model simulation for one year.

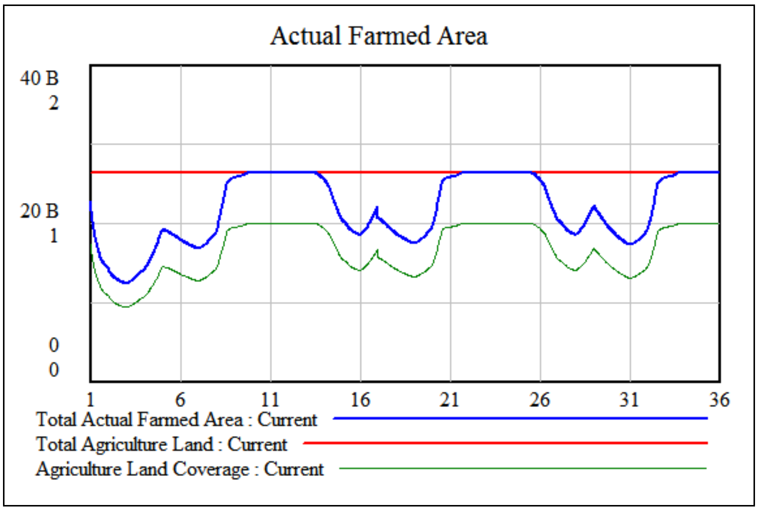


Figure 7-6 (b): The Model simulation for three years.

The unit-models that collectively form the comprehensive model have been examined individually. The variable *Actual Farmed Area* is calculated as a function of *Agriculture Area* and the *Water Coverage* in that area. The water coverage in turn is the ratio between the water available in the canal for irrigation and the water demand. Therefore, the focus is on the water coverage. Two canals at the second level, that have similar *Water Coverage* behaviour in the Base-Run as shown in Figure 7-7, have been selected to study their behaviour in more details (at micro-level). The first canal is the Mahmoudya Canal *1203* at the West of the Delta, and the second canal is the Mansorya Canal *1208* at the East of the Delta. The values of the *Water Coverage* in both canals appear to be under 100% for the first eight months of the first year and six months in the years thereafter.

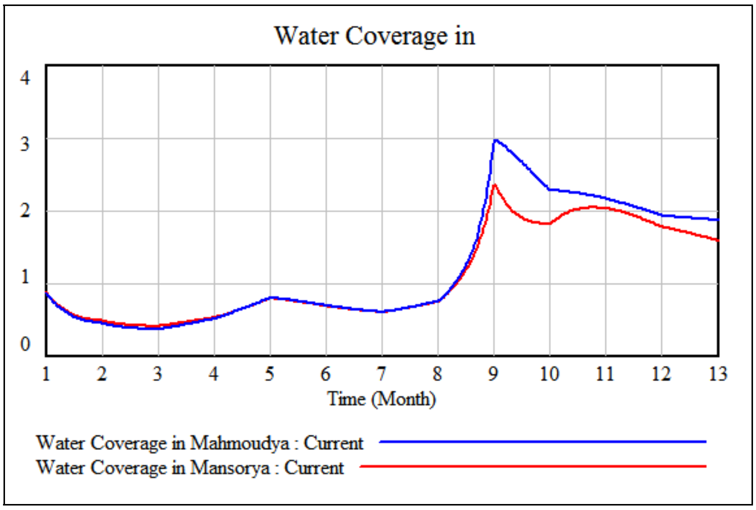


Figure 7-7 (a): Water Coverage Comparison (Base-Run).

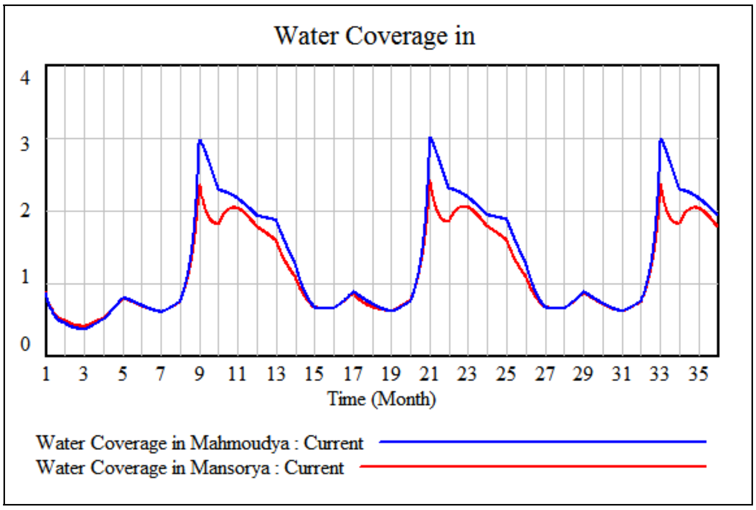


Figure 7-7 (b): Water Coverage Comparison in three years simulation.

The two unit-models have been isolated from the comprehensive model and a slight modification has been made in their structure to substitute the source of water supply from upstream, as shown in Figure 7-8. In this example, the water supply is assumed to be equal to the water demand, and therefore the value of the *Water Coverage* will be, and should be, equal to one (i.e., a hundred percent covered). Consequently, the *Actual Farmed Area* should equal to the *Agriculture Area*. The two unit-models have been simulated and the *Water Coverage* in both canals was compared as shown in Figure 7-9. The *Water Coverage* in the Mansorya Canal appeared to be above one the whole year and, consequently, the *Actual Farmed Area* is fully productive as demonstrated in Figure 7-10 (the blue line). This means that the previous behaviour, of *Water Coverage* being under one exhibited in Figure 7-7, was due to the less quantities of water delivered to the canal from upstream (i.e., the first level canal). When the model has been isolated and the water supply matched the water demand, this inadequate behaviour disappeared. While in the Mahmoudya Canal, which has the same model-structure as the Mansorya Canal, the *Water Coverage* goes below one during the second and the third month and from middle of the fifth to middle of the seventh month. This means that the inadequate behaviour is originating from within the system.

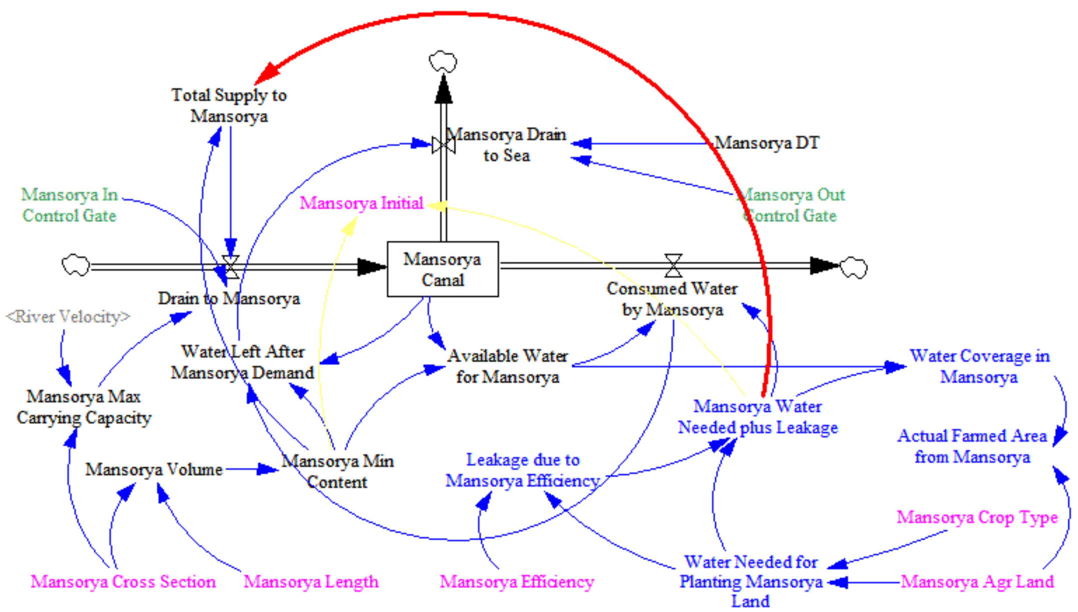


Figure 7-8: Modifying the structure of the unit-models.

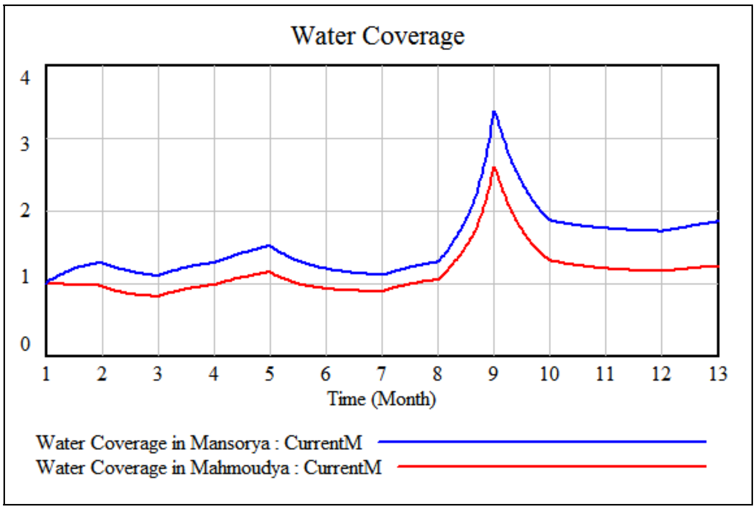


Figure 7-9: The Water Coverage in Mahmoudya and Mansorya Canals.

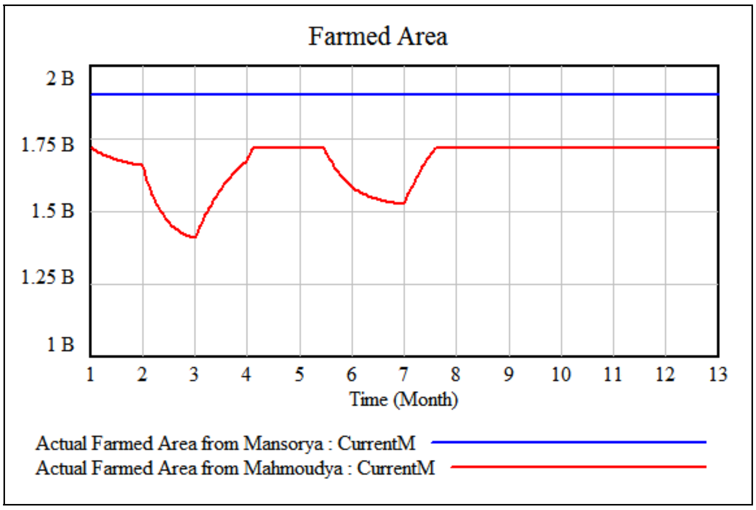


Figure 7-10: The Actual Farmed Area irrigated from Mahmoudya and Mansorya.

The values of the decision variables (i.e., *Canal Length*, *Cross Section*, *Efficiency*, the area of the *Agriculture Land* irrigated from the canal, and the *Crop Type*) in both unit-models are compared and represented in Table 7-1. The values of the *Efficiency* and *Crop Type* variables in both unit-models are identical, while the values of the variables *Canal Cross Section*, *Canal Length*, and *Agriculture Area* are different. This is not surprising because these values are real numbers obtained from the map. In fact, these numbers, to some extent, seem to make sense (shorter length with less cross section in Mahmoudya and longer length with larger cross section in Mansorya). However, the Agriculture Areas that each canal serves seem to be close (1718 sqkm at Mahmoudya and 1898 sqkm at Mansorya) which adds an advantage to

Mansorya Canal. Despite the fact that Mahmoudya Canal receives the water required by the associated Agriculture Land (e.g., the water supply matches the water demand), there still some inadequacy in its performance indicated as losses in the associated *Actual Farmed Area* as illustrated (with a red line) in Figure 7-10.

Table 7-1: The attributes of Mansorya and Mahmoudya Canals

Canal Name	Mansorya Canal	Mahmoudya Canal
Canal Cross Section (sq. m)	250	125
Canal Length (m)	219935	79387.6
Agriculture Area (sq. m)	1.89804e+009	1.71833e+009
Canal Efficiency (%)	80%	80%
Crop Type (Dmnl)	Group 1	Group 1

Obviously, the cause of this inadequacy is caused by the canal's insufficient carrying capacity. By increasing the carrying capacity of the canal, the losses in the associated *Actual Farmed Area* may be eliminated. The question here is how much this capacity should be increased? The answer to this question can be obtained by performing an optimization process for the carrying capacity.

The *Carrying Capacity* is a function of *Canal Volume* and the *River Velocity*. The water velocity through the Nile River is estimated as one to two metres per second [UNEP Report 2000]. However, the water velocity is unified (constant) in all parts of the system. Therefore, the variable in focus is the *Canal Volume* that is calculated as a function of *Canal Length* times the *Canal Cross Section*. At this point, the significance of considering the spatial dimension becomes clear. Within the framework of SD, the optimization process would be made for the *Canal Volume* (which includes the Canal Length). This optimization will produce the optimum value for the Canal Volume that may imply an extension for the Canal Length as well as an increase in the canal Cross Section. But in reality, extending the *Canal Length* will not solve the problem of the *Farmed Areas* who needs a certain quantity of water at certain locations. The SDGIS application that incorporates the spatial dimension with the temporal dimension makes clear that the only solution is to optimize the Canal Cross Section.

The Vensim DSS software package includes an algorithm that can be used to perform optimization (linear programming[52]). The Vensim optimizer produces the same results that are produced by many commercial linear programming solvers [Elmahdi *et al.*, 2005]. However, before we perform the optimization using Vensim, we may increase the *Cross Section* of the Mahmoudya Canal from 125 to 250 (sqm) and study the effect of this change on the *Actual Farmed Area*.

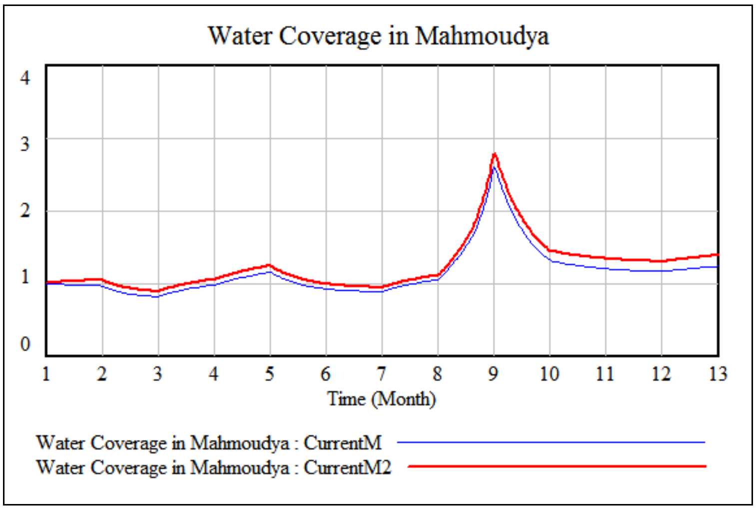


Figure 7-11(a): The water coverage with Canal cross section = 250 sqm.

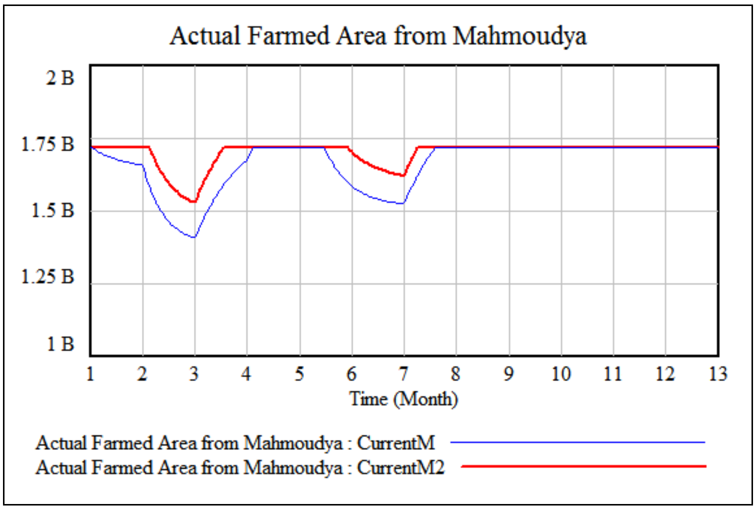


Figure 7-11(b): The Actual Farmed Area with Canal cross section = 250 sqm.

[52] It is linear because optimization in Vensim requires that you define a payoff function that summarizes how good a simulation with a single number. The payoff is always integrated using Euler integration [Ref. Vensim manual]. The Euler method is a first order numerical procedure for solving ordinary differential equations with a given initial value. It is the most basic kind of explicit method for numerical integration for ordinary differential equations.

Figure 7-11 shows a comparison between two simulation-runs. The first one, with the Mahmoudya Canal Cross Section equals 125 sqm (the blue line) and the second run with Cross Section equals 250 sqm (the red line). It is clear that the *Actual Farmed Areas* have recovered some losses, but that there is still room for more improvements. This proves, at least, that the inadequate behaviour was due to the infrastructure. Therefore, we performed the optimization for the *Canal Cross Section* using Vensim. The result, in the form of a text-file produced by Vensim, is illustrated in Figure 7-12.

```
Initial point of search:
Mahmoudya Cross Section = 125.
Simulations = 1.
Pass = 0.
Payoff = -2.1806e+017.
---------------------------------.
NOTE Payoff (-1.30389e+016) realized at multiple parameter values.
With Mahmoudya Cross Section = 450.047 and 483.754.
NOTE Payoff (-1.30389e+016) realized at multiple parameter values.
With Mahmoudya Cross Section = 483.754 and 466.9.
NOTE Payoff (-1.30389e+016) realized at multiple parameter values.
With Mahmoudya Cross Section = 466.9 and 464.962.
NOTE Payoff (-1.30389e+016) realized at multiple parameter values.
With Mahmoudya Cross Section = 464.962 and 457.504.
NOTE Payoff (-1.30389e+016) realized at multiple parameter values.
With Mahmoudya Cross Section = 457.504 and 454.91.
NOTE Payoff (-1.30389e+016) realized at multiple parameter values.
With Mahmoudya Cross Section = 454.91 and 447.888.
Maximum payoff found at:
*Mahmoudya Cross Section = 447.888.
Simulations = 20.
Pass = 3.
Payoff = -1.30389e+016.
```

Figure 7-12: Text file output for optimization result.

It is obvious that the cross section of the Mahmoudya Canal was unsuitable to supply sufficient water to the associated Agriculture Areas and the canal cross section should be increased to 448 sqm. This could be achieved by increasing the width and/or the depth of the canal. The optimal value of the Canal Cross Section has been tested though the simulation and the result, represented by a green line, is shown in Figure 7-13 that indicates a full utilization of the Actual Farmed Areas.

It is important to notice that the optimization has been made on the basis that the Crop-Type used in this example is “group one” and the Efficiency is 80%. Changing the Crop-Type and/or the delivery Efficiency of the canal would generate a different behaviour. In reality, Efficiency improvements require large funds and may be achieved only in the long run, but changing the Cropping Patterns has an immediate influence on the water demands and can be achieved in the short term. Both policies, upgrading the Efficiency and optimizing the Cropping Pattern, are discussed in more detail in the next section.

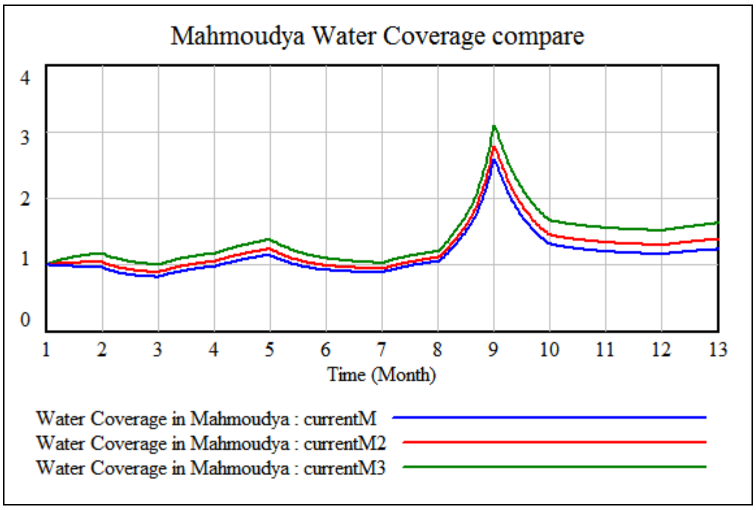


Figure 7-13(a): The water coverage in the Mahmoudya canal with various cross sections.

