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Impacts of future climate on local water supply and demand – A socio-hydrological case study in the Nordic region

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ABSTRACT

Study region: Fårö island, part of Region Gotland, Sweden.
Study focus: Despite its importance for proactive planning and management, understanding of how future climate and socioeconomic trends may interact to influence water supply and demand at sub-regional scale remains limited for the Nordic region. We aim to close this knowledge gap by developing a combined social and hydrological simulation model for Fårö island in the Baltic Sea. We use multivariate Monte Carlo simulations to explore the effects of future climate scenarios (RCP4.5 and RCP8.5) on local groundwater supplies, and subsequent impacts on the housing sector, tourism sector, and municipal water supply system in the period 2020–2050.
New hydrological insights for the region: Our results suggest that groundwater storage will remain critically low in the coming 30 years, with a 60–70% probability of the groundwater head falling to lower levels than experienced in the past 60 years. Low water availability and widespread saltwater intrusion will constrain housing and tourism development by up to 11% and 30% respectively. To sustain growth, the tourist sector will become increasingly reliant on water from private wells, and supplementary water deliveries from neighboring regions will be required to meet water demand on the municipal grid.

1. Introduction

Water scarcity is a problem with impacts for human health, economic development, and ecosystems in many regions around the world (Rijsberman, 2006; Wimmer et al., 2015). It is estimated that up to 50% of the global population will experience seasonal or permanent water insecurity by 2050, caused by a combination of changes in climate, urban and rural development, and population growth (United Nations, 2018). Understanding how trends in climate and socioeconomic development interact to influence water supply and demand across space and time is of great importance to support mitigation and adaptation to water scarcity (United Nations, 2018). Building relevant knowledge is challenging, however, as climate-driven impacts on water resources have been shown to differ substantially both between and within geographical regions (Bessah et al., 2020; Wu et al., 2020). Furthermore, studies in recent years have demonstrated that understanding the interplay between social and hydrological systems is an important component in long-term sustainable management of water resources (Di Baldassarre et al., 2019). Although much progress has been made in

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developing macro-level theories about the mechanisms of socio-hydrological dynamics (Di Baldassarre et al., 2019; Sivapalan et al., 2012), place-specific understanding of human-water systems remains limited (Xu et al., 2018).

Most previous studies assessing the local interplay between climate, hydrology, and the social system have focused on regions with a long history of water scarcity, such as the Mediterranean region (Darvini and Memmola, 2020; Fabre et al., 2015), the Middle East (Gohari et al., 2013), Australia (van Emmerik et al., 2014), parts of the US (Fernald et al., 2012), and different parts of Africa (Bessah et al., 2020; Fraser et al., 2011). The Nordic region is poorly represented in such research, partly because freshwater has historically been a plentiful resource in the region. However, with the anticipated effects of climate change, there is reason to suspect that the Nordic region will not be spared from water scarcity for much longer. Indeed, unusually dry summers in recent years have caused periods of local to regional seasonal water scarcity, even in typically water-abundant areas (Ahopelto et al., 2019; Stensen et al., 2019). Moreover, recent reports project that the frequency, intensity, and duration of seasonal water shortages will continue to increase in the coming decades (Asp et al., 2015). To enable proactive and robust water management strategies to be developed for the Nordic region, improved local understanding of the combined effects of climate and socioeconomic change on water supply and demand is essential.

In this paper, we contribute to this end by presenting results from a case study exploring how climate and socioeconomic processes interact to influence supply and demand for drinking water on the Swedish island of Fårö. We develop a simulation model of the hydrological and socioeconomic mechanisms governing water supply and demand, drawing on a combination of qualitative and quantitative data sources. The model, calibrated to 20 years of historical data, is used in simulation experiments investigating how projected changes in climate are likely to influence water supply and water quality in the coming 30 years. We then explore the implications of these changes for the three largest water-dependent stakeholders on the island: the municipality, the tourism sector, and the housing sector.

The remainder of the paper is organized as follows: in Section 2, we briefly describe the study area and provide an account of how challenges related to drinking water supply and demand have developed in the past 20 years. We present the expected changes in regional climate in the coming 30 year, and we define the aim of this study. In Section 3, we outline the model development process and provide a high-level description of the model structure. We also present the model calibration process, and we describe the experimental set-up used to explore the hydrological and socioeconomic implications of future climate scenarios. In Section 4, calibration results are summarized and we present and discuss the results from the simulation experiments. We first describe climate effects on groundwater supply and then the impact of these effects on households, tourism, and the municipal water supply system. We also highlight some limitations of the study and consider areas for future research to support local water resources management and planning. In Section 5, we summarize our key findings.

2. The study area

Fårö is a small island (114 km^2) in the Baltic Sea (57.9°N, 19.1°E) belonging to the Swedish municipality of Gotland (Fig. 1). The island has an average summer and winter temperature of 16 °C and − 2 °C, respectively, and yearly precipitation of 500–600 mm (SMHI, retrieved 3 February, 2021). The main industries are tourism and agriculture, and the population consists of about 300 permanent households and 1000 holiday households (Lantmäteriet, 2021). Drinking water is obtained exclusively from groundwater sources, mostly from private wells drilled into the limestone-dominated bedrock. The soil layer is shallow (0–2 m) across most of the island except for an area in the northeast, where layers of coarse-grained sandy soil up to 20 m deep make up one of the few large aquifers in the region. This aquifer provides water to the municipal grid, which serves most tourist facilities and about 50 residential households (Brunner, 2014; Rivera and Ridderstolpe, 2011; Sjöstrand et al., 2014).

In recent decades, Fårö has become a popular holiday destination with a growing tourism sector (Fig. 2A). In the high season (June-August), about 10,000 tourists and part-time residents visit the island (Brunner, 2014). Water use has thus increased over time[1] (Fig. 2B). Between 2000 and 2020 water use on the municipal grid increased from about 5500–9500 cubic meters per year. In fact, since 2006 water supply from the municipal aquifer has been insufficient to meet demand in the summer period, requiring supplementary transport of water from other regions of Gotland to secure supply on the municipal grid[1] (Fig. 2C). In 2006 in total 1500 cubic meters of supplementary drinking water was transported to Fårö and by 2019 the figure had doubled to just above 3000 cubic meters. Within the private water sector, the number of holiday homes has also increased over time and increasing incidence of saltwater intrusion into private wells has been detected (Magnus Pettersson, Region Gotland, personal communication 25 January 2021). The growing reliance on transported water and the problem of saltwater intrusion create challenges for the municipality, the tourist sector, and private households. For the municipality, reliance on transported water is a risk as it makes the island vulnerable to disturbances, such as delivery delays, strikes, or unexpected peaks in water consumption. The municipal water supply has already come close to running out on several occasions, because of fluctuations in demand and delivery delays. For the tourist sector, water supply constraints can limit growth and development. In the past ten years, establishment of new tourist facilities has been delayed, or even canceled, because of insufficient water supplies (Rolf Lindvall, Sudersand Resort, personal communication 15 October 2020). For the housing sector, salt contamination of groundwater sources restricts new housing developments, as building permits are not issued in locations with elevated chloride levels (Gotlands Kommun, 2008). Further, if salt intrusion becomes widespread among households outside the public grid, the municipality may become legally required to extend its water management area and provide water services

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[1] Monthly data on groundwater extraction, water supply capacity and water transport volumes are classified information and can therefore not be displayed in the paper (Mikael Tiouls, Region Gotland, personal communication 7 December 2021). For inquiries about the data please contact Region Gotland.