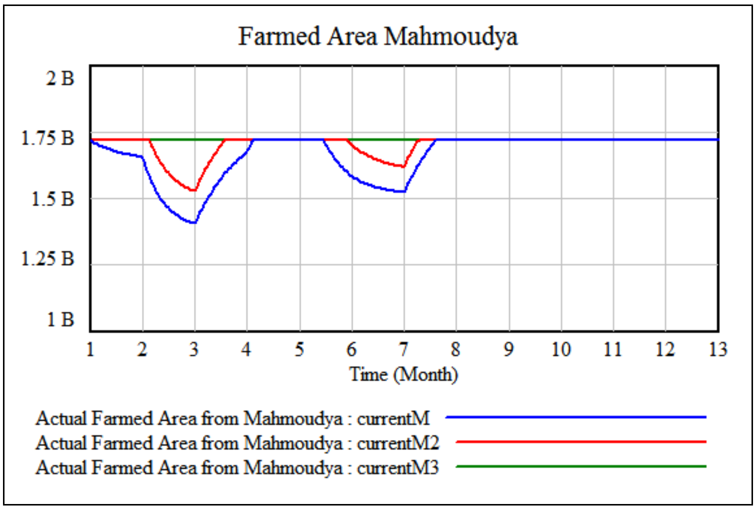


Figure 7-13(b): Actual Farmed Areas irrigated from the Mahmoudya canal.

This example demonstrated the potential benefits of using SDGIS as an optimization tool. Although the optimization process has been performed using the SD modelling tool (i.e., Vensim) which is one of the three components that form the SDGIS application, the other components such as GIS (that represents the spatial dimension), played a significant role in deciding the target variables to be optimized, and draw the attention towards the potentials of optimizing the cropping patterns that have a sever effect on water demands. The GUI of the SDGIS application facilitated testing the optimal values.

7.4 Utilizing the SDGIS as a SDSS

This section includes some illustrative examples for using the SDGIS application as a Spatial Decision Support System and as a policy assessment tool. First, we define the DSS and the Spatial DSS that is a special case of the DSS. We highlight the relationship between the GIS and the DSS and discuss the claim that GIS is a DSS. This greatly helps in the evaluation of the SDGIS application as a true SDSS. Second, we illustrate, by way of some examples, the SDGIS application in a decision making process and the assessment of water preservation policies. This section includes some discussions regarding the water scarcity problem at large, the need for water preservation policies, and the suitability and feasibility of applying such policies in the case of Egypt.

Sprague and Carlson (1982) described Decision Support Systems (DSS) as "computer-based systems that help decision makers confront ill-structured problems through direct interaction with data and analysis models". Sprague (1980) defined three elements that form an operational DSS; the data subsystem, the model subsystem, and the user interface. These elements are presented in Figure 7-14.

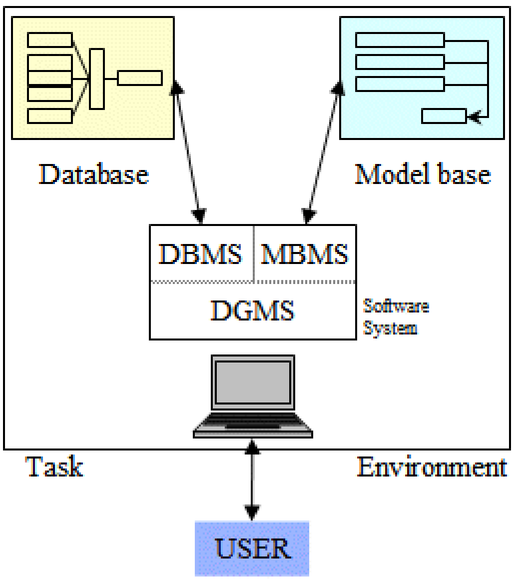


Figure 7-14: Components of the decision support system
Source: Sprague and Carlson (1982)

The first step in the decision making process begins with the creation of a decision support model using an integrated DSS program (DSS generator) such as Microsoft Excel, Lotus 1-2-3, Interactive Financial Planning Systems (IFPS), etc. [Sean, 2001]. The user interface subsystem (i.e., the Dialogue Generation and Management Systems (DGMS) shown in Figure 7-14) is the gateway to both database management systems (DBMS) and model-based management systems (MBMS). DBMS are a set of computer programs that create and manage the database, and control access to the data stored within it. The DBMS can be either an independent program or embedded within a DSS generator to allow users to create a database file that is to be used as an input to the DSS. MBMS are a set of computer programs embedded within a DSS generator that allow users to create, edit, update, and/or delete a model.

Users create models and the associated database-files to make specific decisions. These models, alongside with database-files, are stored in the direct access storage devices. The users will only have to deal with the interface subsystem, - one of several component in the DSS. Therefore, in providing an effective user interface we must address several important issues, including the design of input/output devices, the screen layout (e.g. the use of colours), the data format, and the interface style (e.g., menu-based interaction style, command language style, natural language processing based dialogue, and graphical user interface GUI). GUIs use icons, buttons, pull-down menus, toolbars, and textboxes extensively and have become the most widely implemented and versatile type. The interface subsystem allows users to access; (1) the data subsystem (i.e., the database and the database management software) and (2) the model subsystem (i.e., the model base and the model base management software) [Sean, 2001].

Decision support systems (DSS) cover a wide variety of systems, tools and technologies. Some researchers argued that the term DSS is outdated and that it has been replaced by a "new type" of system called on-line analytical processing or OLAP [Power, 1997]. Others seem to emphasize creating knowledge-based DSS as the "state-of-the-art" in decision support systems. Operations researchers primarily focus on optimization and simulation models as the "real" DSS. However, the term decision support system and its acronym DSS remains a useful and inclusive term for many types of information systems that support decision making.

Within the field of GIS, there are many GIS practitioners who consider GIS software to provide decision support. Indeed, as Maguire *et al.*, (1991) pointed out, some authors have argued that the GIS is a DSS. A substantial number of GIS based applications are described as being DSS. A recent GIS conference was entitled “DSS 2000”. This view of GIS as a DSS may originate from the ability of the GIS to create templates and conduct “what-if’ analysis that allow for some support of decision making activities. We believe, however, that the GIS might resemble the DSS but in fact, the lack of an integrated spatial model management subsystem keeps the GIS at the threshold below the true DSS. GIS does seem suited to help decision makers explore and understand a certain class of problems, but the current level of system complexity that requires expert skill level precludes widespread exploitation of this capability today.

Analyzing the literature, the overwhelming number of cases that claim DSS status refer to relatively simple information and model systems that focus on problem representation and in most cases, “what-if” type scenario analysis. A considerably smaller group addresses optimization tools with usually a strong Operations Research and mathematical programming focus. Another group go beyond the traditional DSS definitions and describe GIS as a Spatial DSS. The SDSS include spatially distributed criteria, -i.e., they use the location and spatial relationships between objects in their analysis [Fedra, 2006]. A good starting point to understand the characteristics of the SDSS can be found at [http://isworld.org/dss/sdss.htm]. However, the important point that we want to emphasize here is that the GIS alone (as a static representation for the features found in the real world) may not be sufficient to warrant the term “true DSS” (or SDSS). The GIS may form an important tool when used as part of a decision process, but the dynamic aspect should be incorporated. As Samuel (1996) has concluded “What is need in SDSS is also the dynamics, in particular, if we design the SDSS for Environmental problems”. Burrough and Frank (1995) argued that “there is a large gap between the richness of the ways in which people can perceive and model spatial and temporal phenomena and the conceptual foundations of most commercial GIS. Unless this gap can be closed, GIS may remain unsuitable for more complex area such as Regional Environment Decision Making". Murphy (1995) supported this approach when stating that: "Information has three dimensions (each of which may have more than one internal dimension): theme or content (also known as attribute), space or location, and time. Many information systems explicitly or implicitly deal with two out of the three dimensions. Transaction processing systems, for example, explicitly manage attribute data and implicitly manage time (i.e., through time stamping). Typical DSS may have mechanisms to represent time (i.e., simulation) and strong attribute manipulation tools, but have no spatial representation. GIS have explicit mechanisms for attribute and spatial data management and may contain implicit tools for managing temporal data (such as versioning or time-slices) while a few leaders are attempting to merge simulation into GIS" [Murphy, 1995].

In this context, the SDGIS application, that tightly couple the GIS models with the SD models under one common interface, may be considered a true SDSS. The application includes explicit mechanism for attribute and spatial data management (through its GIS component), as well as the mechanism to represent time (through simulation using its SD component). By using the SDGIS application, irrigation system managers and decision makers can develop water allocation plans and easily test and assess several water preservation policies. In fact, in this research, we have carried out several runs to test alternative water management scenarios. The application enabled us to study and analyse the behaviour of the irrigation system at micro and macro levels. For example, at the micro level, the user can examine the behaviour of one single canal and/or one main branch and its dependent canals. On macro level, the user can study the behaviour of a group of closely related canals and/or the complete system of canals. The development of this application has also provided the opportunity to study and analyse the feasibility of applying water preservation policies in case of Egypt. In the following paragraphs, we demonstrate the potentials of using the SDGIS as a SDSS for the assessment of such policies by providing a simple example first and, subsequently, discuss the situation in case of Egypt in general. Three examples are presented in this section. In the first example, we illustrate the efficiency upgrading policy. In the second example, we illustrate the water supply/demand adjustment policy and exhibit the effect of changing the water release patterns on the behaviour of the system. In the third example, we introduce a proposed cropping pattern, and discuss the cropping patterns optimization policy. A further discussion concerning the water pricing policy in case of Egypt is provided at the end of this section.

Water Preservation Policies

Scarcity, by definition, is a function of demand and supply. The major water preservation policies recognized worldwide are working on either the demand side or the supply side. The demand side encompasses policies such as cropping patterns optimization and water pricing, whereas policies like upgrading the efficiency of the irrigation system, water allocation, and the adjustment of the water supply with the water demand come under the supply side. From a broader perspective, the concept of demand management implies that any increase in a specific sector (agriculture, industry and domestic) demand must be met through an equivalent reduction in other sectors. From agriculture viewpoint, as mentioned earlier, subsidies of irrigation have participated in emergence of water scarcity conditions. Free resources send misleading message to the consumers about the abundance of water. The illusion of affluent resources finds its confirmation in the high rates of farmers (43 percent) who simply do not know if there is likely to be a problem with enough water supplies in the future [El-Zanaty & Associates, 1998].

Although in the long term there is a little doubt that attention needs to be focused on demand management strategies, there is a sufficient evidence to indicate that significant savings can be made by improvements in the control and management of existing irrigation supplies. Thus, we start by discussing the policies that can be applied in the supply side then the other policies in the demand side.

7.4.1 Improving the irrigation system Efficiency

From the supply side, most studies focus on ***efficiency***. The irrigation efficiency improvements are seen as an effective tool for increasing the water supply sources. As Norton (2004) stated "Increasing the *efficiency* of the irrigation system has two different meanings. Technically, it refers to the reduction of water losses at each level of the irrigation system. In a broader sense, it refers to increasing net economic returns for the system users taking full account of externalities" [Norton, 2004].

Efficiency can be carried out through irrigation improvement plans and better land management. Externalities include a wider set of factors that comes into play. Therefore, the concept of efficiency may be seen in its broad meaning which entails the technical and environmental efficiency aspects. In the following paragraphs, first we provide a simple example for using the SDGIS application to test the efficiency upgrade policy and then discus the limitations of the efficiency definition applied to Egypt. Although the environmental impacts, in their broad meaning, are beyond this study, we will mention some of them very briefly.

Considering the structure of the irrigation scheme in the Delta (as described in chapter 4 section 4.3.2), the water use efficiency can be split into conveyance (or distribution) efficiency and application efficiency as shown in Figure 7-15. In this research, the conveyance efficiency is explicitly represented in the SD spatial mode (by the variable called canal Efficiency and the variable Leakage due to Efficiency that calculates the amount of water lost). In the GIS model, the attribute table associated with the Canals Layer included the field titled *Efficiency* that includes the values of the canals' delivering efficiency. The application efficiency, however, is not considered in this research due to the enormous amount of data required regarding the methods of water application within each field. Nonetheless, it can be easily included *implicitly* in the calculations of the "crop-water needs" and consequently it would be accounted in the water demand calculations.

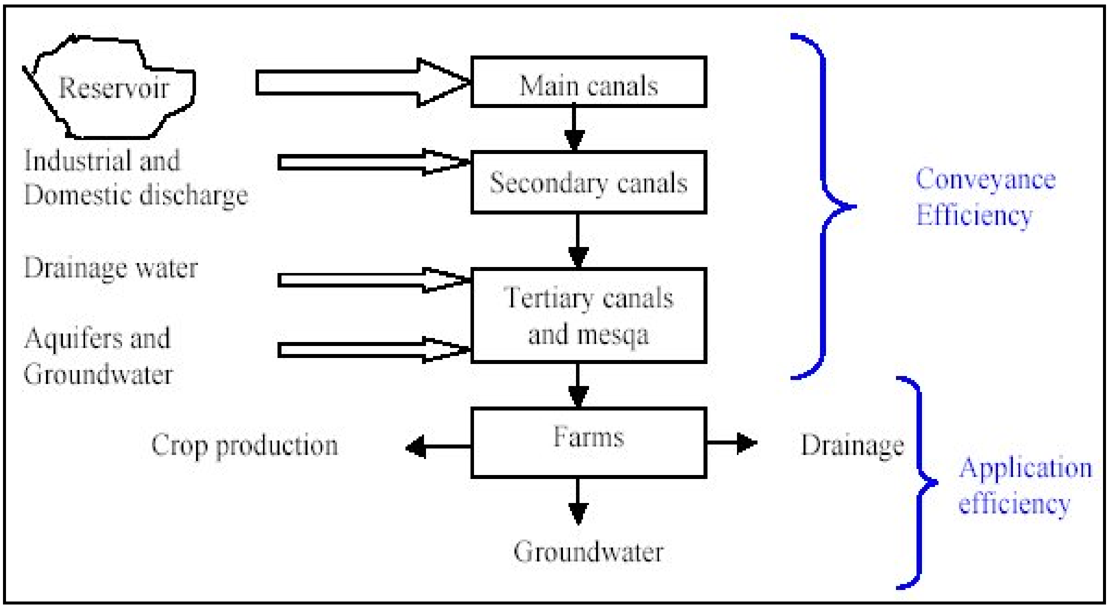


Figure 7-15: Irrigation water distribution scheme
Based on [Tiwari and Dinar, 2002]

The SDGIS application has been used to study the effect of upgrading the conveyance efficiency on the system performance and the effectiveness of such a policy in water saving. For this purpose, two simulation runs have been performed. In the first run, called Efficiency_75, we set the Efficiency value equals to 75% for all canals forming the irrigation network. This percentage simply means that 25 percent of the quantity of water carried though the canal is lost and 75 percent is received at the farm. In the second run, called Efficiency_90, we set the Efficiency value equals to 90% for all canals. For both runs, the model has been calibrated on the basis that the cropping pattern in all agriculture areas within the three Delta zones is unified (i.e., *Crop-Type* group one).

Using the “Model Initialization” panel, these values, shown in Figure 7-16 were assigned to the model (the figure shows the values assigned to Efficiency_75 Run). The results from the two runs are shown in Figures from 7-18 to 7-22. Notice that, for the purpose of comparing the results, we chose to draw the map according to the values of the water leakage (i.e., we chose the water leakage item from the *Draw* combo-box placed in the *Active Layers* Frame as shown in Figure 7-17). This is one way of drawing the map out of six alternatives that the SDGIS application provides.

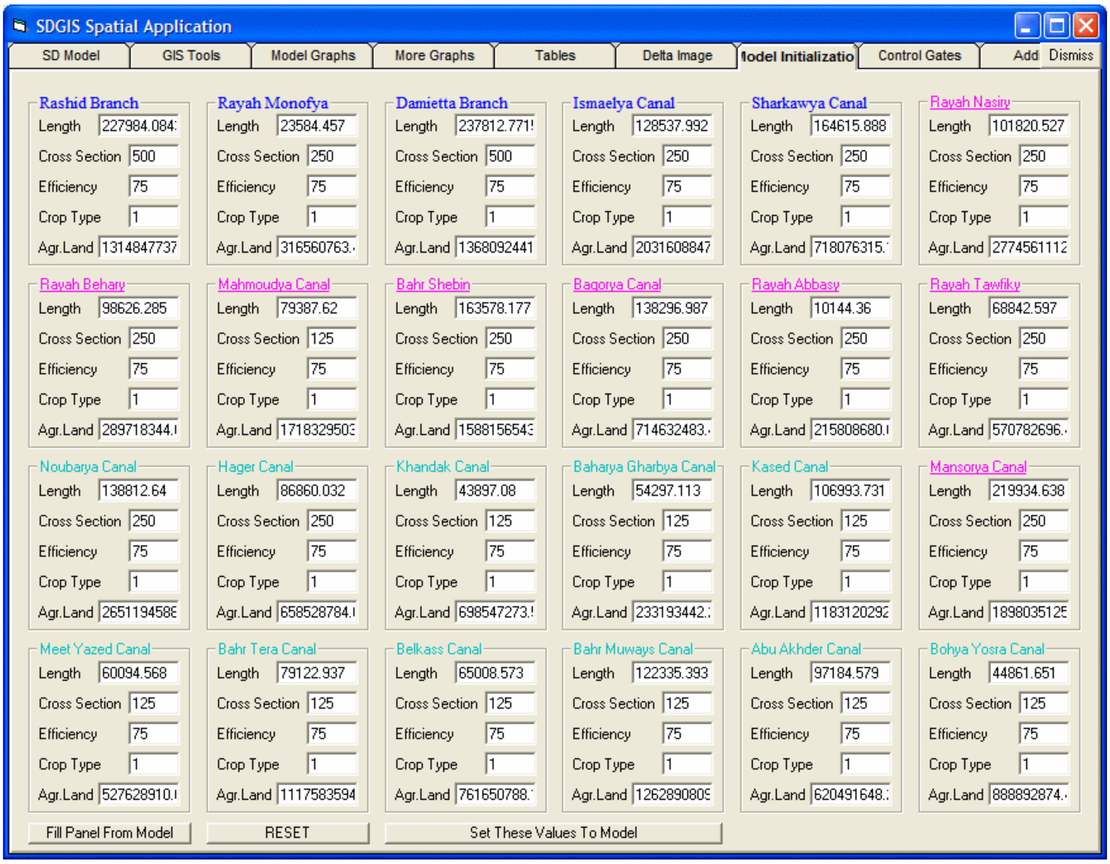


Figure 7-16: the model initialization panel

Figure 7-17: the active layers Frame

By comparing the Figures 7-18 and 7-19, we can notice the difference in the canals' performance. As a general observation, canals in the Efficiency_75 Run appear with darker colours and thicker lines indicating the large amount of water lost. Notice in particular the Rayah Nasiry, the Rayah Behary, and the Noubarya Canal at West of the Delta. These canals serve large agriculture areas that require enormous amount of water to be delivered, consequently, a massive amount of water is lost.

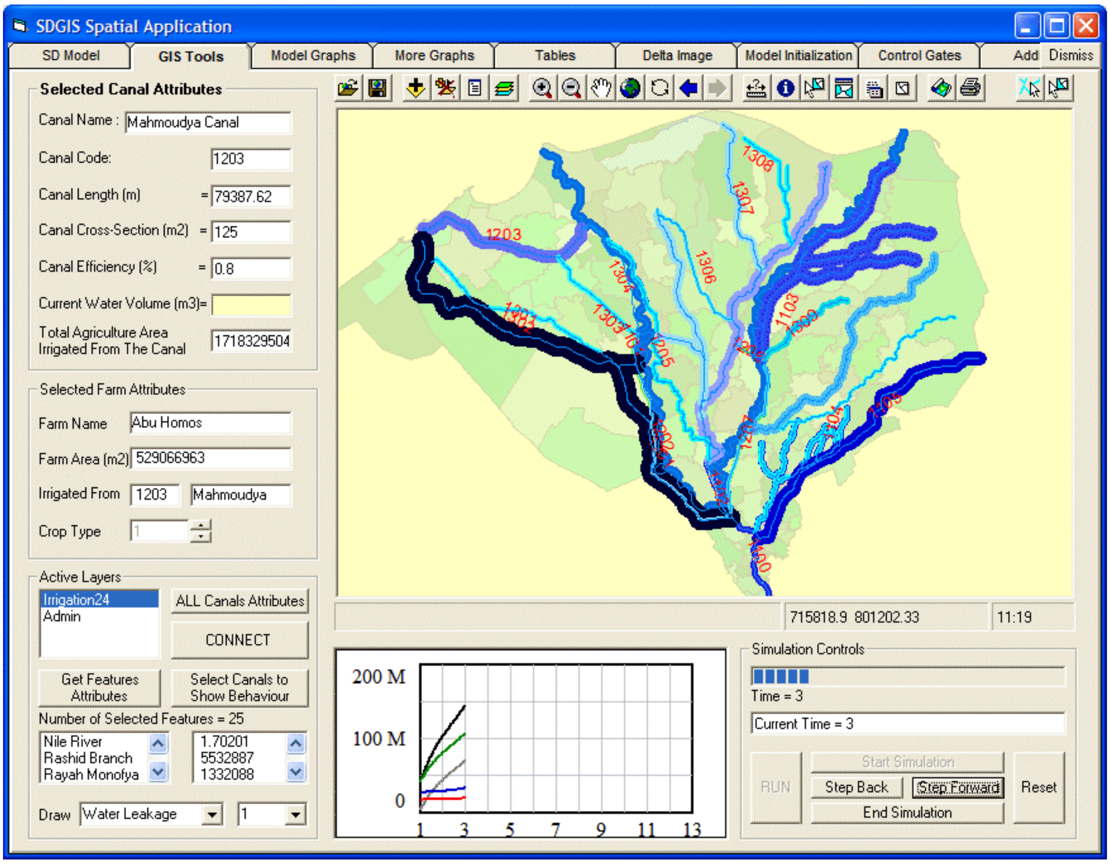


Figure 7-18: Efficiency75 Run at simulation Time = 3

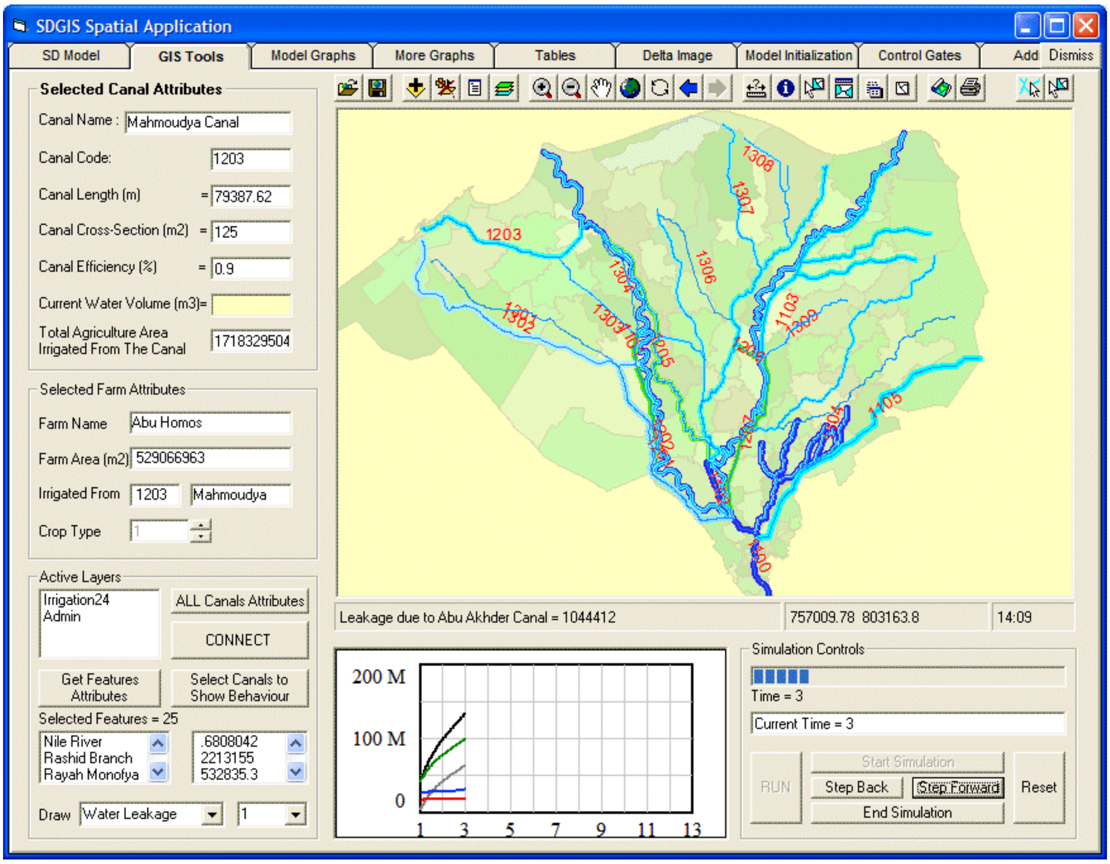


Figure 7-19: Efficiency90 Run at simulation Time = 3

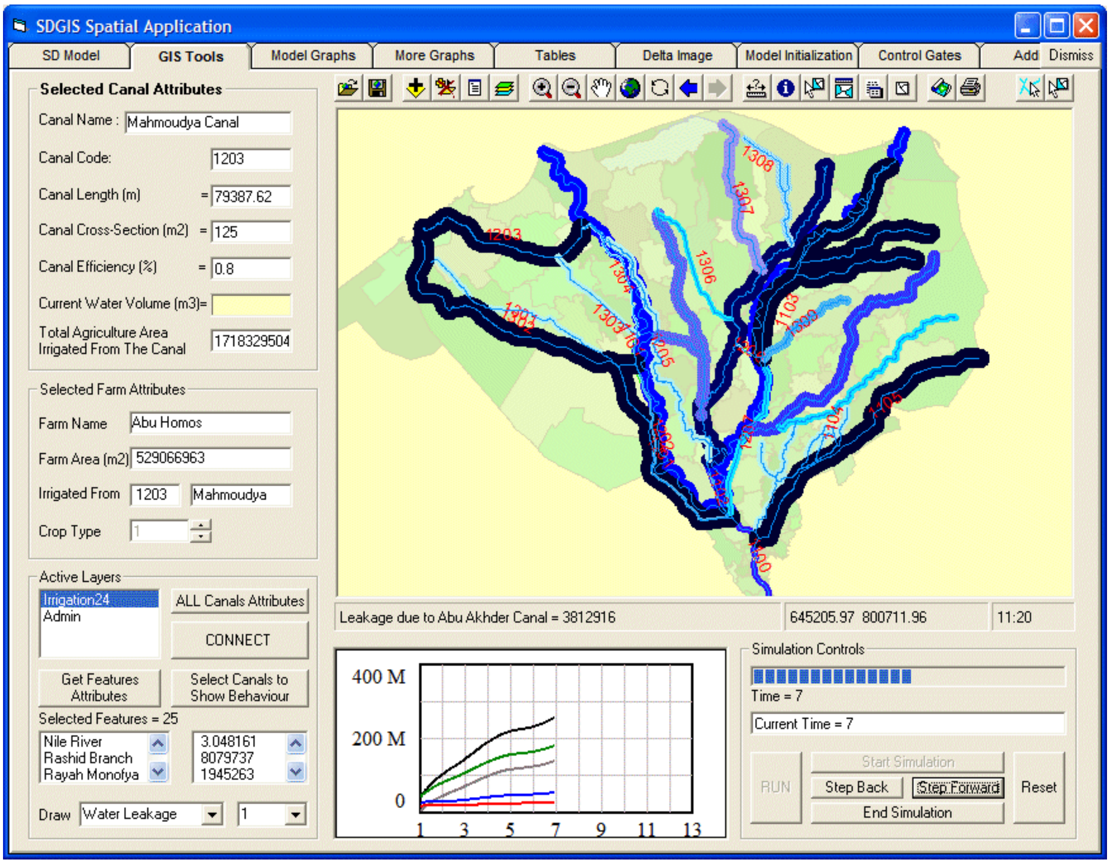


Figure 7-20: Efficiency75 Run at simulation Time = 7

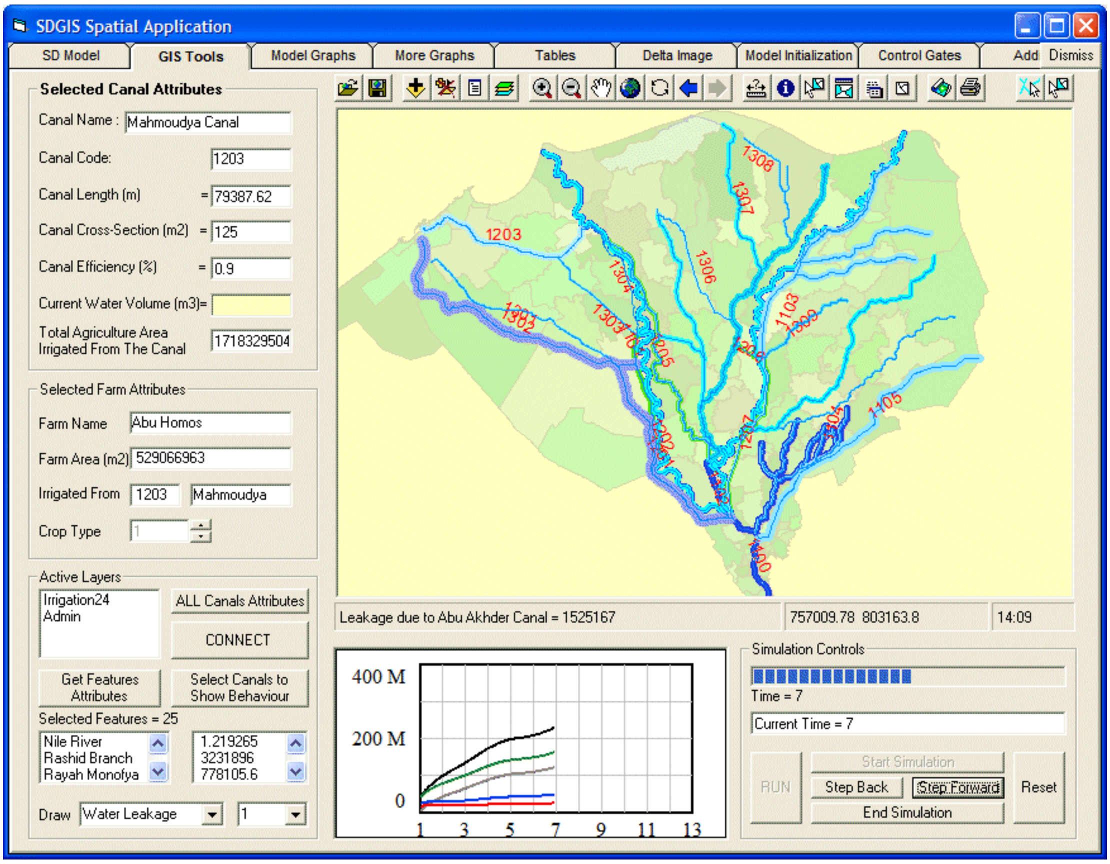


Figure 7-21: Efficiency90 Run at simulation Time = 7

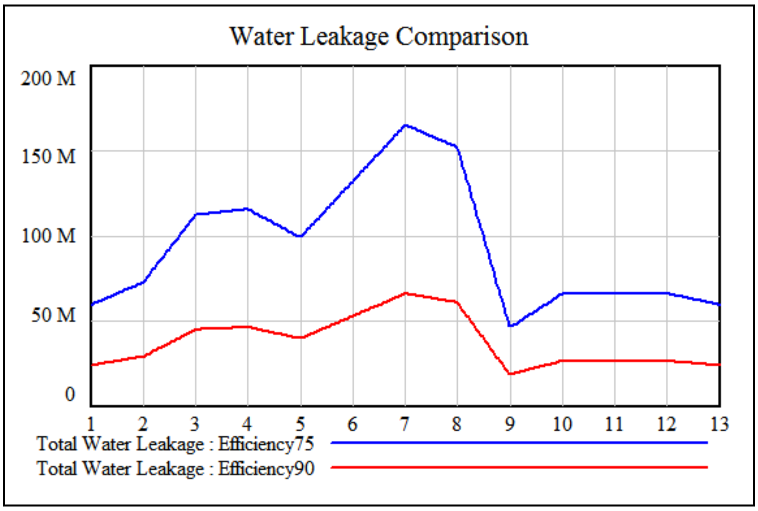


Figure 7-22: A comparison between water leakages in two runs.

Figures 7-20 and 7-21 portray the state of the system at Time = 7, that is the month that witnesses the highest demand of water. It becomes clear that by improving the efficiency, a significant amount of water can be preserved for effective use. This can also be seen in Figure 7-22 where the water losses in the two cases (75% and 90% efficiency, respectively) are being compared. Notice that changing the cropping pattern will change the water demand values through the system and, consequently, the water lost due to lack of efficiency will be altered. This example can be repeated a number of times to study the effect of changing the efficiency on water saving under different cropping patterns scenarios, and can be conducted on the micro or macro levels (e.g., for one canal at a time or for the whole system of canals).

Discussion:

The worldwide overall surface irrigation efficiency is estimated at 37-50% [Carruthers et al., 1997; Tiwari and Dinar, 2002]. Conveyance efficiency is around 60% [Martinez, 1994], application efficiency while using the traditional methods of irrigation accounts for 40%, whereas advanced systems of irrigation exhibit a high performance with 60-70% efficiency [Martinez, 1994; Myers and Kent, 1998]. In Egypt, the average leakage during conveyance from outlets to the fields is 11% and between outlets and main canals 25% [Tiwari and Dinar, 2002]. About 10 BCM are lost annually in canals [Imam, 2003 cited by Malashkhia, 2003]. These figures may at first be interpreted as an indication for a poor performance of the distribution system, - leading us to the suggestion that improvements in efficiency rates may lead to a significant potential for water preservation. *However, the data obtained from the field shows a different scene.*

Irrigation efficiency figures in Egypt seem surprisingly high, taking into account the fact that the most common method of irrigation used in farms is surface flood irrigation. According to the information obtained from MWRI, the average (overall) efficiency rate of the irrigation system is around 75%, which makes it highest in the world. Much the same is observed in the detailed figures of the conveyance and application efficiency. The conveyance efficiency on the old lands is 70% and on new lands it reaches 80%. Application efficiency rates are higher – 80% and 90% on the old land and the new land respectively. Keller (1992) claimed similar rates in his study. He points out to the fact that the efficiency rates in Egypt are remarkably high (89%). These high efficiency figures create much confusion on the background of the *worldwide* irrigation efficiency rates. The significant difference between the *worldwide* average and the Egyptian figures can be explained by the different *methods* applied *to calculate* the efficiency rates [Malashkhia, 2003].

The first method, which refers to the ratio between the amount of water discharged at the root zone (used by the plant) and the amount of water delivered, produces low irrigation efficiency rates [Tiwari and Dinar, 2002]. The second method, which considers the natural water-recycling factor in its equations, produces higher efficiency rates. This method, which is drawn from the so-called "IWMI paradigm"[53], claims that water lost to seepage and percolation during conveyance and application cannot be considered as loss. Water diverted from the reservoir and other sources is partly evaporated. Some fraction of water is consumed by plants and used for evapotranspiration. The other fraction of water is lost to seepage from canals and fields. This fraction percolates to the deep aquifers and groundwater where it is

[53] IWMI – International Water Management Institute. The Paradigm was based on studies of Keller. D and Willardson, L.S.

recaptured and recharges the ground water and aquifers. Thus, the lost water is reused as additional source of supply later on, recovered from wells or aquifers. The drained water, which is collected in drains, is returned to the irrigation system as well. So the water can be returned to the system again and go through the same cycle until almost all of the water is consumed. [Keller, 1992; Perry, 1999] Therefore, the efficiency rates still go high despite the great losses during the conveyance and field application.

The calculations of efficiency suggested by IWMI, which include the natural recycling factor, lead to very controversial conclusions. In fact, it diminishes the importance of efficiency improvement measures. So the study of Keller concludes that due to high irrigation efficiency rates in Egypt, the potential for improving the system performance from a physical water use efficiency standpoint is limited. So does Seckler (1992) in his article when stating “The benefits of investing in on-farm efficiency in such systems are substantially reduced by system wide effects, perhaps even to zero”.

The logic of the paradigm is convincing unless we also pay attention to the deterioration of water quality that accompanies each cycle of reuse. Going through the continuous recycling phase, the water picks up considerable amounts of salt from the soil, saline sinks, fertilizers, and pesticides [Keller, 1992]. The reused water quality becomes so deteriorated that it is questionable whether water can be used for irrigation or not [Martinez, 1994]. In the literature, there is a significant debate concerning the water quality issue. Here we just emphasize the fact that estimates offered by the “IWRI Paradigm” eliminate important factors such as the environmental efficiency[54].

As mentioned earlier, the concept of efficiency may be viewed in its broad meaning that entails the *technical* and *environmental* efficiency aspects and water reuse as well. It seems more appropriate to save water through increasing *technical*

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[54] The paradigm has some other objections as well [Tate, 1994]: Brooks questions the assumption of natural recycling. He finds that the idea about effective natural recycling must be proven and cannot

efficiency of irrigation system so that the high quality fresh irrigation water from the Nile River is not lost. Here, we may suggest (in the application efficiency/on-farm side) to convert "*gradually*" the traditional irrigation method used (i.e., the surface flood) into modern irrigation methods like low-pressure sprinklers and/or drip-emitters systems (with 90% efficiency for both systems). The funds to build such a modern irrigation system (to replace the old one) may be provided from subsidy budgets. The government (i.e., MWRI) may use part of the budget assigned for operation and maintenance (O&M) for this purpose. The benefit in the short term is saving water, and in the long term are eliminating subsidies and increasing the agricultural capital (in terms of advanced irrigation system network). Unfortunately, it is impossible to carry out further studies in the limited time available, to study the feasibility of this proposal. However, the concept of efficiency must be seen in its broad meaning which entails the technical and environmental efficiency aspects in order to understand the reality and consider all side effects.

7.4.2 Water Supply-Demand Adjustment Policy

In this section we represent the current water release policy conducted by MWRI, and compare it with the water demand-driven supply policy (hereafter we call it Adjusted-Release Run). Based on the evaluation of the two policies and their suitability for the present situation that largely affected by the delivery delays and the infrastructure deficiencies that characterize the irrigation system, and the arbitrary cropping patterns, we introduce a new policy where we try to synchronize the water supply with the demand. The purpose of the latter policy (called *Test-Synchronization* Run) is to utilize the water considerably more efficiently. The side effect of such a policy is to provide the opportunity to utilize the water for other purposes, such as expanding the agriculture area through reclamation projects.

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be just assumed. Another point is considerably inefficient use of capital, as the less efficient on-farm consumption needs larger supply and effluent facilities.

The information obtained from MWRI regarding the water release pattern indicates that the average water release from Aswan High Dam is 220 MCM per day. The maximum release of water takes place in June (the high demand season) and accounts for 270 MCM per day. On some occasions, when there is a surplus of water (accumulated from previous years) the MWRI releases 240 MCM per day for a period of three months (June, July, and August) to wash up the canals and reduce the soil salinity. This may occur one time every three or four years.

This information regarding the average water release (i.e., 220 MCM/day), has been included in the model and a new run, called Vast-Release Run, has been completed and documented. Another run, called Adjusted-Release Run, has been simulated where we assigned the water supply (i.e., the water released from the High Dam) corresponding to the *Total Water Demand* (from the agriculture lands in the Delta) as long as the demand does not exceed the maximum allowable release (that is calculated as the annual quota 55.5 BCM distributed over 12 months and taking into consideration the water demand of other sectors).

To include the information obtained from MWRI (i.e., 220 MCM/day) into the model, four variables have been added as shown in Figure 7-23. These variables are: *Average Water Release per day*, *Converter to Monthly Release*, *Agriculture Sector Water Share*, and *Delta Water Share*, respectively. As their names imply, the first variable stores the value 220 MCM/day. The second variable is created to convert this value from a daily to a monthly rate. The third variable sets the agriculture sector water share (i.e., 83% see Table 6-2). The fourth variable sets the Delta water share. Notice that the total agriculture area is about 35,000 sqkm which includes the Nile Valley (about 10,000 sqkm) and the Delta region (about 25,000 sqkm). This means that the Delta constitutes about 71.5% of the total agriculture land. Therefore, the water supply represented in the model for the Vast-Release Run is the Delta water share (71.5%) from the Agriculture sector water share (83%), (i.e., this is equal to 220 MCM/day * 30 days/month * 0.83 * 0.715 = 3.912 BCM/month).

The first variable is modelled as a *parameter* in the model to allow for changing its value during runtime. In the GUI of the application, a new *Slider* control object has been added in the *Additions* panel to receive the user's input and change the value of the water release during the simulation if the user wishes to do so. The new Slider (called *Supply Slider*) is shown in Figures 7-24 and 7-25.

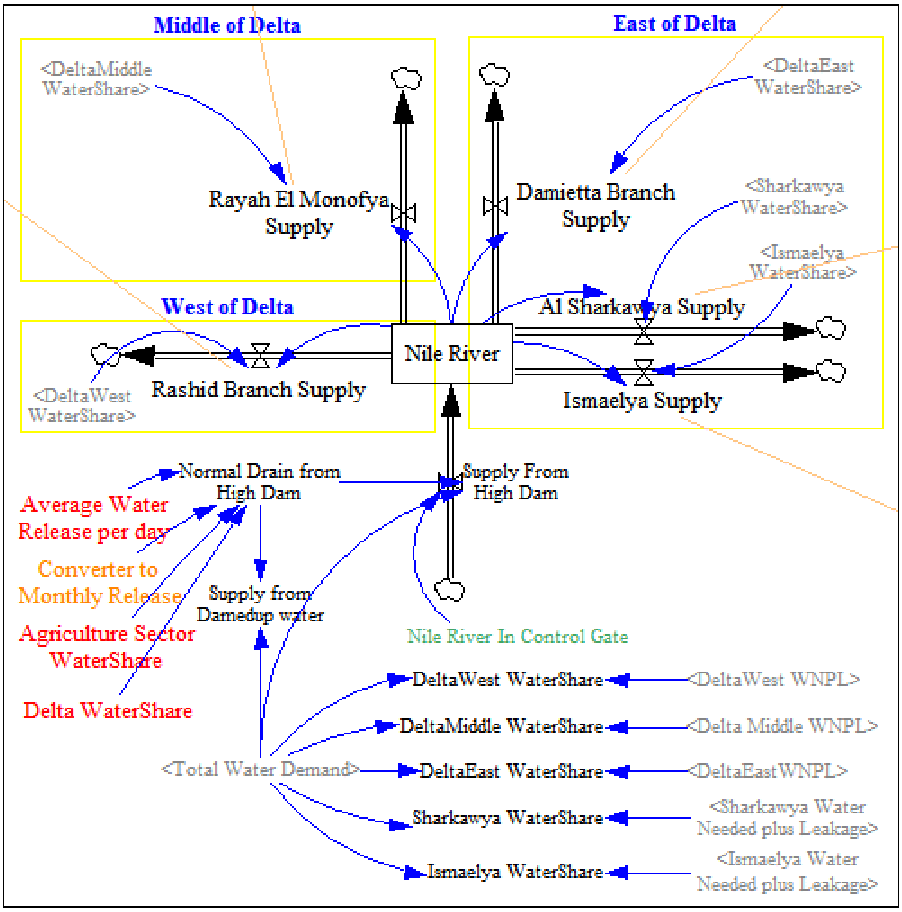


Figure 7-23: The added variables.