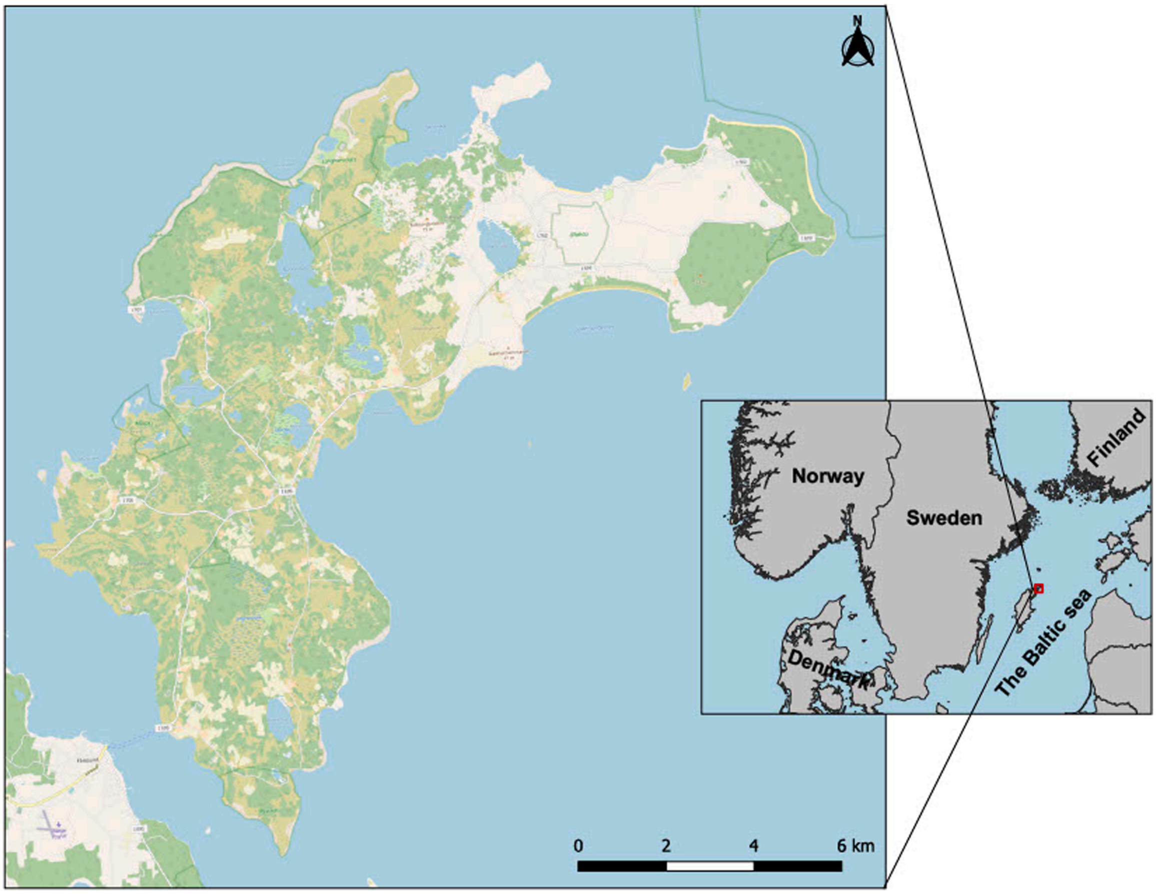

Fig. 1. Map of Fårö island. Location in the Baltic Sea indicated by red box in the small map of the Nordic region.
Source: Open Street Map & Eurostat, 19 November 2021.

to communities currently outside the public grid (Swedish Environment and Energy department, 2007). This could lead to a significant increase in demand for municipal water and could potentially require substantial investments in water transport or alternative water supply technologies.

2.1. Aim of study

Between 2020 and 2050, climate change is expected to increase regional mean temperature by approximately 1.0–1.3 °C and increase precipitation by 2–10% compared with the past 20-year period (Asp et al., 2015). In this study, we investigate how these changes are likely to influence local water supply and water quality, and explore the interplay with existing water supply challenges on Fårö island. The aim is to improve understanding of the local-level impacts of climate change and provide input for proactive water resources planning and management in a hitherto poorly studied region.

3. Material & methods

3.1. Model development

We develop a combined social and hydrological simulation model of the key mechanisms driving water supply and demand on Fårö in Stella Architect by ISEE Systems, Lebanon USA, following the System Dynamics modeling method (Pruyt, 2006; Sterman, 2000). The model consists of six interconnected submodules: *Climate, Public Water Supply, Private Water Supply, Household Water Use, Tourism Water Use,* and *Public Water Supply Demand Balance* (Fig. 3) and simulates from 2000 to 2050 at time units of one month. The causal structure of the model is based on a qualitative modeling study conducted by Lindqvist et al. (2021), exploring the drivers of water scarcity on Fårö. Additional scrutiny of the scientific literature and municipal reports, and repeated consultations and validation meetings with the Department of Water Management at Region Gotland throughout the modeling process, are used to cross-validate the structural and operational representation of the water management system in the model.