Figure 7-24: The new added Supply Slider

Figure 7-25 shows the last panel called *Additions*, where the *Supply Slider* appears at the right-hand-side. Notice that *Additions* panel has been added recently to the application interface for the purpose of representing the current scenario (e.g., allowing for a change in the *Average Water Release* during simulation runtime by way of the *Supply Slider*). In fact, this is one of the advantages of this application. That is, its flexibility allows for adaptations to represent various situations. The only limitation is that the user needs to have the open source code and the programming skills to alter the interface of the application.

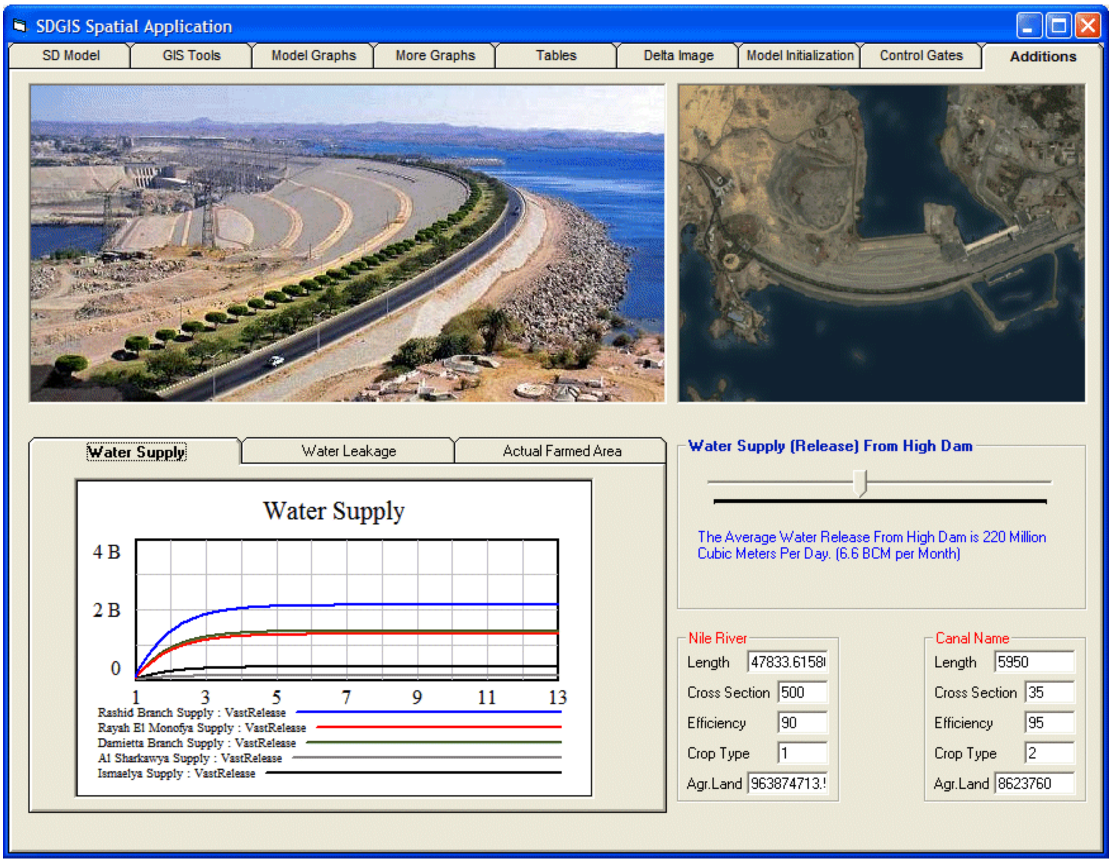


Figure 7-25: The Supply Slider appears in the *Additions* panel.

For both runs, the Vast-Release and Adjusted-Release, the model has been simulated for two years under the same initial conditions (i.e., using the same cropping patterns and the conveyance efficiency rates). The results from the two runs are compared and exhibited in Figures from 7-26 to 7-31.

Figure 7-26 shows the result from the Vast-Release Run. Obviously, the water supply (appearing with blue line) is very high compared to the water demand (the red line). The water consumption (the green line) matches exactly the water demand. The water consumption is the actual water delivered to the farm and utilized for irrigation in addition to the water lost in canals due to lack of efficiency. Notice that, if the water supply is sufficient, the agriculture land will acquire its demand, otherwise, it will receive only the available water in the canal. In this run, we notice that an enormous amount of water drains to the Sea (the grey line) as the supply exceeded the demand to an extreme extent. This confirms the over-supply status that concluded by Lutfi Radwan (1998) in his study that will be described later in this section.

In the Adjusted-Release Run, shown in Figure 7-27, the water supply (appearing with blue line) matches exactly the water demand (the red line). The water that drains to the Sea (appearing with grey line) is very low, indicating the fact that all the water supplied is consumed in the cultivation process. However, the water consumption (the green line) appears lower than the water demand (the red line) for the first half of the year (notice that we focus on the steady-state behaviour in the second year and ignore the transient behaviour at the start of the simulation). This indicates that the water available in the canal is not sufficient. This is due to the delivery delays and, more essentially, the inefficient infrastructure (e.g., the canal cross section). This affects the *Actual Farmed Area* that, consequently, suffers losses during this period (see Figure 7-29 (d)). In the second half of the year, the *effective* water supply (i.e., the supply resulting from the current infrastructure deficiencies) and, therefore, the water consumption catches up with the demand and the surplus water drains to the Sea. It seems that MWRI attempts to avoid the agricultural losses by over-supplying water in the way represented by the Vast-Release Run.

Figure 7-28 shows a comparison between the "total water drain to the Sea" (from all canals) in the Vast-Release Run (appearing with blue line) and in the Adjusted-Release Run (the red line), respectively. Obviously, the difference in water quantity released and lost to the Sea is huge and causes major concerns regarding whether releasing such an amount of water is rational, and whether the objective is to avoid agricultural losses (or say, to regulate the water level in accordance with the High Dam storage capacity, or to feed the hydro-electric power-stations along the Nile downstream).

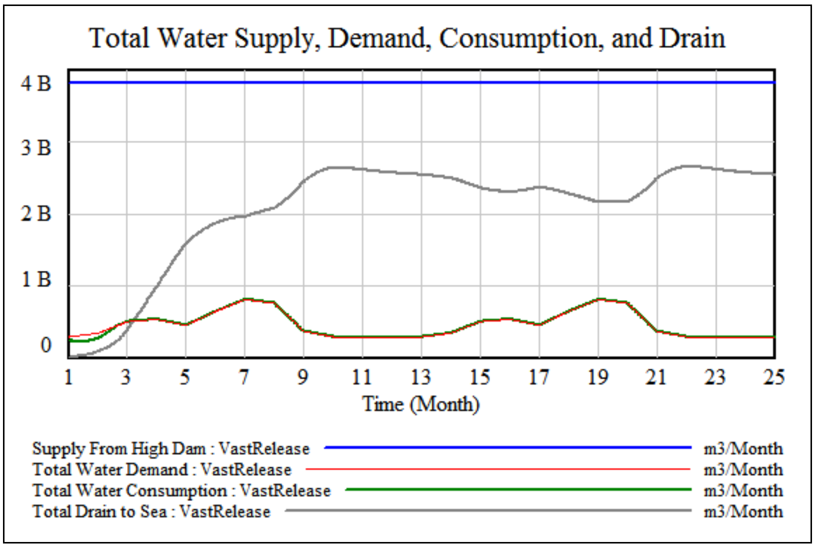


Figure 7-26: The results of the Vast-Release Run.

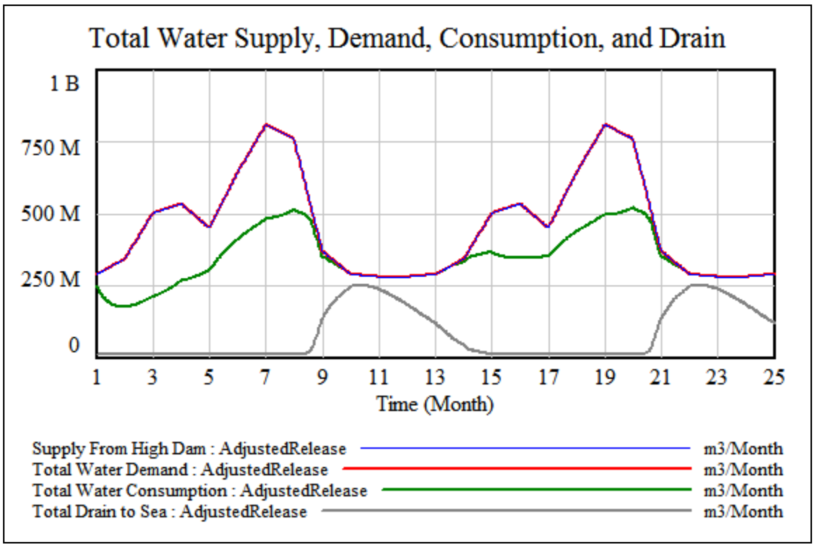


Figure 7-27: The results of the Adjusted-Release Run.

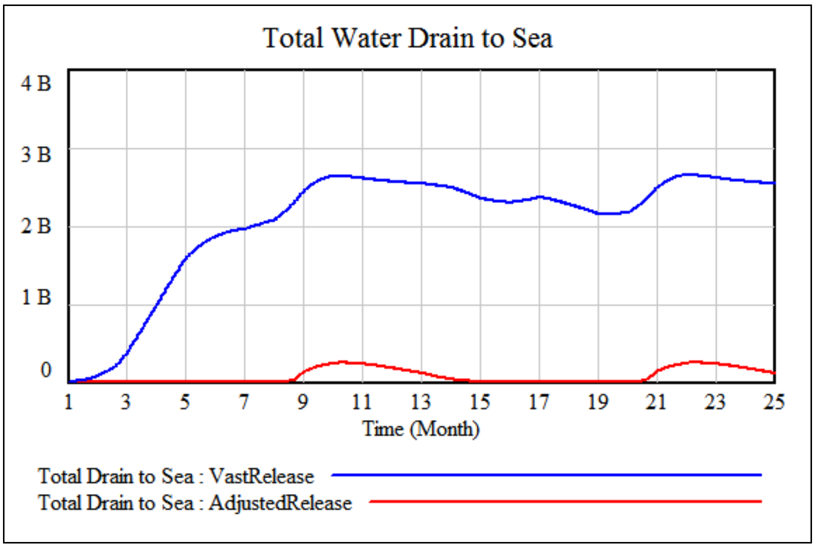
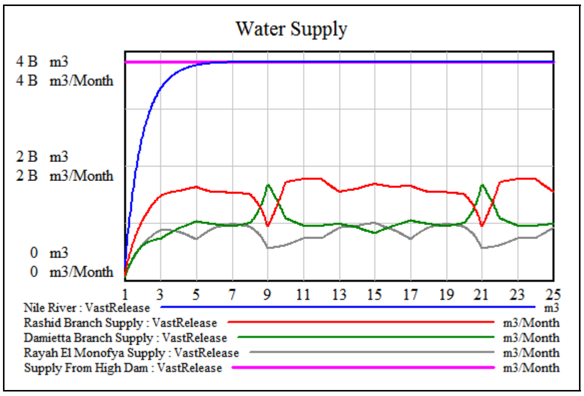


Figure 7-28: A comparison between Total water drain in both runs.

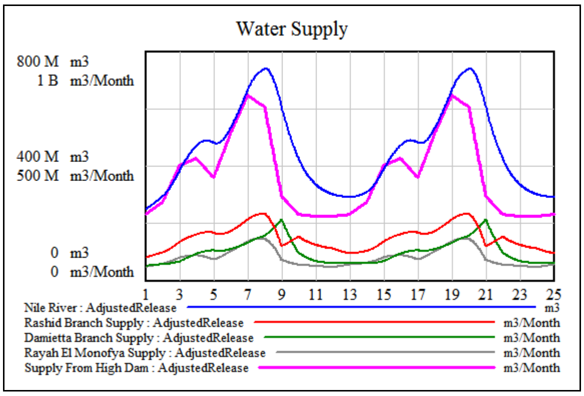
Figure 7-29 includes two sets of graphs. The set on the left-hand-side shows the result of the model simulation in the Vast-Release Run (MWRI information) while the set of graphs on the right-hand-side portrays the results from the Adjusted-Release Run. Graph (a) shows the state of the water volume in the Nile River (the blue line), the constant water supply from the High Dam (i.e., 3.912 BCM/month, appearing with fuchia line), and the water drains from the Nile to the successor canals (first level canals). After a transient period of six months, the Nile behaviour stabilizes indicating that the inflow (the supply from the High Dam) equals the outflow (the drain to the canals at the first level). The outflow from the Nile drains to the canals at the first level, from which it continues to supply the second level and then the third level canals. Portions of this water are consumed at each level for irrigation purposes and, eventually, after the agriculture lands have acquired their water demand, the surplus water drains to the Sea. This explains the huge amount of water that observed drains to the Sea in the above Figures 7-26 and 7-28. In contrast, in the Adjusted-Release Run, the water volume in the Nile River is lower than it is in the Vast-Run and fluctuates in accordance with the water demand as shown in graph (b). Consequently, the water that drains to the Sea is relatively small because the water supply equals the demand and *theoretically* there is no extra water left. However, the water that drains to the Sea, observed at the end of the year in the above Figure 7-27 is due to the delivery delays and infrastructure deficiencies (mainly in the canals at the third level) combined with the drop in the demand, while a large volume of water still remains in the canals upstream.

Graphs (c) and (d) show the state of the *Total Actual Farmed Area* in both runs. In the Vast-Release Run, there are no losses of agricultural production in the Farmed Areas, obviously because of the huge amount of water supply. In the Adjusted-Release Run, there are some agricultural losses as the third level canals do not receive the sufficient amount of water at the right time. Finally, graphs (e) and (f) show the difference in the behaviour of the water levels in the first level canals in both runs.

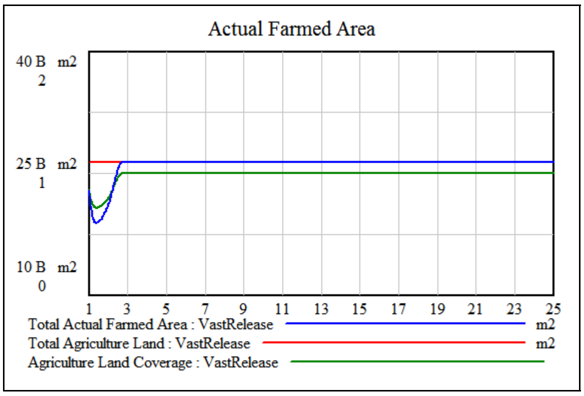
Vast-Release Run | Adjusted-Release Run



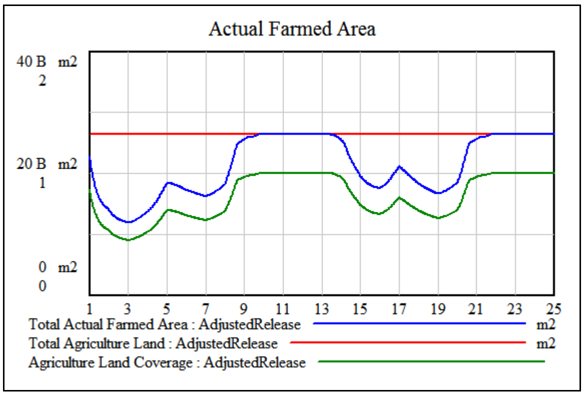
(a) The water supply at 1st level canals Vast-Run



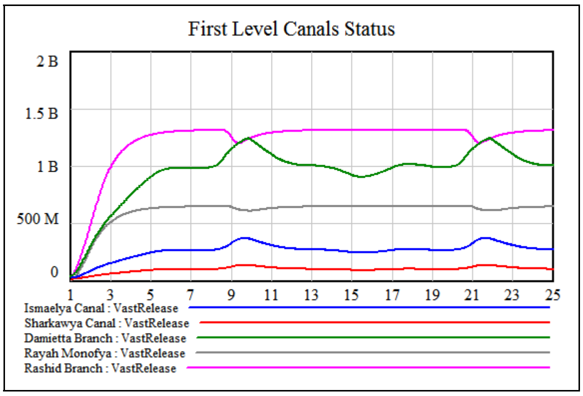
(b) The behaviour of the same canals in Adj-Run



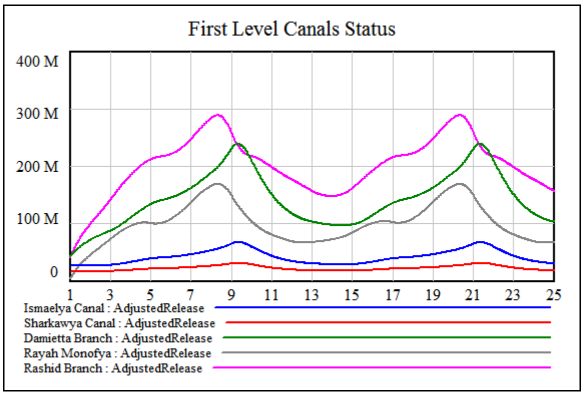
(c) The Actual Farmed Area in the Vast-Run



(d) The Actual Farmed Area in the Adj-Run.



(e) The behaviour of the 1st level canals Vast-Run



(f) First level canals' behaviour in Adj-Run.

Figure 7-29: The difference in the model behaviour.

Figures 7-30 shows the behaviour of the canals at the second level. In the Adjusted-Run (on the right-hand-side), the canals fluctuate in accordance with the water demands. In the Vast-Run, canals at the East of the Delta oscillate with small amplitude, while the canals at the Middle and West of the Delta are stable regardless of the change in the water demands.

Vast-Release Run Adjusted-Release Run

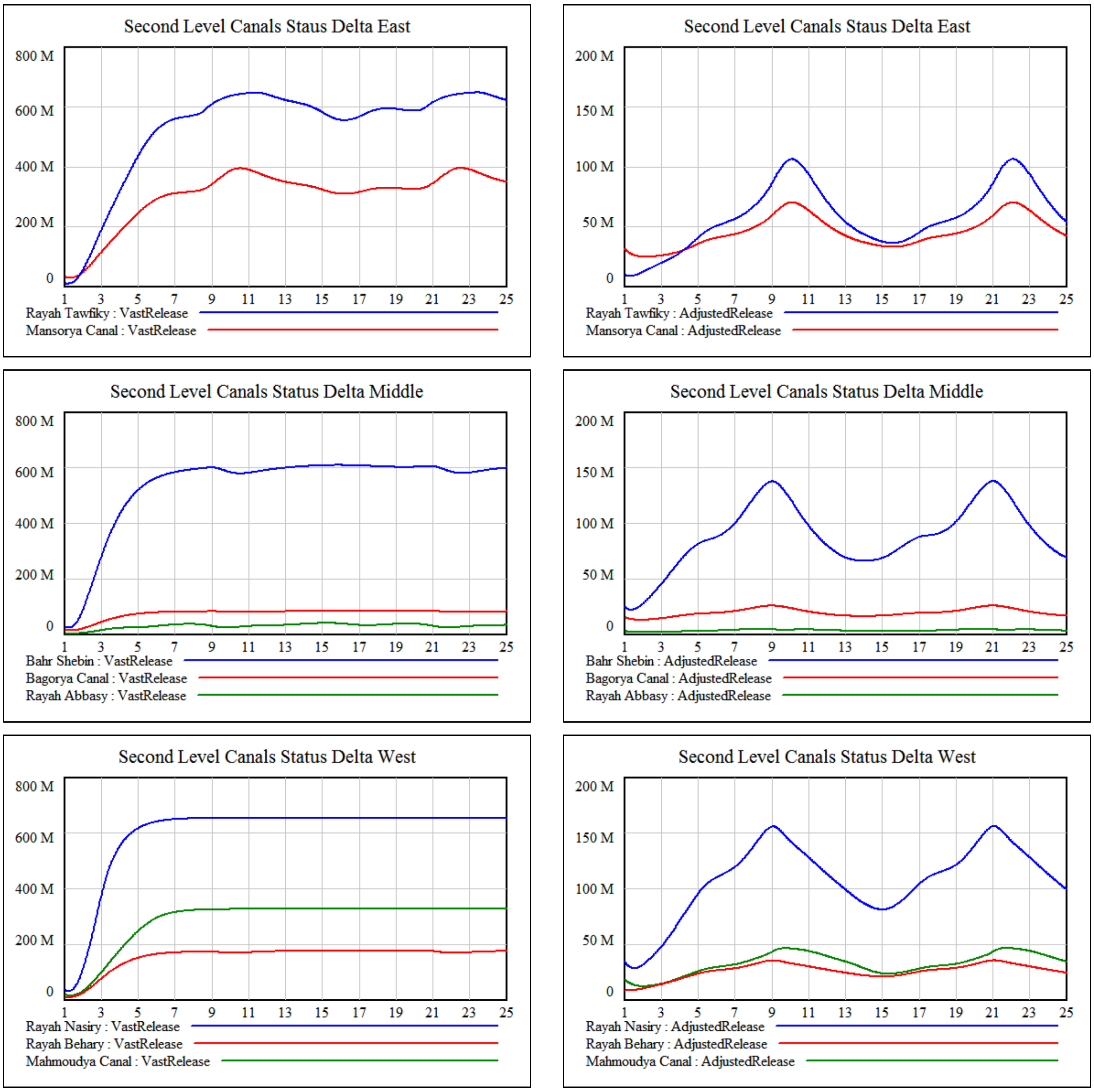


Figure 7-30: The behaviour of the second level canals in the Vast-Release Run *(Lift)* and in the Adjusted-Release Run *(Right)*.

Figure 7-31 shows the behaviour of the canals at the third level. In the Adjusted-Run, the canals are fluctuating in response to the fluctuation in the water demand. Notable, the oscillation behaviour has larger amplitude than it has in the second level canals. These canals are at the tail of the system, meaning that it receives their water supply after the canals upstream have acquired their demands. The effect of the delivery-delays in this part of the system becomes more influential resulting in these high fluctuations. In contrast, the canals at the three Delta zones in the Vast-Run appear stable.

Vast-Release Run | Adjusted-Release Run

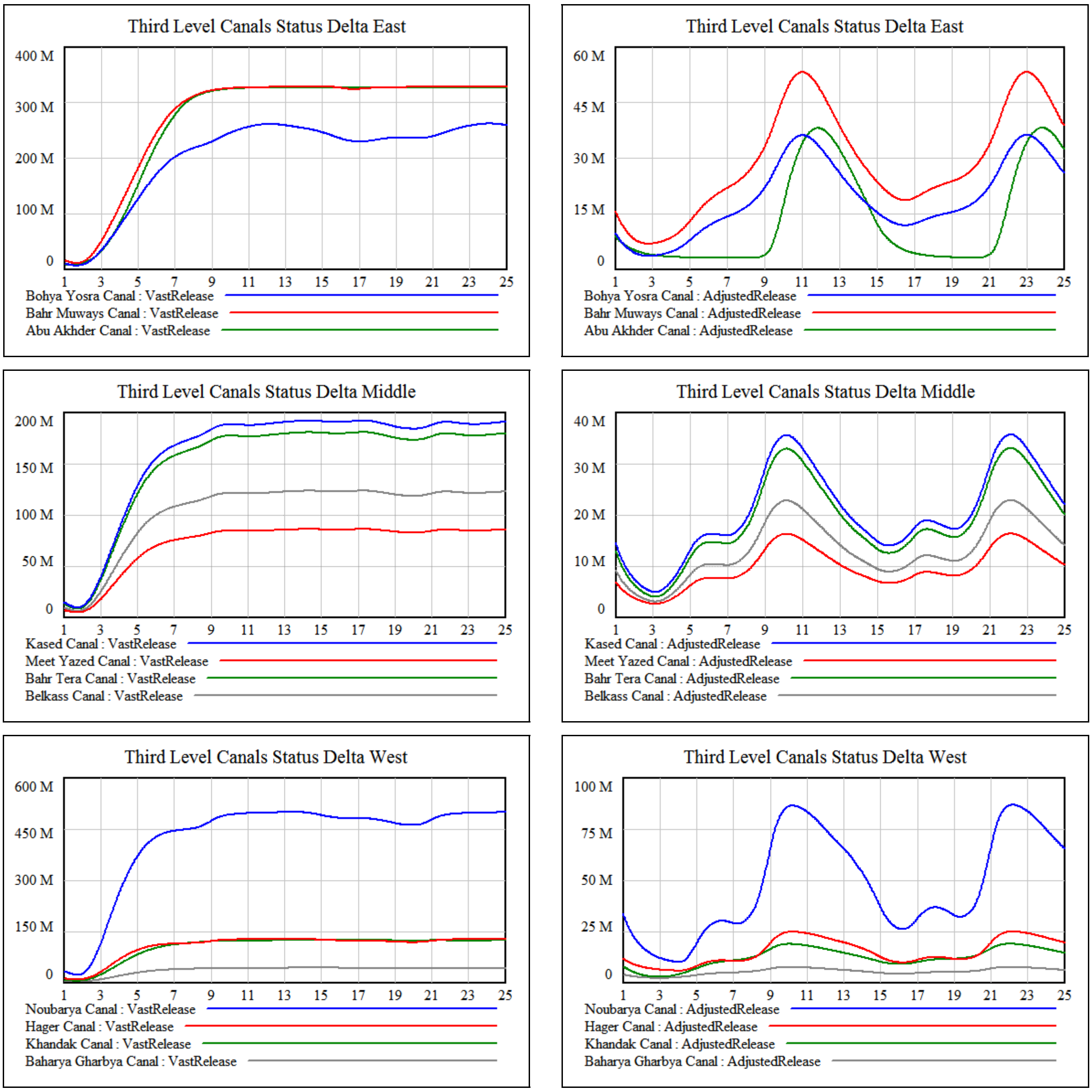


Figure 7-31: The behaviour of the third level canals in the Vast-Release Run *(Left)* and in the Adjusted-Release Run *(Right)*.

Let us contrast the results form the two runs: the behaviour of the system in the Vast-Release Run, results from a release of 220 MCM/day, exercised by MWRI. Obviously, the water supply is very high and a large quantity of water is wasted. On the contrary, the behaviour of the system shown in the Adjusted-Release Run (where the supply equals the demand) exhibits a considerable water saving. However, the simulation did not produce the favourable behaviour regarding the agriculture lands irrigated from the canals at the third level (e.g., there are agricultural losses in the *Actual Farmed Area*).

To solve this dilemma, we used the SDGIS application to simulate the model step-by-step seeking to synchronize the supply with the demand in a way that satisfies both our goals (i.e., to save water and at the same time provide sufficient water for the canals at the third level). The results from this run, called *Test-Synchronization* Run (abbreviated as TestSync in the following graphs), are shown in Figures from 7-32 to 7-37.

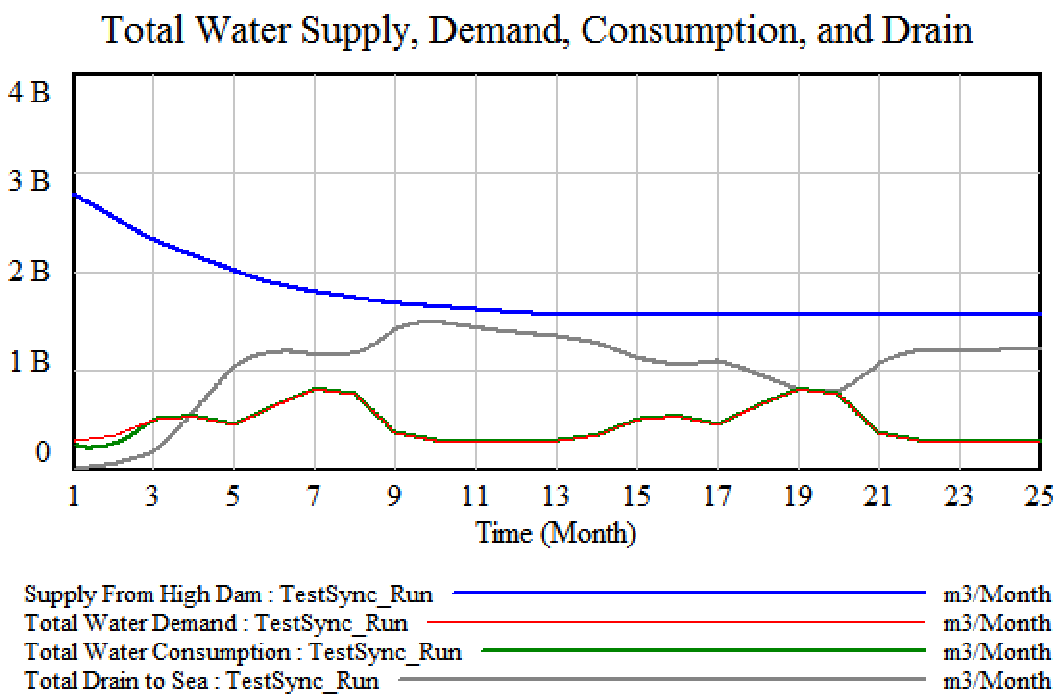


Figure 7-32: The *Test-Synchronization* Run results.

In Figure 7-32, we start the simulation by releasing 160 MCM/day (instead of 220 MCM/day) and gradually reduce the release to 90 MCM/day while observing the behaviour of the *Total Water Consumption* and the *Actual Farmed Area* every time step. As shown in Figure 7-33, the water consumption (appearing as the green line in this run) has been lifted to meet the water demand. Consequently, the *Actual Farmed Area*, shown in Figure 7-34, does not suffer any losses and at the same time, we have obtained a significant reduction in water drained to the Sea (i.e., water losses) as illustrated in Figure 7-35.

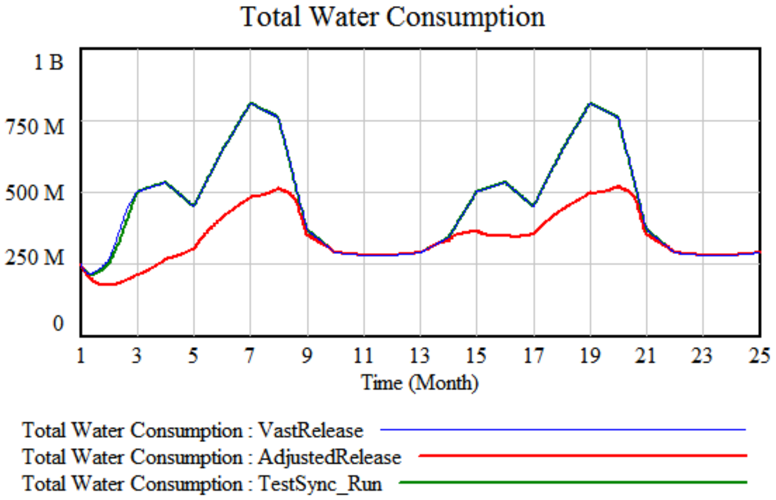


Figure 7-33: The water consumption comparison

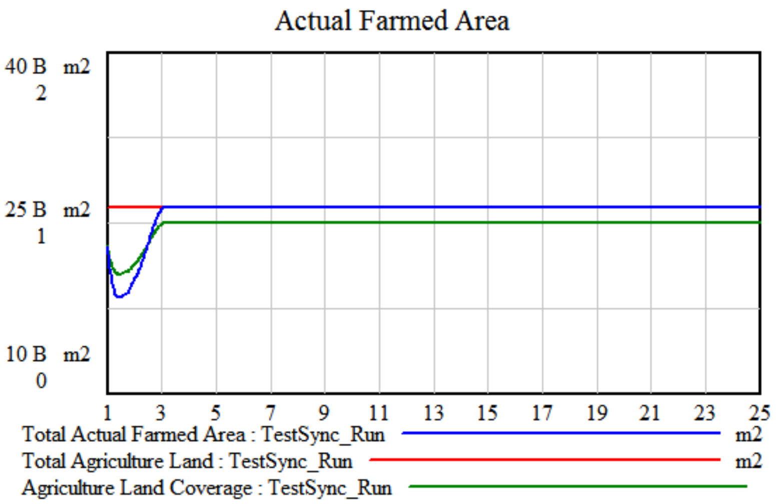


Figure 7-34: Actual Farmed Area in Test-Sync Run.

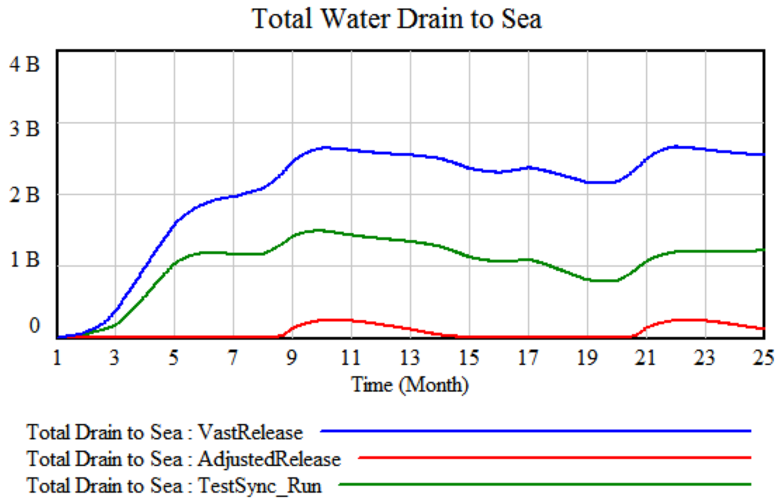
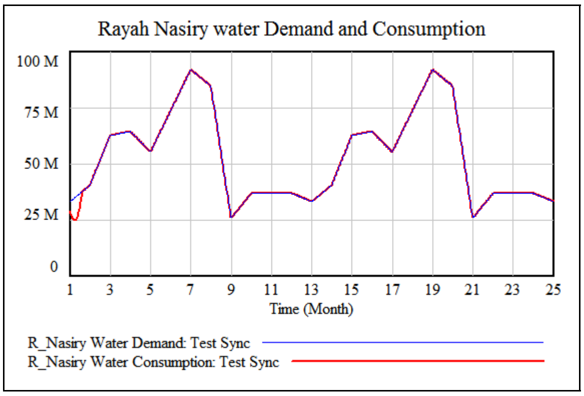


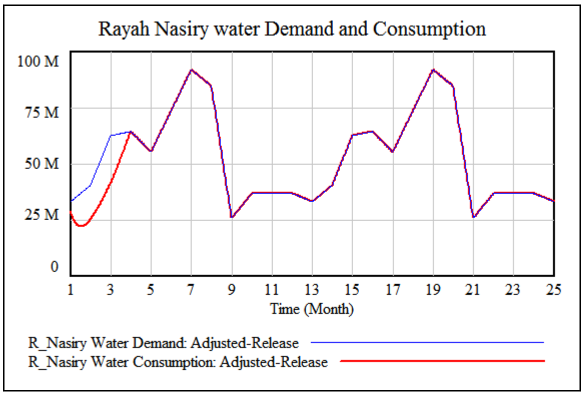
Figure 7-35: The total water drain comparison

More results are shown in Figures 7-36 and 7-37. Figure 7-36 includes three graphs illustrating the behaviour of the water demand and the water consumption in the Rayah Nasiry (at the second level), the Noubarya Canal (at the third level), and the Hager Canal (also at the third level), respectively at the Test-Synchronization Run. We compare these graphs with their counterparts in the Adjusted-Release Run. In both runs, the canals at the second level, appearing in graph (a) and (b), have a satisfactory behaviour (the water consumption matches the water demand), and therefore, there are no agriculture losses in the Actual Farmed Area, appearing in Figure 6-37 (a). However, the inadequate behaviour of third level canals in the Adjusted-Run (see graph (d) and (f) in Fig. 7-36), has been significantly improved in the *Test-Synchronization* Run (see graph (c) and (e) in Fig. 7-36). Consequently, the Actual Farmed Areas irrigated from the Noubarya and Hager canals for example, have avoided the agriculture looses witnessed before in the Adjusted Run as illustrated in Figure 7-37 graph (b) and (c). This means that our policy to synchronize the supply with the demand has successfully achieved our two goals (i.e., to save water and at the same time provide sufficient water for the canals at the third level).

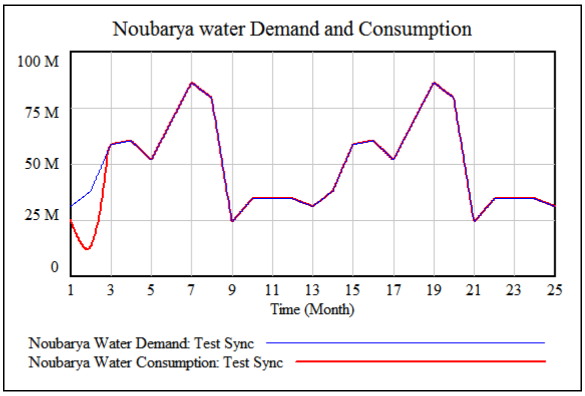
Test-Synchronization Run | Adjusted-Release Run



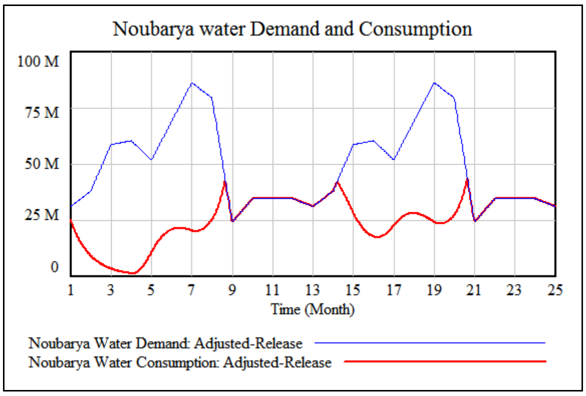
(a) Rayah Nasiry Water Demand & Consumption



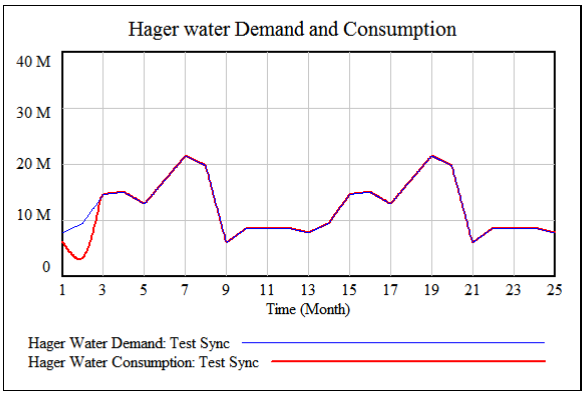
(b) Pervious behaviour in Adjusted-Run



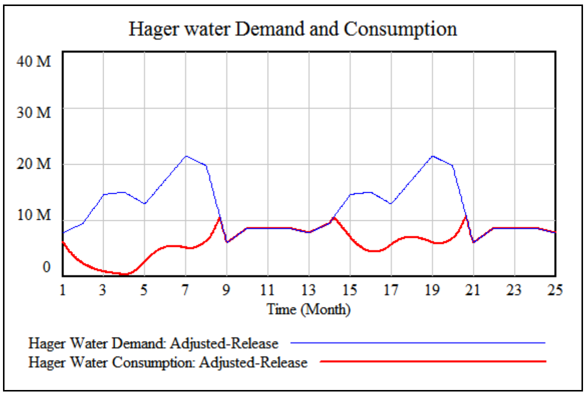
(c) Noubarya Water Demand & Consumption



(d) Noubarya behaviour in Adjusted-Run

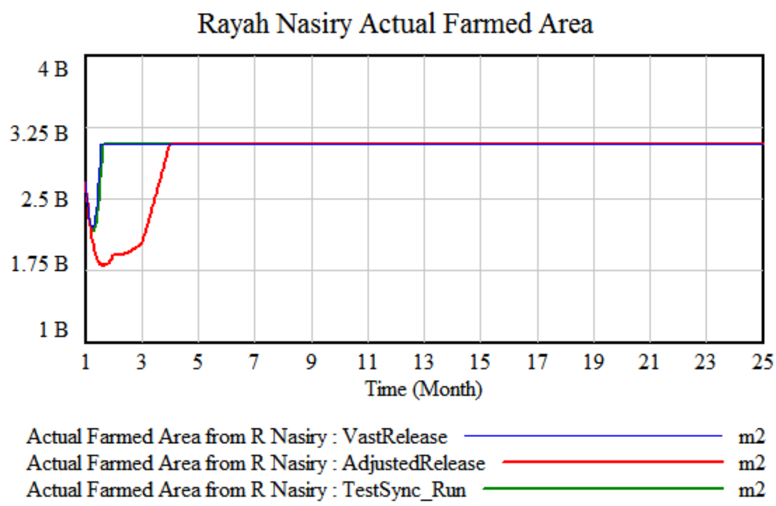


(e) Hager Canal Water Demand & Consumption

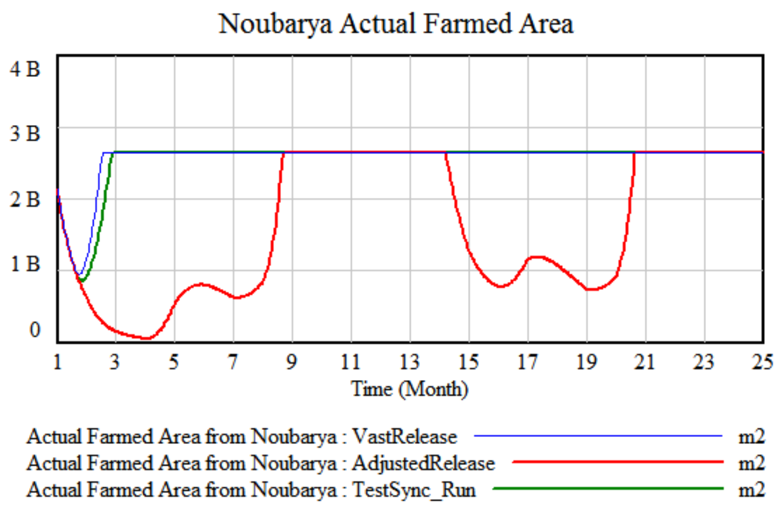


(f) The Hager behaviour in Adjusted-Run

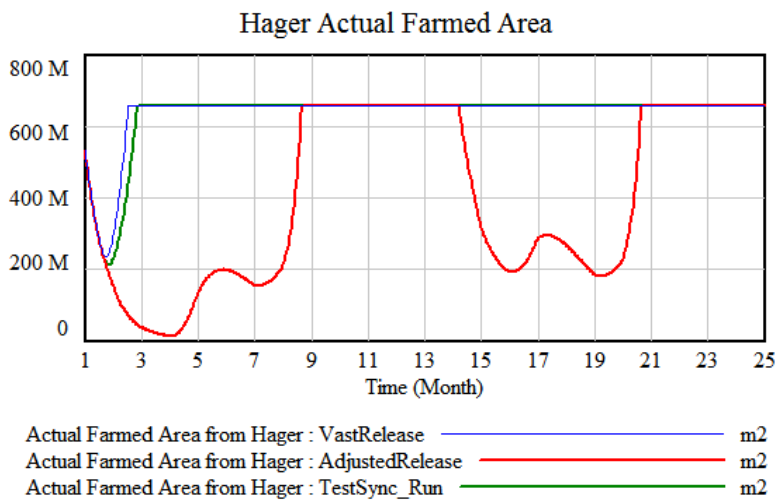
Figure 7-36: the water shortages in canals at 2nd and 3rd Levels.