An overview of the structure, data inputs, and data outputs for each submodule is presented in Sections 3.1.1–3.1.6. For full model

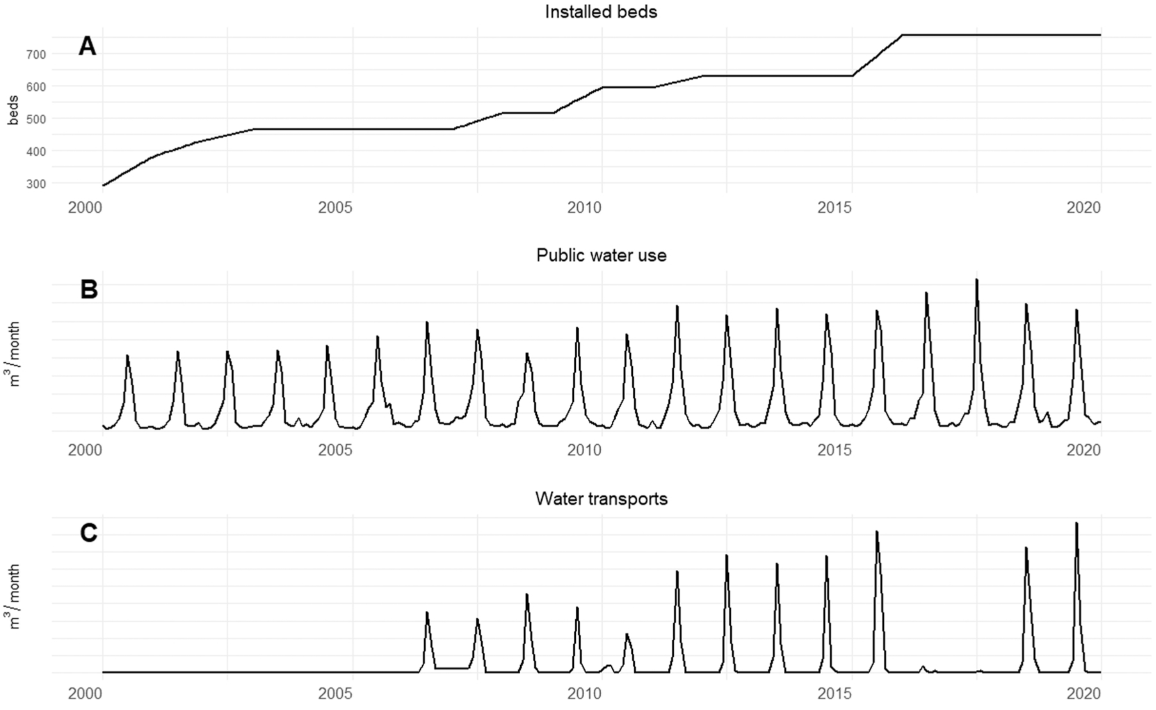

Fig. 2. Installed beds (A) (Region Gotland, 2021a), water use on the municipal grid (B) (Region Gotland, 2021b), and water transported to Fårö (C) (Region Gotland, 2021b) in the period 2000–2020. Water use and water transport volumes is classified information, scales intentionally left blank.

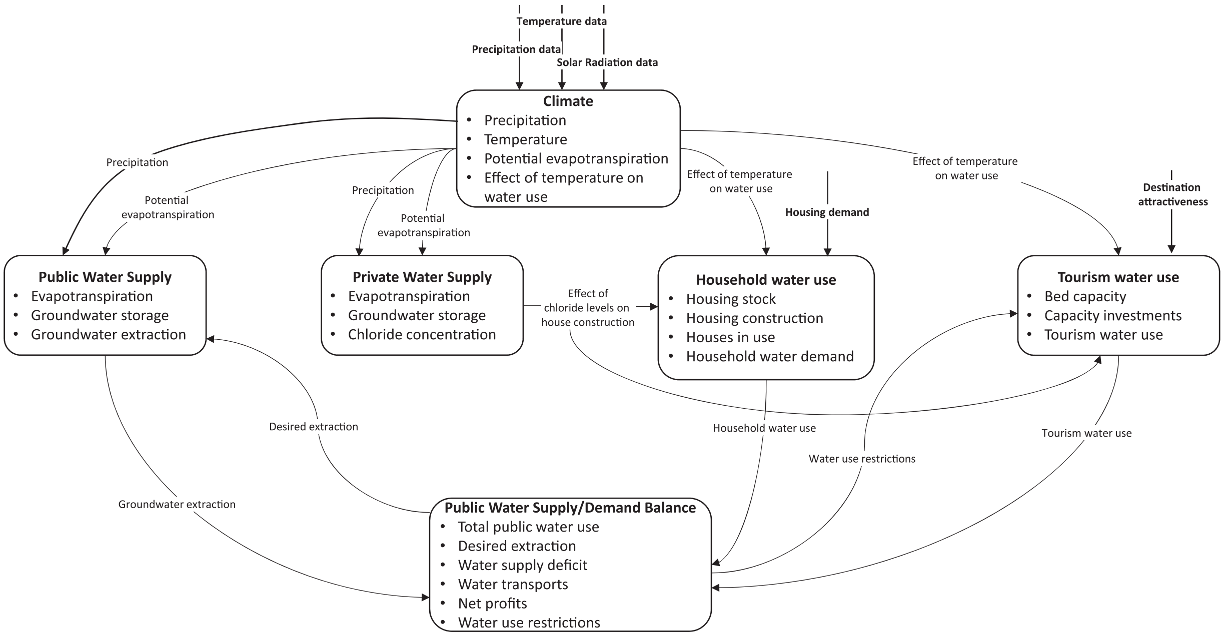

Fig. 3. Diagram of the full model. Boxes represent the six submodules with their key processes, and stock variables indicated. Arrows represent exogenous data inputs (bold) and information exchange between modules.

documentation, see the appendix A.

3.1.1. Climate

The Climate module (Fig. 4) imports monthly data on temperature, precipitation, solar radiation, and wind speed, and calculates *potential evapotranspiration* (*PET*) using the Penman-Monteith method (Penman and Keen, 1948). The *effect of temperature on per capita water use* is also calculated, assuming that water use increases by 2% for every °C by which the daily maximum temperature of the month exceeds 15 °C (Dimkić, 2020). Outputs to other submodules are *precipitation*, *PET*, and *effect of temperature on per capita water use*.

For the historical period 2000–2020, we use observation data from local weather stations (SMHI, 2021) as climate inputs. For the future period 2020–2050, we used projected values provided by SMHI (Asp et al., 2015). These projections were produced by the regional climate model RCA4 (Strandberg et al., 2014), by downscaling and averaging across an ensemble of climate scenarios produced by nine global climate models (CanESM2, CNRM-CM5, GFDL-ESM2M, EC-EARTH, IPSL-CM5A-MR, MIROC5, MPI-EMS-LR, NorESMI1-M and HadGEM2-ES) (Sjökvist et al., 2015) for the two Representative Concentration Pathways RCP4.5 and RCP8.5 (IPCC, 2013) (see appendix A for details). To simulate between-year variations in future climate inputs, we sample future precipitation, temperature, and solar radiation values from their respective probability density functions, parameterized using the SMHI projected mean and historic standard deviation values.

3.1.2. Public Water Supply

The Public Water Supply module (Fig. 5) simulates the dynamics of the public water supply system, including the hydrology of the municipal aquifer and groundwater pumping in municipal wells. The aquifer is modeled using Budyko-based methods for water balance modeling as described by Zhang et al. (2008), adapted to meet the requirement of unit consistency under System Dynamics modeling conventions (Sterman, 2000).

In the model, the aquifer consists of two connected cylindrical stocks, the top representing *soil storage* and the bottom representing *groundwater storage*. The dynamics of the stocks are governed by the flows of *infiltration*, *evapotranspiration*, *recharge*, *deep evapotranspiration*, *base flow*, *horizontal groundwater flow*, and *extraction. Infiltration* is calculated as a nonlinear function of the demand/supply relationship between the level of the *soil storage* stock (demand) and the incoming *precipitation* (supply) (Zhang et al., 2008). As the saturation level of the *soil storage* stock decreases, the proportion of *precipitation* partitioned to *infiltration* asymptotically approaches one. The shape of the partitioning curve is governed by the *rainfall retention capacity* of the catchment, a model parameter representing the physical capacity of the soil and vegetation of the aquifer to retain water (Zhang et al., 2008). The outflow from *soil storage* is partitioned between *evapotranspiration* and *recharge* according to similar functions as applied for *infiltration*. *Evapotranspiration* is calculated as a function of the relationship between *soil storage* and *PET*, and *recharge* as function of the relationship between *soil storage* and the *storage capacity of the aquifer.* As *soil storage* increases, *recharge* will also increase and *evapotranspiration* will approach *PET.* The relative proportion of available water that goes to *recharge* or *evapotranspiration* is controlled by the *evapotranspiration efficiency* of the catchment. Higher *evapotranspiration efficiency* means that more available water goes to *evapotranspiration* and less to *recharge* (Zhang et al., 2008). The *deep evapotranspiration* flow ensures that if the *groundwater level* approaches the shallow soil layer, groundwater also becomes available for *evapotranspiration* (Yeh and Famiglietti, 2009).

The groundwater *base flow* is modeled as the product of the *groundwater storage* and a constant discharge factor, and the *extraction* flow represents groundwater extraction by pumping by municipal wells. *Extraction* is set equal to *desired extraction* (calculated in the *Public Water Supply Demand Balance* module) if the *groundwater level* in the aquifer remains above the average depth in the municipal wells. As the *groundwater level* approaches the depth in the municipal wells*, extraction* declines linearly. Lastly, the *horizontal groundwater flow* represents the exchange of water between the municipal aquifer and its surroundings. This allows *groundwater storage* to adjust to the groundwater level in surrounding catchments, and is calculated using Darcy's flow equation (Hillel, 2004).

3.1.3. Private Water Supply

The Private Water Supply module (Fig. 6) simulates the groundwater dynamics and the chloride concentration in aquifers outside the public water system. The water balance structure is similar to, and uses the same climate inputs, as that presented in Section 3.1.2, but it only accounts for natural water fluxes (*infiltration, evapotranspiration, recharge, deep evapotranspiration* and *baseflow*). *Extraction* is

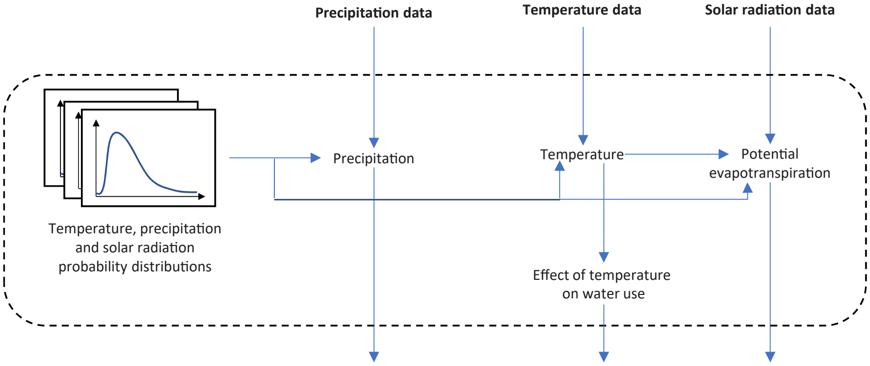

Fig. 4. Graphical representation of the Climate module. The dashed box represents the module boundary. Blue arrows represent information flows, variables in bold are exogenous data inputs, variables in normal font are endogenously calculated, and boxes with distribution curves represent the probability distribution functions used in simulation of inter-annual variations in climate inputs.

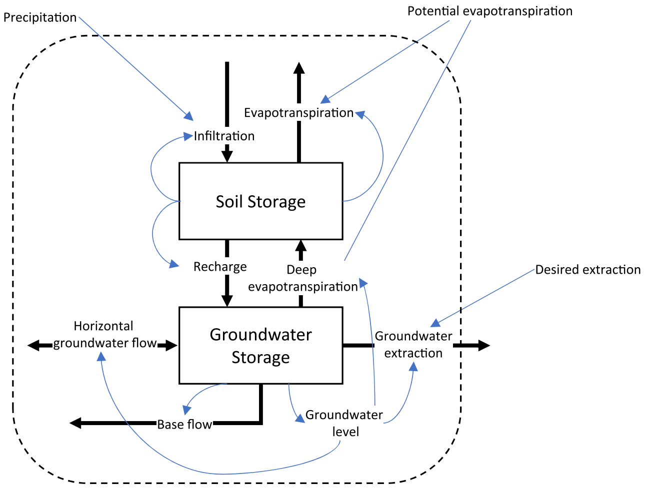

Fig. 5. Graphical representation of the Public Water Supply module. Boxes are stock variables, representing accumulation and storage of water in the shallow soil (*Soil Storage*) and deep groundwater layer of the aquifer (*Groundwater Storage*). Black arrows represent the flow of water within the aquifer and exchange of water between the aquifer and the surroundings. *Precipitation* and *potential evapotranspiration* are inputs from the Climate module, *desired extraction* is an input from the Public Water Supply/Demand Balance module, and *extraction* is an output to the Public Water Supply/ Demand Balance module.

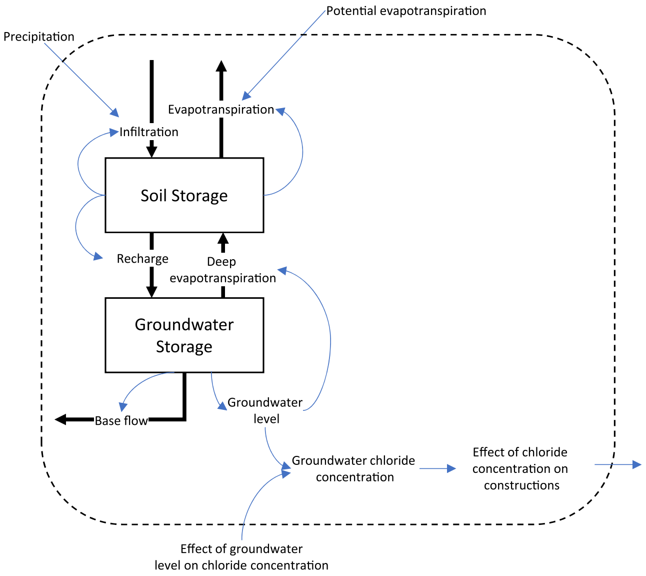

Fig. 6. Graphical representation of the Private Water Supply module. *Precipitation* and *potential evapotranspiration* are inputs from the Climate module, *effect of groundwater level on chloride concentration* is an exogenous constant, and *effect of chloride concentration on constructions* is an output to the Household Water Use module**.**

deliberately excluded because of lack of reliable data on historical extraction rates, and because water quality (measured by chloride concentration), rather than water quantity, has historically been the determining factor of household water supply (Magnus Pettersson, Region Gotland personal communication 25 October 2021). *Horizontal groundwater flow* is also excluded from the private water supply module, assuming homogeneous groundwater levels across the island.