(a) The Actual Farmed Area irrigated from the Rayah Nasiry.



(b) The Actual Farmed Area irrigated from the Noubarya Canal.



(c) The Actual Farmed Area irrigated from the Hager Canal.

Figure 7-37: A comparison between the AFA behaviour in both runs.

This example demonstrates the potential benefits of using the SDGIS application. During the simulation runtime the user may choose to change the amount of water released from the High Dam using the *Supply Slider*. As illustrated in the first two runs (Vast-Release, Adjusted-Release), the behaviour of the system is largely influenced by the amount of water released. In that, the system may exhibit either an over-supply and sever waste of water or, water shortages and agricultural losses in Farmed Areas. In such a situation, the irrigation system operators and managers must seek the best strategy to satisfy the water users and at the same time save water. They may use this application to develop and test such strategy. The application provides various tools such as the *Supply Slider* (to change the water release), the control gates (to divert water within the network), Text-Boxes to set cropping patterns, etc., to adjust the supply with the demand, and ultimately, to develop and test such a strategy which we consider to be a real challenge.

In our subsequent discussion, we try to shade light on the relationship between the water supply and the water demand in the case of Egypt.

Discussion:

Considering the Nile flood season described in chapter six (section 6.3.2), the Egyptian agricultural calendar is divided into three seasons: the summer season from 1st of April to 1st of August; the flood season from 1st of August to 1st of December; and the winter season from 1st of December to 1st of April. The chief crops of the summer are corn, cotton, sugarcane, and rice. Corn and rice are cultivated in the flood season too. Wheat, barley, beans, and clover are the most important winter crops. Winter was formerly the principal agricultural season, following the rise of the Nile as it did before the High Dam construction. But under perennial irrigation, crops can be grown all the year round. We must notice that seasons sometimes overlap; crops are frequently sown before those of the previous season are harvested. In this way, about one-half of the agriculture land of the Delta is made to produce two crops a year. In the case of cotton, for example, the planting process begins in February and lasts until early April. The land is watered once before planting, and again after the seed is sown. Thereafter it is watered at intervals of fifteen to forty days. Between late August and early November the fields are picked over two or three times; and when the cotton has been removed, clover is usually sown as a winter crop, also under irrigation. Some fields are made to yield three crops annually, if carefully selected crops are planted.

The flood calendar describes the supply side while the agriculture calendar represents the demand side. The two calendars are, to large extent, correlated and there is a lag / shift between them. In fact, the agricultural calendar depends on the flood calendar. Any slight disturbance in the flood inflow will result in a magnified disturbance in the agricultural rotation. Farmers may not be able to cultivate the land if the water inflow is curtailed, or they may miss the opportunity to cultivate the desirable crops if the water inflow is delayed, forcing them to plant alternative crops. This compulsory shift in the cropping pattern feeds back to alter the water demand plans that were previously prepared by the MALR and delivered to the MWRI to set the water release schedule.

Based upon the cropping pattern submitted by MALR, the national water demands for irrigation are calculated by the MWRI who sets the corresponding schedules for water release (water supply). However, regarding the cropping pattern plans prepared by MALR, the process by which the data is gathered at the cooperative level, one may experience significant over-estimates of cultivated land area and inaccuracies in cropping patterns. Evasion of regulations concerning land use is commonplace, particularly in the transferral of agricultural land to residential use, and it is estimated that arable land area may be overestimated by up to five percent [Radwan, 1997].

In addition to the overestimation of available land, the MALR conducts only a general overall recording of farmers' cropping patterns, - one that covers only the principal crops (maize, wheat, clover, cotton). The minor vegetable crops are not recorded, nor the short season *corn fodder* crop grown from October to December. This imprecision in the recording process goes back to the era of the quota system, -

i.e., when farmers were forced to deliver a certain quota from their land yield to the landlords (or to the regime). This legacy has led farmers to supply inaccurate data about their cropping patterns and encouraged cooperative officials to concentrate on recording areas for only a narrow range of specified crops. Such inaccuracies give rise to important variations between the actual and officially calculated crop water requirements. This is most significant, for example, for the *corn fodder*. If official calculations were to be applied precisely, there would be a deficit during that period (from October to December) of 22% of the water requirements. Furthermore, when using regional cropping patterns as a basis for deciding water requirements, one ignores requirements caused by the canal/mesqa level variations. Finally, it was noted that the optimal planting and harvesting dates were assumed to be valid across the various regions, yet observations in the field indicates that farmers' actual planting and harvesting dates would often be delayed or put forward up to one month as a result of various localized factors.

[Radwan, Lutfi 1998] studied the water flow patterns along the ditches and the main distributor canal in the Monofya province (at the Middle of the Delta). Measurements of flows indicated that the inflows to the majority of ditches were above the demand throughout the entire year (see Figure 7-38).

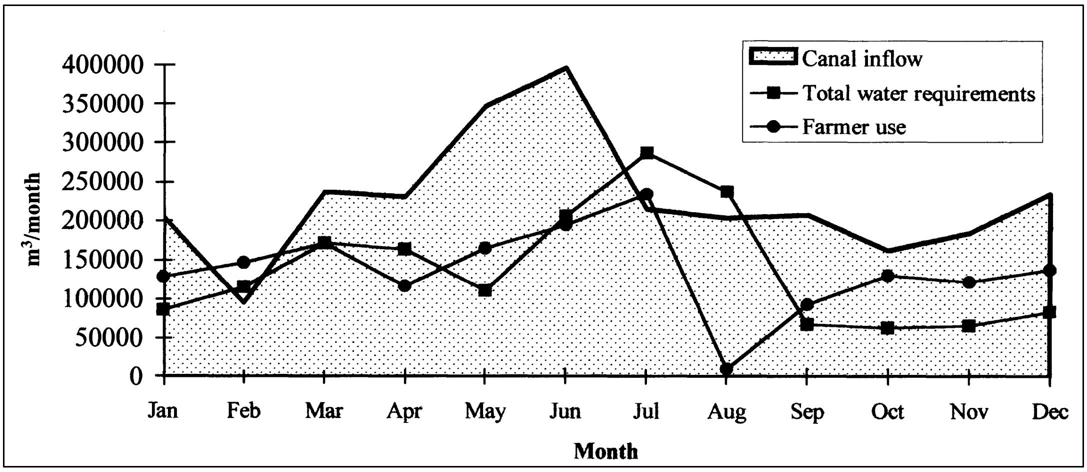


Figure 7-38: Total water requirements, farmer use and canal inflow at Um-Aisha Mesqa. Source: Radwan, Lutfi 1998

He compared the actual inflow into one mesqa, called Um-Aisha, to the observed farmer use patterns and both were contrasted with: (i) the total water requirements calculated from local data on cropping patterns, (ii) planting/harvesting dates and conveyance efficiency. He found that whilst farmer use patterns exhibited a high degree of correlation with estimated total water requirements, the actual releases into the canal were 64% higher than the total water requirements for this period (including all conveyance requirements). He concluded that this pattern of over-supply was largely the result of the mismatch between the supply and demand, and that there is a need to ensure that sufficient water is available when farmers need to irrigate.

The irrigation department officials defend such behaviour (over-supply patterns) by claiming that individual farmers at the head of the canal are over-using and wasting water. Therefore, additional water is supplied to ensure that sufficient water reaches farms located further along the canal (tail-enders). In reality, field observation have indicated that this argument could not be applied to most of the ditches where tail-end water levels were generally high and few tail-enders mentioned any serious occurrences of shortage.

Most of the discrepancies between supply and demand result from the variance between the officially estimated cropping patterns, planting/harvesting dates, and those actually observed. Briefly, the origin of the problem lays in the *lack of integration* between the MWRI-administered rigid patterns of supply and the informal farmer patterns of demand.

To close, the SDGIS application has been employed to test various scenarios. Each scenario includes a different cropping pattern and different conveyance efficiencies for the canals. Using the *Supply Slider* to change the water release (supply schedule) and the control gates to steer the water flow (to divert water from one portion to another), several runs have been performed and analysed. As a general observation, we found that if supply patterns more closely matched the demand patterns, it would be possible to obtain a significant reduction in total water consumption and the water losses could be minimized. However, it is unlikely that demand patterns be greatly modified and the change must, therefore, occur in the supply pattern. This is due to a number of reasons, one of them is the popular crop-rotations inherited and used by farmers and, therefore, it would be difficult to impose a rigid structure of patterns of demand as these are varying in response to a wide range of social, physical and economical influences. Planting and harvesting dates can be delayed or brought forward for many reasons and consequently, rotational and daily irrigation patterns will be affected. It is necessary, therefore, that the supply patterns be in some way modified to match more closely the demand pattern. This is likely to be effective only if farmers are involved in defining the actual agricultural water requirements (i.e., water demand plans).

7.4.3 Cropping Pattern Policy

The effect of changing the cropping pattern has been demonstrated in chapter six (section 6.4). For the purpose of this chapter (i.e., to demonstrate the capabilities of the SDGIS application), a new map called Crop-Distribution has been developed to represent our scenario of redistributing various crops on the agriculture land[55]. The map is based on our personal knowledge regarding the popular dominant crops in each province in the Delta. In this map we tried to achieve a balance in distributing the three cropping patterns considered in the SD spatial model in each zone in the Delta. Figure 7-39 shows the agriculture lands and their corresponding canals (i.e., the number appears on each land is the Ncode of the canal that serves this land). Figure 7-40 shows the Crop-Distribution map where the number appearing on each land is the *Crop-Type* assigned to that land (e.g., *Crop-Type* group one, two, or three). In fact, we can use the Model Initialization panel to assign the various *Crop-Types* to the agriculture lands and will obtain the same results, but we chose to do it in this way to demonstrate the flexibility of the application to allow for the integration of new maps. In real world, managers and planners (water allocation planners, agriculture planners, or agro-economists)

[55] Notice that we do NOT suggest a certain cropping pattern to be implemented. Rather, we just developed the map to demonstrate the capabilities of the application.

usually need to develop a number of maps, each of them representing an alternative for crop distribution. Such maps are developed based on a certain criteria (e.g., the dominant crop). It might be useful to provide each map with a unique name and store it alongside with its simulation results for further comparison and evaluation. Thus, using the SDGIS application will greatly help managers and planners to test and evaluate each alternative (map). In this example, we have distributed the three cropping patterns over the three Delta zones as shown in Figure 7-40. Then, the Crop-Distribution map has been loaded into the application as shown in Figure 7-42. The model has been simulated for one year and a new run called CropDistribution has been created.

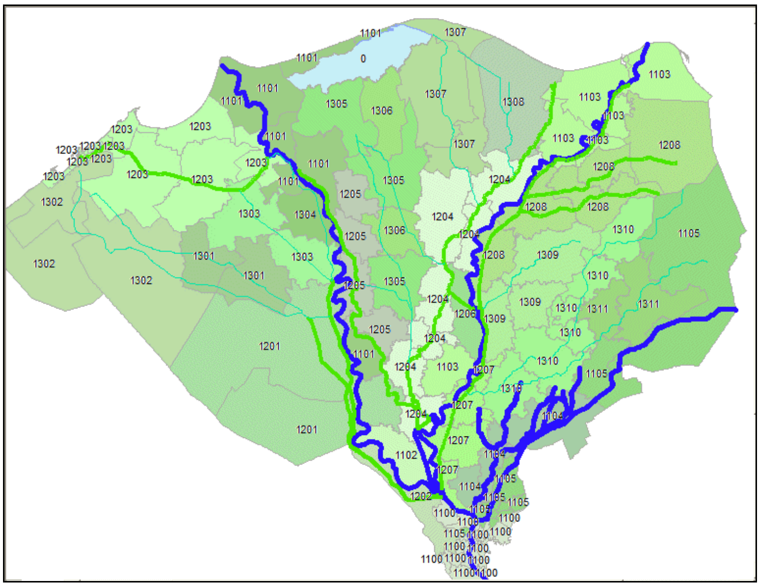


Figure 7-39: The Agriculture land and the correspondent canal.

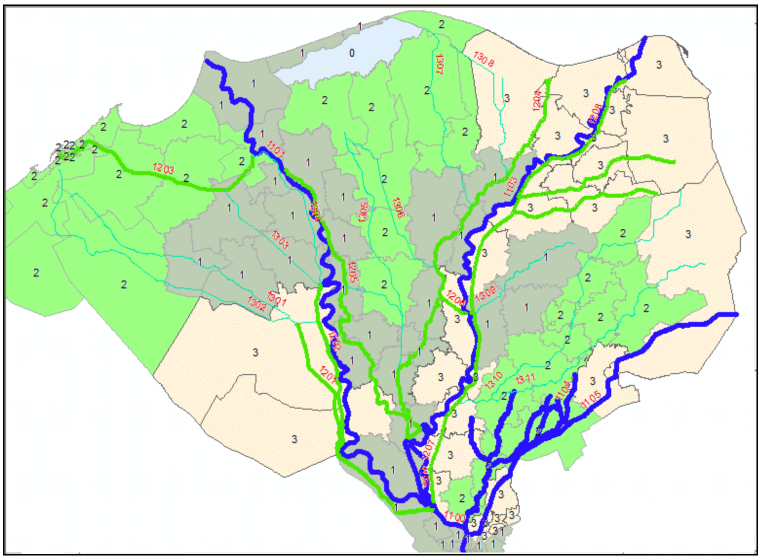


Figure 7-40: The Crop Distribution Map.

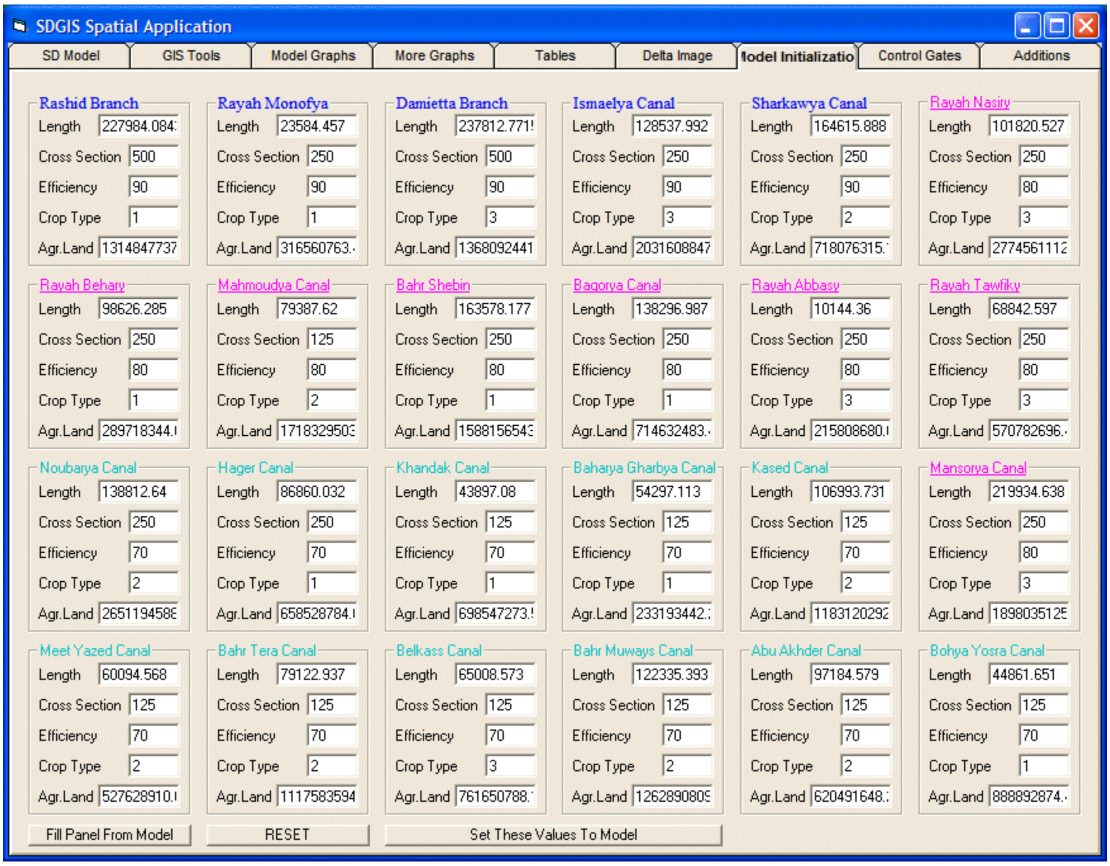


Figure 7-41: cropping patterns initialization.

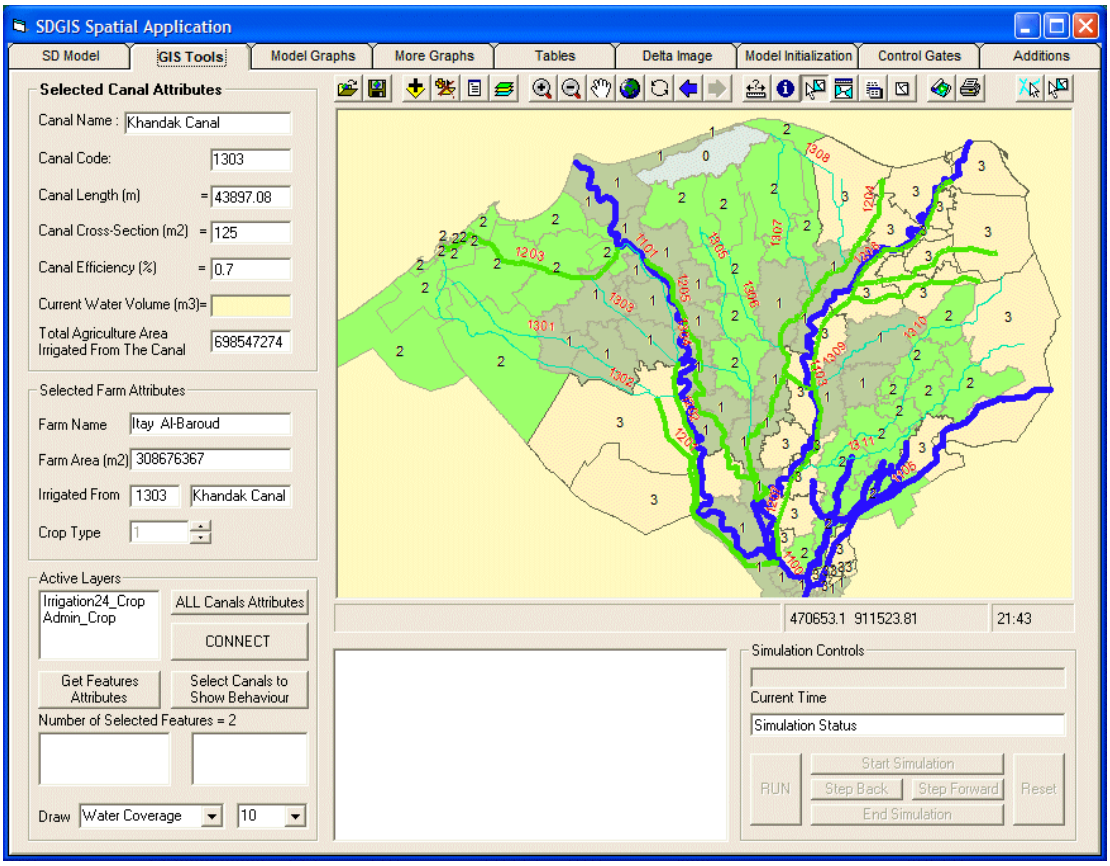


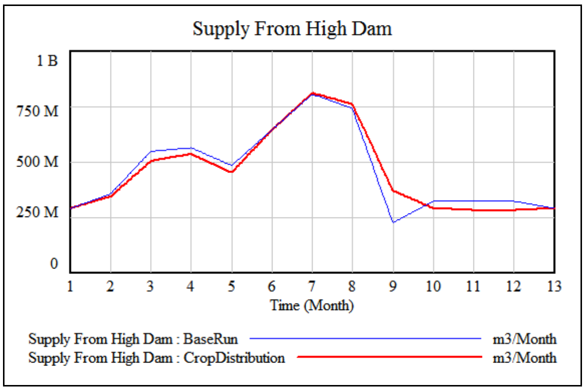
Figure 7-42: The crops distribution map.

Figure 7-43 show the results of the CropDistribution Run compared to the Base-Run. Graph (a) shows the difference in the quantity of water released from the High Dam with respect to the change in the water demands. In general, there is some overall water saving over a period of a year, except in August and September months, which can be compensated by the Nile flood. This can also be noticed in graph (b) that illustrates the behaviour of the Nile River. Graph (c) shows the difference in water consumption in the agriculture lands irrigated from Rayah Monofya (a first level canal at Middle of the Delta). There has been a significant water saving. In graph (d), the water consumed by the agriculture lands irrigated from the Damietta Branch has been almost the same. However the pattern of water release has changed. There is an increase in water demand in September and October (which can also be covered by the Nile flood). Much the same is noticed in graph (e) that portrays the change in water consumption in the agriculture lands irrigated form the Ismaelya Canal (a first level canal at East of the delta). Some may argue that this cropping pattern scenario (represented in the Crop Distribution map) has not significantly changed the overall situation regarding the water consumption (i.e., the *Total Water Consumption* shown in graph (f) has not been changed significantly). However, the overall behaviour of the system shows an important shift in the *time* that the water demand presents itself and, consequently, the water requirement is moved towards the flood season period. This lifts the burden from the months when the supply of water is supported by the dammed up water.

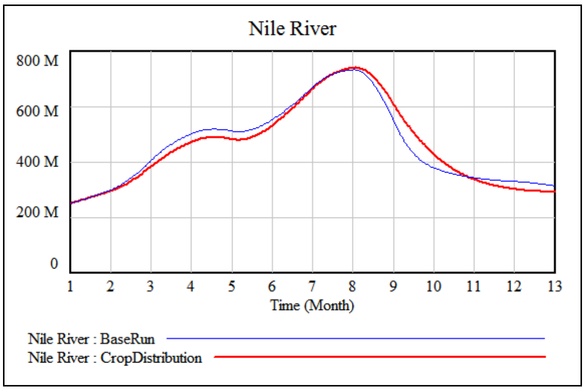
In the following paragraph, we discuss the feasibility of applying a cropping pattern optimization policy in the case of Egypt. We do so from a somewhat broader perspective.

Discussion:

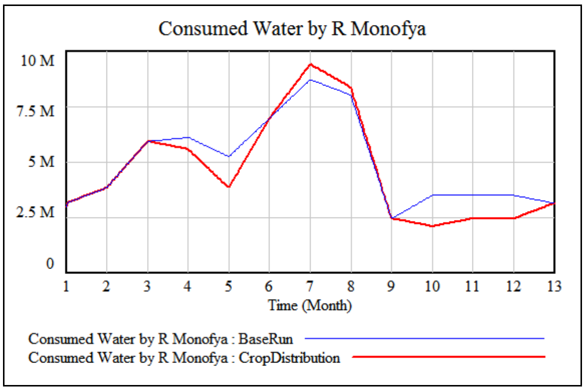
Historically, the single most important change in the cropping pattern in Egypt's modern history was the introduction of cotton during the reign of Muhammad Ali (1805-1849), because it led to the transformation of irrigation methods. Cotton requires a good deal of water in summer when the Nile water is low, and it must be harvested before the flood season. This necessitated the regulation of the Nile flow and shifting the irrigation method from basin (flood) to perennial (roughly, on demand) irrigation. Perennial irrigation not only made cotton growing possible, it also permitted double and even triple cropping on most of the arable land. Furthermore, it enabled farmers to switch the crop rotation from three-year cycle to two-year cycle. The original three-year cycle included clover and cotton in the first year, beans and fallow in the second year, and wheat/barley and corn in the third year.



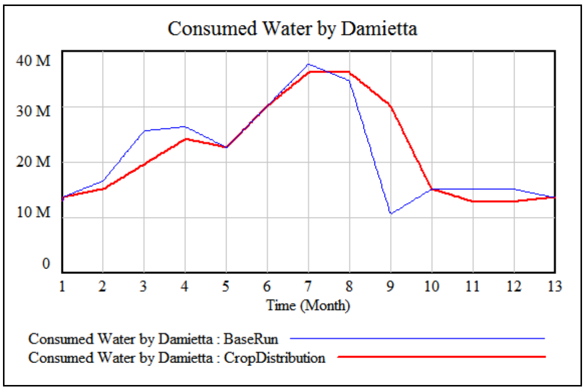
(a): The difference in the water supply.



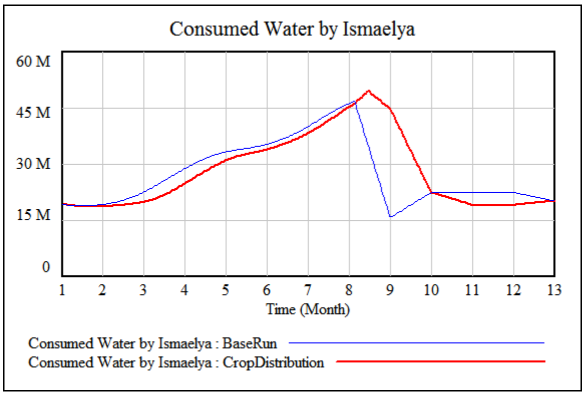
(b): The Nile behaviour in both Runs.



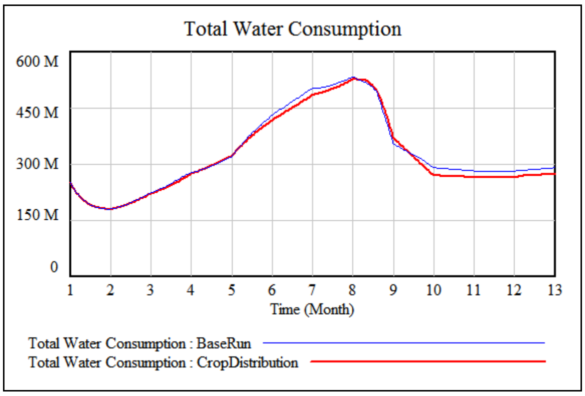
(c): consumed water in Monofya Agr. Land



(d): consumed water in Damietta Agr. Land



(e): consumed water in Ismaelya Agr. Land



(f): The total water consumption.

Figure 7-43: The CropDistribution Run results compared to Base-Ran results.

The two-year cycle consisted of clover or fallow followed by cotton in the first year, and wheat/ barley or beans followed by clover and corn in the second year. By year 1890 about 40 percent of the land was put on a two-year rotation. The biennial rotation was believed to be harsh for the land, and the government tried to eliminate it in 1950s. In 1990s, farmers have resorted to both rotations flexibly.

Using the SDGIS application to study the effect of applying various cropping patterns on water consumption, the application exhibited a significant change in the patterns of water demand when we assigned different crops for agriculture lands (see the example above and the example in section 6.4.3). This has raised the question “what is the optimum cropping pattern that will achieve: (i) the ultimate utilization of water and the agricultural land, and (ii) the highest profitability for farmers’ welfare and the economy of the country at large?”

[Saleh and Bayoumi, 2004] have tried to answer this question. They conducted a remarkable study concerning the optimum cropping patterns that may be applied in Egypt. They state that “the current cropping pattern is not economically efficient in terms of the utilization of the available water resources, and major improvements should be done”. They suggested a certain cropping pattern that would achieve the best economic utilization of water resources. They developed an “optimization model” to obtain the optimal cropping pattern for Egypt, which maximizes the net income return per cubic meter of water. The results of their study are summarized in Table 7-2.

As Saleh and Bayoumi pointed out, the proposed improvements would save around 4.2 BCM of irrigation water. However, the net agriculture income would decrease by 100 million pounds. Nevertheless, the 4.2 BCM water saved can be used to cultivate new reclaimed land, which in turn will generate an additional agriculture income. This newly reclaimed land can be planted with wheat in the winter season and maize in the summer season [Saleh and Bayoumi 2004].

Table 7-2: Optimal Results of the FPP[56] (thousand faddans)

	Crop	Land planted in year 2002	Optimal Land indicated	
			Local Scenario	International Scenario
1	Wheat	2450	2869.4	2400
2	Barley	79	72	72
3	Broad bean	303	165	165
4	Chickpeas	17	11	11
5	Fenugreek	16	3	20
6	Lupine	9	6	6
7	Lentil	5	4	4
8	Sugar beet	300	300	300
9	Winter clover	1960	2000	1800
10	Flax	21	21	21
11	Winter onion	64	25	80
12	Garlic	21	30	30
13	Winter tomatoes	173	173	173
14	Winter potatoes	77	77	77
15	Maize	2078	2078	2078
16	Sorghum	382	251	251
17	Rice	1340	811	811
18	Peanut	151	78	82.957
19	Sesame	68	52	52
20	Soya bean	13	9	9
21	Summer onion	24	15	30
22	Sunflower	46	32	32
23	Summer potatoes	113	130	130
24	Summer tomatoes	273	300	300
25	Cotton	731	600	600
26	Sugarcane	312	222	222
27	Summer clover	44	50	17

Source: Saleh and Bayoumi, 2004

Despite the significant results of this study, it does not consider the geographical distribution of the crops, which is affected by many factors such as the land availability in different zones, the local climate variation between north and south, the land fragmentation and the size of farms, the soil quality and fertility, and above all, the farmers' acceptance. Here we may recall the spatial correlation relationship mentioned in the introduction paragraph of chapter six -i.e., whatever is causing an observation in one location also causes similar observations in nearby locations. For example, the planting of certain crops in nearby areas within a province tend to caused by factors such as socio-economic status; so that the features that attract one farmer will also attract others. Second, in terms of land availability for

[56] FPP stands for Function Programming Problem. This is the main function that has been used in their optimization model. For more details see [Saleh and Bayoumi 2004].

example, the Nile banks in the south range from 4-18 kilometres span and are surrounded by plateaus and mountains which limit the expansion of agriculture, unlike what is the case in the Delta region, which is widely open, flat, and have no barriers for expansion. These issues should be considered when studying the cropping pattern policies. Moreover, the differences in climate conditions (rainfall, temperature, moisture, etc.) between the north and the south have, in many respects, an impact on the geographical distribution of crops. For example, humidity in the Delta suits long-staple cotton while the dry-hot climate of the south favours planting sugarcane, onions, and lentils.

In terms of land fragmentation[57], cropping patterns and crop yields differ depending on the farm size. It is difficult to describe farming patterns in more detail, because the available information is inconclusive and sometimes contradictory. A survey of three Delta villages conducted in the year 1984 indicated that farmers who cultivated one *faddan* or less were more likely to grow cotton than those with holdings greater than ten *faddans*, a conclusion that contradicted findings of an earlier study. It also revealed that yield levels of different-sized farms varied by crop. For instance, wheat yields were higher on small farms, while the opposite was true for rice. The reasons were not clear, and the findings contradicted a large body of evidence from other countries that showed yields were invariably greater on small farms. There was an agreement, however, that larger farms produced proportionally more fruit crops, probably because the large capital investment and the long-term

[57] In 1950s and 1960s, agrarian reforms undertook the land redistribution and set the ceiling for individual land holdings by the average of 2.1 faddans per landholder for the whole country. The land is continuously subjected to subdivision through inheritance [Holmen, 1991]. Notice that cultural patterns also facilitate further fragmentation. The farmers prefer to buy a plot in the old lands where the size of the land is already small neglecting the possibility to purchase the lands in reclaimed areas where the size of landholdings are considerably higher. Thus at present 7.8 million faddans are under cultivation of 10 million landholders with average less than one faddan per landholder. Trends of land fragmentation is more severe in old lands where only 10% of landholdings exceed 3 faddans, and 7% of landholdings from 3 to 5 faddans, and the rest is less than 3 faddans [DWIP, 1997]. It is expected that due to population increase and limited land availability, the size of the farms might further decline. This will negatively affect the efficiency of the irrigation system, as a part of water is lost during the distribution to each small tiny plot [MWRI, 2002a].

commitment required would be prohibitive to small farmers, who needed more flexibility.

Despite our concerns mentioned above, Saleh and Bayoumi's study is valuable and maybe applicable if the agriculture lands and their suitability for various crops are carefully selected.

7.4.4 Water pricing policy

Irrigation water pricing is one of the widely recognized measures for demand regulation. The main objective of the water pricing policy is maximizing efficient allocation of water resources and promote water conservation, while at the same time not compromise the social objectives such as affordability of water resources [Rogers et al., 2002]. According to Rogers, the full price of water consists of "operation and maintenance" cost together with capital charges, adding economic and environmental externalities. Different methods have been used for pricing, which can be classified into four major categories: volumetric pricing, non-volumetric pricing (based on land size or crop cultivated on land), quotas, and water markets [Johansson, et al., 2002; Yang et al., 2003]. During the fieldwork, we have focused on the first two pricing mechanisms leaving out the quota and market considerations.

[Ahmad, 2000; Mahmood, 2000; Bazza and Ahmad, 2003; Massarutto, 2002, 2003] argued that charging farmers for water, would induce incentives for eliminating wasteful irrigation practices and alter the cropping patterns, shifting it towards crops that consume less water but have high values.

In view of the water scarcity threats in Egypt, limited and almost exhausted sources for supply and heavily subsidized irrigation service raise the question why this economic instrument has not been implemented in Egypt?

Water pricing has many constraints. First of all, it is the cultural perception, believes sanctioned by religion and tradition, which perceive water, not as a commodity, but one of the basic human needs. It is a free gift from God for all to share and, therefore, can not be traded. Thus, the perception of water as a non-commodity resource averts the introduction of charging for irrigation services [Abu-Zeid, 1998; Rogers et al., 2002].

Water pricing was unacceptable for Egyptian reality in most of the discussions that were conducted during the fieldwork. The representatives of MWRI, Ministry of Social Affairs, and farmers were opposed to the idea of imposing the irrigation service charge due to affordability reasons. However, there were some respondents who do recognize the significance of a water pricing policy for valuing water, to convey the main massage to the users regarding the water scarcity problem, and to reduce the burden of subsides.

[Perry, 2001; Rogers et al., 2002] argued that water pricing policy as an effective measure for water conservation causes some doubts, as the practice (in various countries) does not confirm the emergence of water saving habits among farmers if they have to pay a fixed price/charge for water per hectare. In this situation the cost for maintenance and operation might be recovered, but the main objective of water saving is not achieved, as farmers do not have the motivation for optimizing the water use. Only high prices would result in substantial water saving levels, but will compromise the social welfare of user groups.

From a personal perspective, high charges for water will increase farmers' payments and negatively affect their income levels. The majority of the poor population is settled in rural area and is mainly involved in agricultural activities. The average land size is quite small (see land fragmentation notes above) and the majority of farms are subsistence farms. Produced food in such farms is mainly for family uses; the surplus is sometimes sold on markets. Therefore, the vulnerability of such farms, i.e., the probability that they will be abandoned, is quite high and can easily be affected by a small changes in the price of agriculture inputs, - including water for irrigation.

Even though the water provision in canals is free of charge, farmers have to bear indirect cost of water supply, which includes the expenses for transporting water from the mesqa to the fields. The government finances all costs only below the delivery point [MWRI, 2002a]. But most of farmers do need to pump the water from the canal to deliver it to fields. The annual expenses of the farmer in irrigation and drainage services countrywide are estimated to be from 350 to 400 LE [MWRI, 2002b]. The main cost elements are; pumping water (250 LE), cleaning mesqas (60 LE), and land tax (30 LE). The total farm production cost is about 3000 LE per faddan, which makes the irrigation and drainage cost only 12 percent of the total production cost [MWRI, 2002b]. The introduction of a charge for irrigation service would increase the expenses. To a certain extent, farmers can bear these costs, but then they would give up cultivation for economic reasons [Bazza and Ahmad, 2003]. This would create negative social effect and force the society towards a more severe economic and social situation. Imposing the charge for the irrigation service could result in a decrease in water consumption levels, - but at what expenses? As suggested by respondents of interviews, yields might be subjected to reductions, as low affordability of farmers would not allow for purchasing the water. The farmers would rather shrink the crop area, which will result in a further worsening the farmers' income as net-returns will drop. Poor yields limit the ability for proper farm management, this may lead farmers to abandon agriculture and immigrate to the cities with the hope of better life. Overpopulated cities cannot carry large numbers of immigrants from rural areas and immigration will cause major social problems, which may cause negative consequences for national interests.

Declining water consumption levels enhanced by imposed user charges will negatively contribute to emerging soil salinity problems, which has harmful effects on the yield and the farmer's income as well [Umali, 1993; Hillel, 2000]. Under such conditions, the gloomy scene perspective makes the water pricing policy politically unacceptable due to its potentially harmful social implications.

Concluding Remarks

The water preservation policies recognized worldwide are working on either the supply side or the demand side. On the supply side, there is the upgrading of the irrigation system efficiency policy and the adjustment of the supply to closely match the real demand policy. On the demand side, there is the cropping pattern optimization policy and the irrigation water pricing policy. Each of these policies has advantages and disadvantages. The key issue in applying any of these policies in any country is the potential *negative* impacts of that policy on the local society, the environment, and the economy.

In the supply side, most studies focus on irrigation efficiency. Efficiency includes the conveyance efficiency and the application (on-farm) efficiency. In the case of Egypt, the figures of the irrigation efficiency seem to be very high (i.e., 75% overall efficiency rate). However, the detailed figures show that the conveyance efficiency in the old lands (i.e., most of the Delta) is 70%. This means that there is still a good potential for improvements in the conveyance efficiency, leaving a significant potential for water saving. Equally important, one may consider the improvements in the application efficiency that might be vulnerable to more deterioration due to the land fragmentation.

One of the policies that we consider very effective in water saving is the synchronization between the supply and the demand. The mismatch between the supply and demand has been demonstrated in empirical studies (e.g., Lutfi Radwan study, 1998); by using actively the water release pattern (e.g., 220 MCM per day) as a regulator, - tested through the SDGIS application; and by analysing ways to prepare the cropping pattern by MALR, the national water demands prepared by MWRI, and the pattern of water release conducted (also by MWRI). The origin of the problem is believed to be in the *lack of integration* between the MWRI-administered rigid patterns of supply and the informal farmer patterns of demand. We believe that if the supply pattern in some way be modified to match more closely the demand pattern, a considerable amount of water saving could be achieved. This is a real challenge, but not impossible. This policy is likely to be effective only if farmers are involved in defining the agricultural water requirements.

The demand side management entails some potential for water saving which might be possible though cropping patterns optimization. Cropping patterns play a vital role in defining the water demands. However, cropping patterns are vulnerable to unexpected shifts due to a wide range of social, natural, and economical influences. Selecting a crop to be planted is mainly subject to the farmers' expenditure capacity, water availability, and crop profitability, - besides many other natural factors, including the soil and climate suitability. To some extent it might be easy, *theoretically* to propose a certain cropping pattern or to develop an optimization model to obtain the optimum cropping pattern that would result in the ultimate utilization of agriculture land and available water resources. But it is more difficult to apply such a pattern in reality (i.e., to impose a certain cropping patterns on farmers), unless we establish favourable preconditions for the cropping pattern policy. Preconditions imply dissemination of information regarding the crop profitability, food market needs, community involvement in canal management, and improving farmers' awareness, attitudes, and practices concerning the water resource management.

The irrigation water pricing policy is one of the financial instruments for water conservation. Although it has been discussed in this chapter, it was impossible to test this policy using the application (or the SD model) because of the uncertainty associated with the society's reaction to such a policy. The main objections to the water-pricing policy are the negative social effects that may result, and the environmental implications of such a policy. The introduction of water charges at this stage might inevitably cause social unrest and political problems.