Groundwater chloride concentration represents the average chloride level in groundwater across the island and is calculated as a linear function of the groundwater level using the basicTrendline package (Mei and Yu, 2020) in RStudio (R Development Core Team, 2019). The linear model was calibrated using five years of groundwater level data and data on chloride levels in 328 water samples from across the island, yielding a statistically significant negative *effect of groundwater level on chloride concentration* ($P < 0.01$). The *groundwater chloride concentration* is used to estimate the proportion of well sites with chloride levels exceeding the recommended limit values set by the Swedish Food Agency (2017) (100 and 300 mg/L chloride (Cl)) as limit values for technical and drinking use, respectively) and the maximum permissible chloride concentration when granting building permits (100 mg/L Cl). The proportion of well sites exceeding the limiting value at any given chloride level is obtained by linear (100 mg/L Cl) and nonlinear (300 mg/L Cl) regression (Mei and Yu, 2020), with the *groundwater chloride concentration* as the independent variable, and the fraction of samples above 100 mg/L Cl ($P < 0.05$) and 300 mg/L Cl ($P < 0.01$) as dependent variables. The *effect of chloride concentration on house construction* represents the limiting effect of groundwater chloride levels on new construction in the housing and tourism sector. If *groundwater chloride concentration* increases, fewer building permits will be issued and construction rates will decline.

3.1.4. Household Water Use

In the Household Water Use module (Fig. 7), the size of the household sector and total *household water use* is calculated. The total *housing stock* is divided into two groups (k) based on the water source (public water or private well), and each group is further segmented into two types (j) based on utilization (permanent or part-time). New houses are added to the system by the flow *construction starts*, which adds to the stock of *houses under construction.* The rate of *construction starts* is influenced positively by higher *housing prices* and negatively by the *effect of chloride concentration on house construction*. After a 12-month time delay (representing the house construction time), houses flow from the *houses under construction* stock to the *housing stock* via the *construction finalization* flow.

Construction starts is governed by a simple supply-demand structure where a stock of *potential buyers* is compared to the number of houses finalized each month to give a demand-supply ratio that is used to set the *housing price*. The base rate at which new buyers are added to the *potential buyers* stock is set using exogenous data on *housing demand* (based on data on building permits issued between 2000 and 2020, (SCB, 2021), and the stock is drained at the rate of *construction finalization*. The *housing price* is used as an indicator of *household affluence* (Englund, 2011), and it influences the quantity demand for houses by regulating the flow of new *buyers added* to the *potential buyers* stock and the number of *construction starts.* We use a price elasticity of demand and supply of -0.5 (Englund, 2011) and 0.1 (International Monetary Fund. European Dept, 2015), respectively.

The number of *houses in use* at any given point in time depends on the household type and the duration of the tourist season. Permanent households are in constant use, while the proportion of part-time households in use is determined by multiplying the number of part-time households by a *tourist season* utilization factor. This factor takes values between zero and one depending on the time of the year (here based on estimates by Region Gotland). *Water use per household* is the product of the number of *residents per household* and *normal water use per capita* (140 L/person/day, (Swedish Water, 2020)), and responds dynamically to changes in temperature through the *effect of temperature on water use* from the Climate module (Dimkić, 2020), and the level of *household affluence* (Höglund, 1999; Wiedmann et al., 2020). The total *household water use* is the product of the number of *houses in use* and the *water use per household,* and provides input to the Public Water Supply Demand Balance module.

3.1.5. Tourism Water Use

The Tourism Water Use module (Fig. 8) simulates the development of the tourist sector and its total water use. The size of the tourist sector is measured by its bed capacity and it is modeled by a three-compartment aging chain (Sterman, 2000) consisting of the stocks

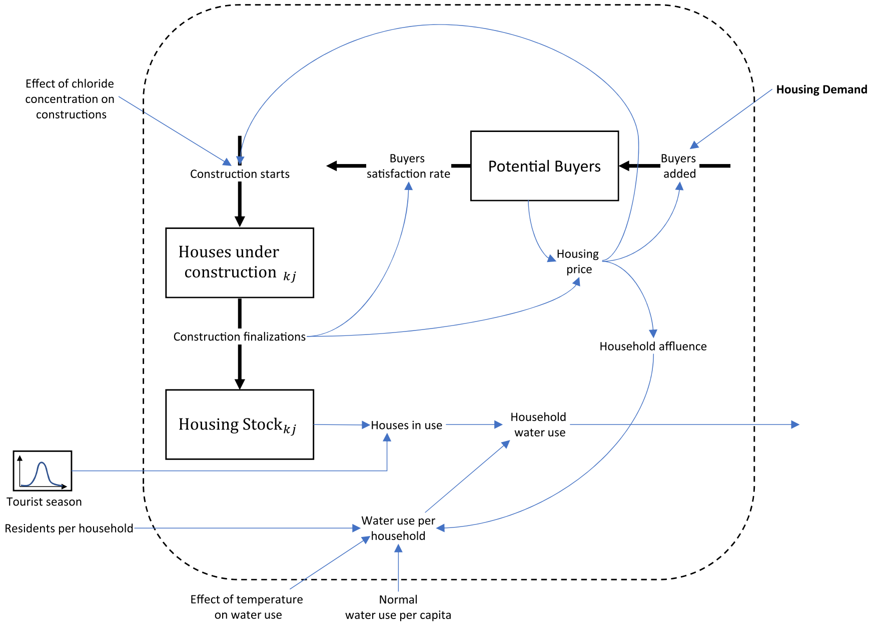

Fig. 7. Graphical representation of the Household Water Use module. *Housing demand* is an exogenous data input representing the demand for housing. *Effect of chloride concentration on construction* and *effect of temperature on water use* are inputs from the Private Water Supply module and the Climate module, respectively. *Residents per household* and *normal water use per capita* are model constants, and *tourist season* is a lookup function adjusting the number of *houses in use* according to the duration of the tourist season. *Household water use* is an output to the Public Water Supply Demand Balance module.

beds planned, beds on order, and installed *beds*, linked by the flows *adding beds to plan, ordering new beds*, and *installing new beds*. The number of *tourists* is modeled as an additional stock that increases or decreases with the flow of *net arrivals*. *Net arrivals* fluctuate with the tourist season using the same *tourist season* utilization factor as in Section 3.1.4. and respond to changes in *destination attractiveness* (assumed constant in the base case scenario). The number of beds added to the system each month is controlled by a goal-gap function where the level of *capacity utilization* (the ratio of *tourists* to installed *beds*) is compared to a *desired capacity utilization*. If *capacity utilization* exceeds *desired capacity utilization*, this leads to an increase in *desired expansion* and an inflow to *beds planned*. Beds move in batches from *beds planned*, through *beds on order,* to installed *beds* with a total planning and construction delay of 24 months. Bed capacity investments are bounded by the water self-sufficiency of the public grid and the possibility of tourist facilities to drill their own wells. If public water self-sufficiency is low, *water use restrictions* (calculated in the Public Water Supply Demand Balance module, Section 3.1.6.) will limit planning and investment in new bed capacity. This will force tourist facilities to search for private water supply sources by drilling new wells, making the *groundwater chloride concentration* the limiting factor for tourism growth.

Total tourism water use is calculated as the product of *normal water use per tourist,* the number of *tourists,* and the *effect of temperature on water use* imported from the Climate module, and it provides input to the Public Water Supply Demand module.

3.1.6. Public Water Supply Demand Balance

The Public Water Supply Demand Balance module (Fig. 9) sums up the total water use from the tourist sector with the total public water use in the household sector to calculate the *total public water use*. The *total public water use* dictates the *desired pumping* from the public aquifer (in the Public Water Supply module, Section 3.1.2.) and, when multiplied by the consumer *water price*, the *municipal revenues from water tariffs*. *Desired extraction* is compared to the actual *groundwater extraction* from the Public Water Supply module, to calculate a *water supply deficit*. The deficit triggers *water use restrictions* that limit further expansion of the tourist sector (Section 3.1.5.) and increases the volume and costs of *water transports.* The difference between revenues and costs of the water supply system is used as an estimate of the *net profits* of the municipal drinking water system.

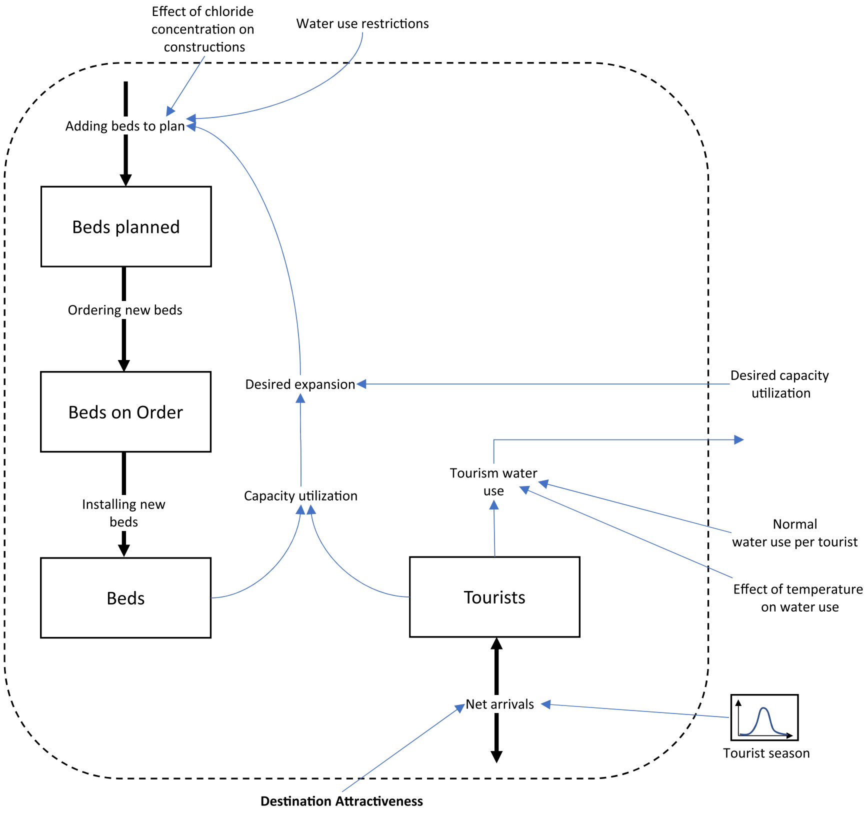

Fig. 8. Graphical representation of the Tourism Water Use module. *Destination attractiveness* is an exogenous data input. *Effect of chloride concentration on construction, water use restrictions*, and *effect of temperature on water use* are inputs from the Private Water Supply module, the Public Water Supply Demand Balance module, and the Climate module, respectively. *Desired capacity utilization* and *normal water use per tourist* are model constants, and *tourist season* is a lookup function adjusting the number of *net arrivals* of tourists according to the duration of the tourist season. *Tourism water use* is an output to the Public Water Supply Demand Balance module.

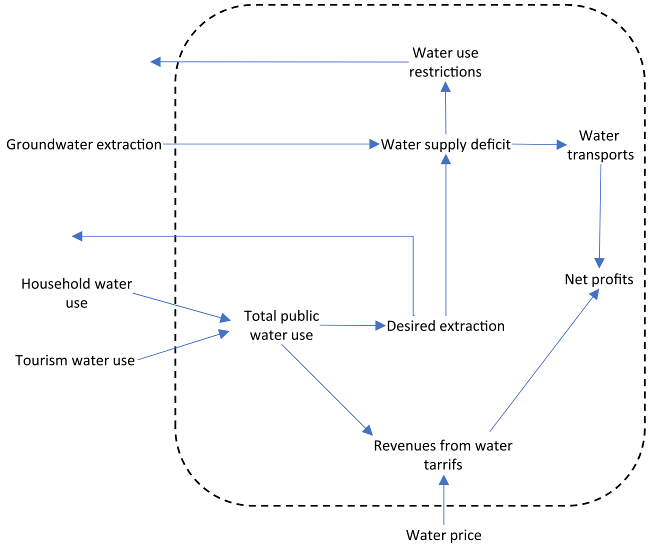

Fig. 9. Graphical representation of the Public Water Supply Demand Balance module. *Groundwater extraction, household water use,* and *tourism water use* are inputs from the Public Water Supply, Household Water Use, and Tourism Water Use modules, respectively. *Water price* is a model constant, and *desired extraction* and *water use restrictions* are outputs to the Public Water Supply, Household Water Use, and Tourism Water Use modules.