It is worth noticing that applying a single policy is not sufficient to successfully achieve significant water savings. We typically need to combine two or more policies. In this context, we believe that, in the short term, applying the supply-demand adjustment policy alongside with a cropping pattern optimization policy may result in a significant reduction in water consumptions. The appropriate cropping patterns will lead to a more accurate determination of the irrigation water demand. In the long run, upgrading the conveyance efficiency may be applied alongside the upgrading of the application efficiency. Converting, gradually, the traditional irrigation methods (i.e., surface flood) to modern irrigation systems will increase the water availability. The water thus made available may be utilized for additional land reclamation processes.

It is not an easy task to address the water scarcity problem, but still there is a hope that the negative effects of mitigating policies may be minimized. To address such a problem, we must have an inclusive picture of the problem with all factors involved. In the current study, we have taken a step to show some fragments of the whole picture, but for further understanding of the problem, other factors must be added, this could be a subject for future studies.

7.5 Conclusion

The SDGIS application consists of three main components; the SD simulation model, the GIS model, and the modules that include functions facilitating the integration between the two models in addition to the GUI. The SD simulation model has been built using the Vensim software (classified under software that facilitates feedback-oriented continuous simulations) in a way that allows the managers and the operators of the irrigation system to test and evaluate alternative management policies under various scenarios. The GIS model provides information regarding the structure of the irrigation network, the spatial location of the irrigation system components and their attributes, required to undertake this management task. The modules of the SDGIS application and the GUI provide significant supplementary information such as the cropping patterns, the crop-water demand, the pattern of water releases, etc.,. Therefore, the SDGIS application is an Interactive Learning Environment that comprises background and supplementary information, source materials, and working instructions integrated into a single computer application. The SDGIS application, as an ILE, provides the potentials for supporting learning and training for the operators and the managers of the irrigation system so that they understand their part of the system in the context of the system as a whole, - through providing a virtual world and the capability to test alternative policies in various contexts in an inexpensive and risk free environment. This has been demonstrated through an example that represents a case of diverting water from one portion of the system to other portions.

The SDGIS application, including the three components, has been used as an optimization tool. Although the optimization process has been performed using the SD modelling tool (i.e., the Vensim software), the GIS component (that represents the spatial dimension), plays a significant role in deciding the target variables to be optimized. This has been demonstrated using an example of optimizing the performance of one canal within the irrigation network. The example draw the attention towards the potentials of optimizing the cropping patterns that have a sever effect on water demands.

The SDGIS application, that tightly couples the GIS models with the SD models under a single common interface, may be considered a true SDSS. The application includes explicit mechanisms for attribute and spatial data management (through its GIS component), as well as the mechanism to represent time (through simulation using its SD component). By using the SDGIS application, irrigation system managers and decision makers can develop water allocation plans and easily test and assess several water preservation policies. The potential benefits of using the SDGIS application as a SDSS have been demonstrated through three examples. The first example represents the efficiency upgrading policy. In the second example, we illustrated the water supply/demand adjustment policy and exhibit the effect of changing the water release patterns on the behaviour of the system. In the third example, we introduced a proposed cropping pattern, and discussed the cropping patterns optimization policy. The development of this application has also provided us with the opportunity to study and analyse the feasibility of applying water preservation policies in the case of Egypt.

Our use of the SDGIS application has demonstrated its flexibility with regard to integrating new components so as to represent various scenarios. For example, we have added the *Supply Slider* control object, the *Additions* panel, and a new Crop-Distribution map to test various scenarios. Similarly, the user may add desired control objects, panels, and/or menus to provide additional control mechanisms to the models, to test scenarios, to improve visualization, and to create the desired graphs. Only moderate programming skills and the open source code are required to accomplish this.

Chapter 8

The Research Conclusion

Conclusion, Impact, and further Work

8.1 CONCLUSION

The main contribution of this research is the SDGIS application. This application tightly couples the SD simulation models with the GIS spatial models. The *tight coupling* method, also known as the integration under one common interface, facilitates the direct communication between the SD model and the GIS model through the dynamic data exchange (DDE) without the need for an intermediate program (or software such as Excel) and data import/export operations. It allows for "the user interactions" to take place during the simulation runtime, and consequently, provides a continuous feedback between time and space. These features are not possible with the loose coupling method. On the other hand, the application has been developed using the current available technologies (software) with less effort, time, and cost compared to the mega projects intended to perform similar operations such as SME, IDLAMES, and WaterWare. Because the tight coupling method has been used, we were able to keep the SD modelling tool (e.g., Vensim) as the main model development environment which provides the opportunity to build models using graphical icons. At the same time, there was no need to translating the SD model equations into a programming language to run in the GIS. These features are not possible when employing the embedded coupling method. The various objects, -i.e., the SD model components and the GIS spatial features, are linked explicitly through the SDGIS application that employs the Object Orientation as a common platform for the integration process. This type of integration (i.e., tight coupling) provides: (1) a consistent user interface and data structure (that cannot be implemented when using a loose coupling); (2) the support for development and modification of models (not possible with embedded coupling) and; (3) the user interaction during the simulation runtime (again, not possible with loose coupling).

The SDGIS application is developed using Microsoft Visual Basic. It consists of three Standard Modules and one Form Module. The Standard modules include: (1) the "SD Model Functions" Module that includes functions to facilitate communication with the simulation model through the dynamic link library (DLL) of the Vensim software; (2) functions that provide the spatial and visualization tools implemented through the embedded ArcObjects (this module is called the GIS Functions Module); (3) functions for handling the errors that may arise as a result of the user's incorrect actions (Error Handling Module).

The Form module, that is the GUI of the application, includes *Objects* and *Functions*. The *Objects* explicitly connect the SD model components with their associated spatial features in the GIS model (e.g., the canal stock is linked to the canal feature and the flow-rates are linked to the control-gates). The *Functions* facilitate the user's interaction during the simulation runtime; provide the user with a full control over the models and the simulation performance, the map display, and the creation of reports.

Three versions of the SDGIS Application have been created. The first version is intended to incorporate a simple SD simulation model (i.e., the molecule model that includes one single canal) and a simple map covers one administrative area (i.e., Gharbya province at the Middle of the Delta). This version of the application includes most of the primary Objects and Functions that are required for the integration process (a sizable number of functions were designed to integrate the models). The application was successfully able to connect, simulate, and display the results on the map. The application performance worked sufficiently fast.

The second version of the application was developed to cope with the *Array* structure of the SD model, and the network of canals that are classified in accordance with their geographical locations and rank-order and cover the whole study area. The map includes nine canal classes and three different types of cropping patterns. In this version, the visualization capability was improved by providing various alternatives to represent the results from the simulation run on the map - i.e., the map may be drawn so as to represent the values taken at any time by various model variables, such as the current water volume in canals, the water coverage, the water supply, the water leakage due to lack of efficiency, and the water consumption. In this sense, the map is employed to display a variety of different variables during the simulation runtime. This is one of the significant distinctions of this version from the previous one.

In the third version, that is the SDGIS Spatial Application, we extended the functionality of the application in compliance with our case study. The application has been adapted to the irrigation system in the Nile Delta region. The adaptation process included adapting all three components of the application; the SD model, the GIS model, and the associated modules of the SDGIS. The GUI has been improved by adding a number of control-objects and functions to improve the visualization and the analytical capabilities of the application. Finally, the capabilities of the SDGIS application have been demonstrated through some illustrative examples. The application can be used as an interactive learning environment ILE, an optimization tool, a Spatial Decision Support System SDSS, and as a policy assessment tool through providing a virtual world and the capability to test alternative management scenarios in an inexpensive and risk free context.

The development of the three versions of the SDGIS (with different structures - i.e., simple structure and Array structure; and different extent – i.e., one province and/or the complete irrigation system within the study area) has demonstrated that the application, and, consequently, our method of integration, is not limited to a particular simulation model and/or to certain maps. The SDGIS application supports effectively any SD model and any number of maps associated with such a model.

The underlying approach, resulting in the creation of the SDGIS application, provides a much-needed capability to model spatially distributed, dynamic feedback processes in time and space, while facilitating an understanding of the interactions between various components within the system. The main strength of this approach is the two-way simultaneous exchange of data between the SD and GIS, providing feedback in time and space. The technique used to build the SDGIS application is different than existing techniques for dynamic modelling such as Cellular Automata; Agent-Based simulation and GIS Model-Builder, and addresses most of the limitations present in these techniques.

The implementation of the SDGIS Application and its adaptation to the case study has many consequences. It improved our analytical capabilities and enhanced our understanding of the dynamics of the water scarcity problem. Incorporating the spatial dimension in the SD model and the temporal dimension in the GIS model, and integrating both models in a single system demonstrated clearly the significance of considering simultaneously *Time* and *Space* when we model spatially distributed dynamic systems.

The SDGIS application is not the only contribution of this work. There are at least four other tasks have been implemented in this research by which we believe this research contributes to the science, i.e. is original in its nature.

First, synthesizing SD models with GIS (in particular, the vector-based GIS) in a tightly coupled way using Object-Orientation, has, to our best of knowledge, not been made before.

Second, the technique used to tightly couple the SD model components with the spatial features as explained in the conceptual framework, and implemented in the SDGIS and its application in the irrigation system, is original as we see it.

Third, in terms of cross-disciplinary studies, this research crosses several disciplines including system dynamics, geographical information systems, and object orientation in the context of Environmental modelling. The essential literature of the four disciplines has been covered in chapter two. However, in terms of the employed methodology, we developed two different models for the study area (SD model and GIS model) and developed the SDGIS application that integrated both models and applied this application for the water scarcity problem. As Phillips (2000) put it "Being cross-disciplinary and using different methodologies is considered original".

Finally, the empirical work that has been conducted regarding the analysis of the water scarcity problem and the current irrigation system in the Nile Delta region; and the evaluation of the water preservation policies, and the assessment of their feasibility in the case of Egypt, is again original as we see it.

8.2 Summary

This thesis includes eight chapters. In the first chapter, we described the research problem, the aim of the research, our motivation, the research approach, and the outline of the research. The objective is to set the framework of the research and to provide the context of the study. In this chapter, (i) we have identified the need for the integration of SD and GIS and the potential benefits resulting from such an integration; (ii) we have drawn a clear picture, and outlined the relationship between the four disciplines considered in this study.

In the second chapter, we discuss the essential literature regarding the main disciplines related to this research: the Environmental Modelling domain, the Geographic Information System, the System Dynamics, and the Object Oriented Paradigm.

In the first section of this chapter (i.e., the environmental modelling domain), we describe the state of the environmental modelling domain with respect to modelling the environmental problems with GIS and the environmental simulation models. We conclude that in more sophisticated environmental models there is a call for the system dynamics approach to deal with the temporal dimension, feedback loops and overall the dynamics and complexity of the environmental systems. There is also the need for the GIS to represent the spatial dimension. Simulation, spatial distribution, increased dimensionality and resolution, are one straightforward way of "improving" environmental modelling domain.

In section two (i.e., the GIS domain), we shed light on the origins and nature of the GIS, emphasized the significant of time in GIS, and reported the attempts at incorporating the temporal dimension into the GIS. The conclusion made is that, until the GIS explicitly integrate the temporal dimension in its data structures, its role will largely be limited to an input data provider and an output display and mapping device.

In section three (i.e., the SD domain), several simulation modelling techniques were described. The strength and weaknesses of each technique were reported. We concluded that the main differences between these techniques originate from the different theories underlying each of them (i.e., the control theory and the complexity theory). All the techniques have produced rich bodies of research and literature on widely overlapping fields of application. A cross study of these bodies of literature is overdue. Results on identical or neighbouring research topics should be compared. The comparison of results in the same subject areas will most probably lead to some fine insights. It would also be desirable to see, for example, an Agent-Based implementation for some SD classic models such as the "beer game" which, in particular, may have the potential to become a classic in the agent-based modelling field as well.

In the last section of chapter two (i.e., the object oriented domain), we gave a brief overview of the history of the object oriented paradigm, and the main concept and terms used. We concluded that Object-orientation is perhaps the most effective framework that can embrace both System Dynamics and GIS models in a single coherent information system because both geographical features (spatial entities) and system components can be represented as Objects that have properties and behaviours (methods).

In chapter three, we reported, to our best of knowledge, the significant prior attempts at integrating the simulation models (in broader context), with GIS. These attempts have made use of different integration strategies (ranging from loose to embedded coupling), and different simulation approaches and GIS representations. We addressed the gap found in the literature, and clarified the position of this research.

Chapter four was the point of departure to develop the new application SDGIS from which we explain our new method of integration. First, we provided a brief description of Object Oriented GIS (OOGIS) and explain the differences from the traditional GIS. Then, we highlighted the relationship between the Object Oriented paradigm and System Dynamics. The result of this chapter was the design of the Conceptual Framework of the SDGIS application.

In chapter five we developed the SDGIS application. We described in detail the steps of creating the application, the connection between the SD model and the GIS model, and the representation of the simulation results. A number of custom tools were built to: (1) facilitate access to and communication between the two pieces of software used to build the models, (2) control the simulation process, and (3) handle the display of the results in two ways (i.e., on maps and graphic charts).

Chapter six is the first part of our case study that deals with the application of the SDGIS to the irrigation system in the Nile Delta, Egypt. In this chapter, we first described the water scarcity problem that may emerge in the near future in Egypt, analysed its driving forces and highlighted the factors that tend to intensify and possibly escalate the problem. Second, we described the geographical and topological characteristics of the study area focusing on the irrigation system. Third, we explained the adaptation of the SDGIS application to the present irrigation system. Finally, we documented the results of running the SDGIS application to test its operability and performance.

In chapter seven, that is the second part of the case study, we demonstrate the capabilities of the SDGIS application through illustrative examples for employing the SDGIS as: (i) an interactive learning environment for the educational purpose of explaining the complex irrigation system behaviour and management to non-technical individuals; (ii) an optimization tool for the irrigation network and the agriculture lands to attain the ultimate utilization of water and land resources; (iii) a spatial decision support system (SDSS) for supply, demand, and water allocation management and as a policy assessment tool for the water preservation measures.

Chapter eight includes the research conclusions, this summary for the research, its anticipated impact, and a vision for the future work.

8.3 The Research Impact

The first impact that we may witness in the near future is that a considerable number of system dynamists would consider and represent explicitly the spatial dimension in their models. The spatial dimension may constitute a substantial part of the structure of the system and may be considered as a *structural component* that significantly affects the behaviour of the system. So far, a few system dynamists seem to concern themselves with the space as a structural component to the extent that they take the spatial dimension explicitly into consideration the way the geographers typically do when they utilize GIS. The reason for that might be the lack of a mechanism that represents the spatial dimension explicitly, properly and effectively in system dynamics. Developing such a mechanism is a major challenge. But we have taken a significant step in this research and demonstrated that the integration of SD with GIS is possible, and, more significantly, can be implemented using currently available software. The advent of technology (particularly, object orientation and COM compliant objects) made it possible to develop an application in a matter of a few hours. We have also demonstrated the potential benefits of the integration for both SD and GIS technologies.

There will be a good response also from the geographers and GIS practitioners who are eager to add the dynamics to their static GIS maps, and consider the temporal dimension in their spatial analysis. Needless to say, many processes in nature are time-varying. Such variations are often obvious, say, in hydrology studies where temporal analysis for surface water flow is in demand. GIS really does not lend itself to time-varying studies because there is no explicit representation of time in the data structures. This is why one cannot readily model the evolution through time of spatial variation in a phenomenon within GIS. For this reason, we have seen, in the literature, serious attempts at incorporating temporal data models into GIS. Despite these attempts, two facts remain clear. First, GIS users are no longer satisfied with their access to static data. From wildfire management to urban growth models, scientists and GIS users are wondering what GIS can offer. There is significant demand for adding the temporal dimension to the GIS and users lay a heavy burden on the shoulders of the GIS Technology developers to continue evolving the GIS. This research may constitute a point of departure for them to accomplish that mission.

This research may stimulate many IT developers to strive to create new *Spatial Dynamic Objects* that incorporate the characteristics of the SD building blocks (Stock and flow) and the characteristics of the spatial features (geometry shape and coordinates). For example, if the object will act as a stock, it may include (in addition to the initial value, the integration method, and/or the equation) the geographical location (in terms of *X*, *Y*, and *Z* points) in addition to a geometry shape (point, line, or polygon). The modeller will then have the choice to add these values to the stock if the model represents a spatially distributed system, or to use the default values (say for example (X,Y,Z)=(0,0,0) and the geometry shape is *point*). Such objects will significantly influence the evolution of both technologies (the SD and the GIS).

It is also possible to imagine that similar applications to the SDGIS will be developed, using the same method of integration, to study and analyse a variety of systems that are spatially distributed, dynamic feedback systems such as urban sprawl, transportation, flood disasters management and the flood planes.

It is anticipated that the SDGIS Application (and the underlying approach used to develop it) will capture the eyes of the politicians, decision-makers, executive managers, and operators who would like to improve the performance of the irrigation systems. It will also attract researchers who try to find out solutions and to design strategies to cope with water scarcity problem.

8.4 Future Work

In the future, it is highly desirable to see more improvements to be added to the SDGIS application. Improvements may include, for example, using satellite images to identify various crop-types that are currently planted. Satellite images (usually) include a thermal band layer that can be used to identify/classify the planted crops, calculate their actual areas and, subsequently, constitute the foundation for very accurate actual water demand calculations. The satellite image may then be integrated into the application, and the water releases can be adjusted to match the demands, displaying the results simultaneously on the map. Using the satellite images, the actual water demand for irrigation can be calculated for, at least, three months ahead (i.e., the shortest crop growing period). That will greatly help managers and decision makers to design and implement better water release/saving policies. In addition to the satellite images, several other layers can be added to the application such as the soil-types layer, aquifers, and the drainage network, all subject to a development (dynamics) over time.

There are many water preservation policies recognized worldwide. Only four of them have been discussed and three have been evaluated in this research. More policies and water management strategies need to be tested and evaluated using this application in the future.

The application has been developed as a standalone using Microsoft Visual Basic. It is likely to see the implementation of this application, and its functions, using Visual Basic for Applications (VBA), as a custom ArcMap extension that provides the foundation for integrated water resources management.

Currently, this application has been designed for a specific case (i.e., the irrigation system in the Nile Delta region) using a modest level of aggregation. The application has been built, however, using modules to enhance its extendibility to other cases. More generic modules need to be developed to populate and generalise the application.

8.5 Final Remarks

Although the computer technology for Spatio-Temporal analysis exists, the GIS community must undergo a paradigm shift to fully appreciate "spatial dynamic GIS" benefits. It is not just a matter of collecting time-based data within the GIS, but also developing - a new way of thinking about time in a spatial sense; - a new way of thinking about feedback loops and delays; and - a new vision to the cause and effect (causality relationships) that draw changes in geographic processes. Correspondingly, the SD community must appreciate the spatial dimension in their models, taking into consideration the spatial bounds between the components of the system and their properties that vary with the geographical location. Equally important is that both communities must start working together. I was fortunate to incorporate the benefits of the SD and GIS in my work only because I studied both disciplines in previous stages of my education and gained sufficient understanding of the capabilities of both technologies, as well as a good experience in software application development.

It is not difficult to imagine that a conclusive synergy may combine the spatial representations of GIS with the temporal characteristics of SD models in a single integrated software. To find out how these tools should be made more interdependent and interactive, more research efforts should be undertaken. To solve pressing environmental problems, we will need different tools than currently available that work effectively together and are easy to use, and may be employed in a flexible manner to address complicated problems that arise in the context of multidisciplinary dynamic, spatially distributed feedback systems. Without taking the first step, the allure of constantly improving technologies will continue to draw both SD and GIS along separately. Without formalization of an effort to achieve integration, only the very fortunate individuals will be able to incorporate the benefits of SD and GIS in their work because only they will have sufficient understanding and resources to overcome the difficulty of coupling tools that remain in many respects dissimilar.

9. Appendices

Due to the large size of the appendices (over 400 pages), we decided to keep them on a Compact Disk (CD) attached to the Thesis at the end. The CD includes five folders, three folders for the appendices A, B and C; a folder contains a digital copy of the thesis, and "EgyptMaps" folder that contains the maps, the SD models, and the three versions of the SDGIS Application. To install and run any of these applications the user should have the following software installed on the machine:

1. Vensim DSS 32 version 5.2a or higher.

2. ArcGIS 8.1 (recommended) with ArcObjects Developer Kit (the objects should be registered in Windows registry file before running the application. ArcGIS 8.3 may be used but the user may need to change the name of the MapControl object in the Form Module (GUI) from "ESRI MapComtrol 8.1" to ESRI MapControl 8.3). However, in the later releases of ArcGIS such as ArcGIS 9.x ESRI has changed the names of some Objects and divided some Objects to two. Advanced programmers may need to change the Object names in the code page of the application (in the Form Module and the GIS Functions Module).

3. Microsoft Visual basic version 6.0 (higher versions may be operate but it has not been tested)

It is highly recommended to copy the folders from the CD (with the same folder's structure) to the drive "D:\" on the machine otherwise you may need to change the path and/or the driver letter in some maps.

For any further information and/or assistance to install and run the application, please email to: sameh.gharib@ifi.uib.no ; samehgharib@gmail.com

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