3.2. Model calibration

Calibration is conducted by varying module parameter inputs to optimize the fit of the simulation outputs to historical data on groundwater levels, water use, tourism and housing development, provided by Swedish Metrological and Hydrological Institute (SMHI, 2021), Geological Survey of Sweden (SGU, 2021a, 2021b), Statistics Sweden (SCB, 2021), and Region Gotland (Region Gotland, 2021a, 2021b). Each submodule is first calibrated individually, adhering to strategies for partial model calibration described by Homer (2012), followed by a final round of full model calibration and evaluation to ensure consistency with historical data is maintained with the complete set of between-module feedbacks active. Parameter estimates are selected based on literature studies, expert opinions, local empirical data or, if beforementioned information sources are not available, best estimates by the modelers. Parameters with high uncertainty regarding their true values, and with high impact on simulation results, were numerically estimated using Powell optimization (Powell, 2009). The squared error between simulated and observed timeseries is used as payoff function in the parameter estimation process, and results are evaluated quantitatively, using Theil Inequality Coefficients (Sterman, 1984), and qualitatively by comparing the derived parameter estimates with ranges suggested in the literature and by local experts. For a complete list of calibration inputs and outputs see appendix B.

Due to lack of data on historical groundwater levels in the municipal aquifer, a two-step procedure is used for groundwater calibration. First, the aquifer structure presented in Section 3.1.2 is calibrated to 25 years of data (1971–1996) on historical groundwater levels from an aquifer in southern Sweden (SGU, 2020) that has similar geological and landcover characteristics as those found on Fårö. This step ensures that the structure can replicate the general groundwater dynamics of the aquifer. In a second round of calibration, the pre-calibrated structure is finetuned to represent the municipal aquifer on Fårö by optimizing its fit to available data on municipal groundwater extraction between 2000 and 2020. Calibration results are presented in Section 4.1.

3.3. Experimental set-up

For future climate, two climate scenarios are considered, Representative Concentration Pathway (RCP) 4.5 and 8.5 (IPCC, 2013). In the RCP4.5 scenario we assume, depending on season, a 2–11% increase in monthly mean precipitation and a 0.96–1.24 °C increase in monthly mean temperature between 2020 and 2050. In the RCP8.5 scenario, the corresponding values are a 5–11% increase in precipitation and a 1.6–1.32 °C increase in temperature (Asp et al., 2015). For future solar radiation we use monthly averages from the past 12 years (SMHI, 2021), and for future mean monthly wind speed we use historic averages (Alexandersson, 2006). We assume new house constructions will continue to occur primarily outside the public water grid, and in the tourist sector we expect the growth in demand for hotels and other tourist facilities to continue at the same rate as seen in the past 20 years. Lastly, we assume that water transports will continue to be the main municipal strategy to cover seasonal peaks in water demand.

To handle the uncertainty embedded in long-term policy and strategy planning, it is necessary to explore a wide ensemble of plausible futures and let the full outcome space inform the decision-making process (Bankes, 1993). To this end, we carry out multivariate Monte-Carlo (MC) simulations, varying model parameters governing future climate (precipitation and temperature), housing supply and demand (future demand for houses, price elasticity of demand, price elasticity of supply, and price sensitivity of the ratio between demand and supply), groundwater chloride levels (effect of groundwater level on chloride concentration), the effect of chloride levels on tourism and house expansion (effect of chloride concentration on house construction), and per capita water use (affluence effect on water use). The parameters included in the MC analysis, and their associated ranges, are selected based on extensive partial model sensitivity testing, and the availability of reliable empirical or literature-based estimates. In other words, parameters that show a significant effect on simulation outputs and a high uncertainty with regards to their true values were included in the MC analysis (see appendix C for a full list of parameters, distributions, and ranges chosen).

We simulate the model 1000 times with randomly selected parameter values taken from predefined probability distributions within specified ranges. Results are reported as outcome ranges, bounded by the 95% confidence intervals, and the mean of the 1000 simulations is used to study long-term trends in groundwater levels using the seasonally adjusted Mann-Kendall trend test (McLeod, 2011). To assess the effect of future climate on groundwater levels, we compare the results from our MC simulations to the simulated groundwater regimes in two reference periods (P1, P2). P1 is the period 1961–1990, a commonly used reference in climate impact assessments (Asp et al., 2015; Sjökvist et al., 2015). P2 is the more recent period 2000–2020. Comparison against Pl gives a long-term perspective of the groundwater regime in the future and makes our results comparable to those of other studies, but it is less relevant for planning and policy purposes. P2 is the period during which water scarcity has developed into a problem on Fårö and is therefore a more relevant reference for policy makers when assessing the impacts of future groundwater levels.

Additionally, for planning and management purposes, an indication of variations and the risk of extreme events is equally, if not more, important than the average trajectory suggested by the MC ensemble (McCollum et al., 2020). We therefore calculate the probability of future extreme groundwater drawdowns, defined as the fraction of simulated scenarios where the groundwater head

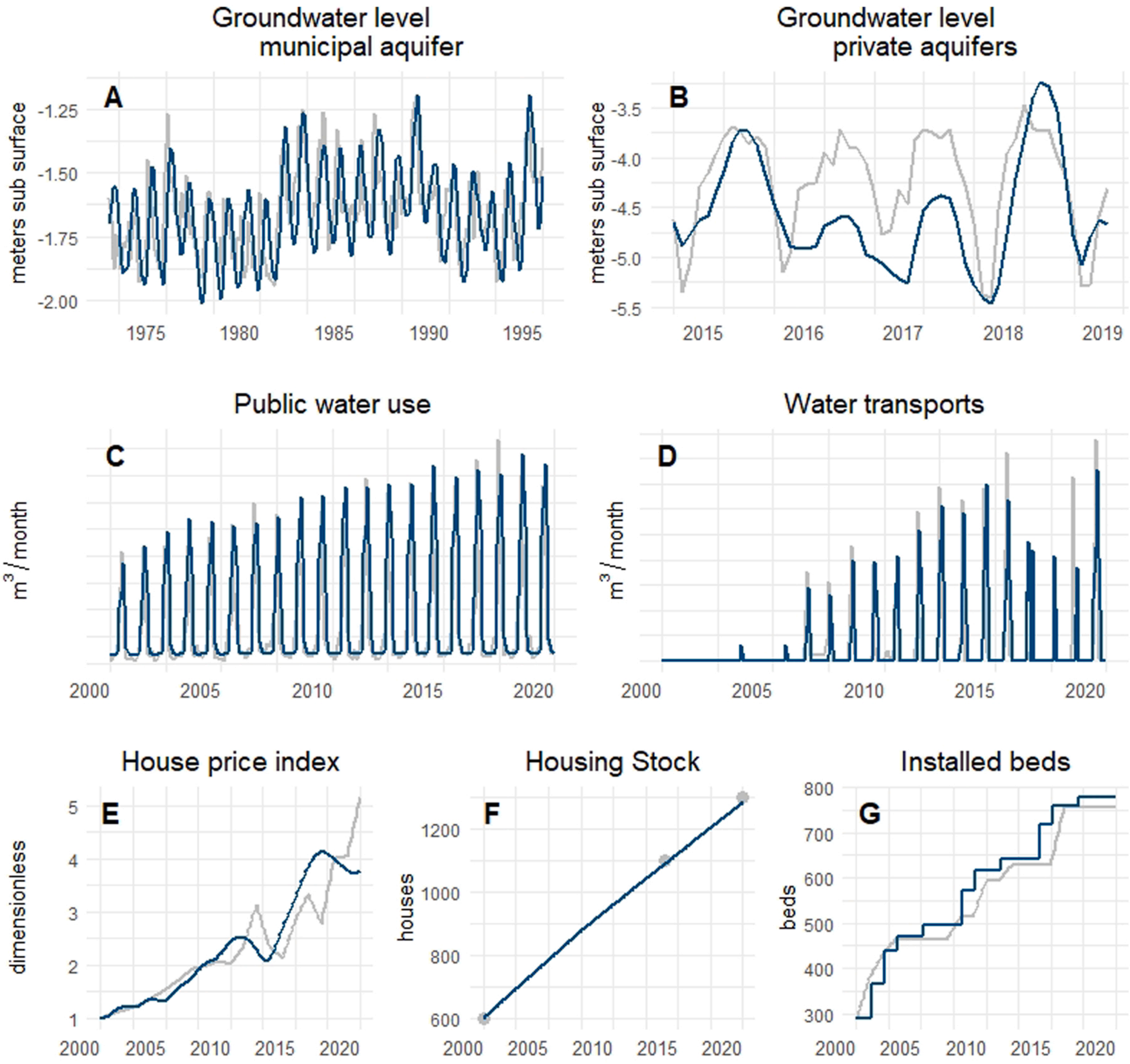

Fig. 10. Observed (grey) and simulated (blue) values for historic groundwater levels (A & B), public water use (C), municipal water transports (D), house price index (E), housing stock (F), and installed beds (G) in 2000–2020. Public water use and historic water transports is classified information and scales have intentionally been left blank.

reaches a level more extreme than the 2.5th percentile of its range in P1 and P2, or more extreme than the lowest groundwater level experienced in either P1 or P2.

To assess the implications of changes in future groundwater quality and availability on the housing and tourism sectors, we compare the results from the MC analysis with a simulated scenario where housing and tourism development is not constrained by water availability. In other words, we simulate a scenario where the growth of the two sectors is allowed to reach its full potential, and we use this as our baseline for assessing the impact of water scarcity on socioeconomic development in the region.

4. Results and discussion

4.1. Calibration results

Our calibration results show an overall acceptable fit to available hydrological and socioeconomic data (Fig. 10). Most importantly, the model captures the general trends of increasing summer water use and growing reliance on water transports. Furthermore, the mean absolute error (MAE) of the groundwater simulations is low (12 and 48 cm for the municipal and private aquifers respectively), with most of the error caused by unequal covariance between the observed and simulated timeseries (98% and 56% for the municipal and private aquifers respectively). This indicates a low level of systematic error and provides confidence that the model is capable of replicating the dominating behavior trends in the hydrological system (Sterman, 1984). Summary statistics for the calibration results are presented in Table 1.

4.2. Effects of future climate on groundwater storage and groundwater quality

The mean of our MC ensemble shows that groundwater levels in both public and private aquifers on Fårö are likely to remain within the range seen in the previous 20-year period (P2) (Fig. 11). A slight, but statistically significant ($P < 0.05$), increasing trend in groundwater storage in both aquifer types can be seen from 2030. These trends aside, compared to the reference period P1, the projected groundwater levels remain critically low, suggesting continuation of the decades-long regime of low groundwater storage. These results are in line with findings in monitoring studies conducted by SGU that most aquifers on Gotland have been at historically low levels for most of the time since the turn of the millennium (SGU, 2021a). Therefore, the slight increase in groundwater storage suggested by our simulations is from a historically low level and should not be interpreted as a return to some long-term historical normal.

Both aquifer types show substantial variation in groundwater levels between the upper and lower bound of the simulated outcome space (Fig. 11). The difference between the higher and lower confidence interval is up to 90 cm in the public aquifer and about 180 cm in private aquifers. It is important to acknowledge that the confidence bounds do not represent individual scenarios from the MC analysis. Rather, they mark extreme values taken by any of the 1000 independent simulations, and should therefore be interpreted as plausible ranges within which groundwater levels are likely to fluctuate in the coming 30 years. Analyzing the extremes of the outcome space makes this clear (Table 2). Between 2020 and 2050, a groundwater level more extreme than the lowest level ever experienced since 1961 occurs at least once in between 60% and 70% of the simulated scenarios. On average, such an extreme month occurs 14 times for the public aquifer and four times for private aquifers in the 30-year period. Months with groundwater levels lower than the 95% range of P1 and P2 occur at least once in more than 80% of the scenarios, or on average 211 and 36 times for the public aquifer, and 31 and 10 times for private aquifers.

Like the groundwater level, the ensemble mean suggests no significant change in chloride concentrations compared with the P2 period. However, because of the high probability of recurring periods with low groundwater levels it is likely that the number of households experiencing occasional water quality issues will increase in the coming decades. Likewise, between-year variation in groundwater chloride (SD = 45.9 mg/L Cl) can result in some locations, in years with high groundwater levels, shifting from being just above to just below the building permit threshold (100 mg/L Cl), and thereby increase the potential for new housing projects. The low spatial resolution of available data does not allow us to identify in what locations on Fårö large fluctuations in chloride levels are most likely. However, previous studies by Dahlqvist et al. (2015) have shown that there are substantial geographical variations in chloride

Table 1

Summary statistics from model calibration results. MAE = mean absolute error, MSE = mean square error, RMSE = root-mean square error. See Sterman (1984) for a detailed description of the summary statistics components. See appendix B for the underlying input and observation data used for the calibration.

						Error decomposition		
Payoff variable	MAE	MSE	RMSE	Correlation	R^2	Bias	Variation	Covariation
Public water use (Cubic meters/month)	354	343 k	585	0.859	0.737	0.184	0.155	0.661
Water transports (Cubic meters/month)	110	85.2 k	292	0.592	0.351	0.004	0.009	0.987
Beds (beds)	29.4	1.48 k	38.5	0.976	0.953	0.221	0.194	0.585
Groundwater level in the municipal aquifer (meters below ground)	0.118	0.020	0.143	0.647	0.419	0.0004	0.022	0.977
Groundwater level in private aquifers (meters below ground)	0.483	0.315	0.561	0.665	0.443	0.434	0.003	0.563
House price index (dimensionless)	0.301	0.192	0.438	0.903	0.815	0.015	0.013	0.972

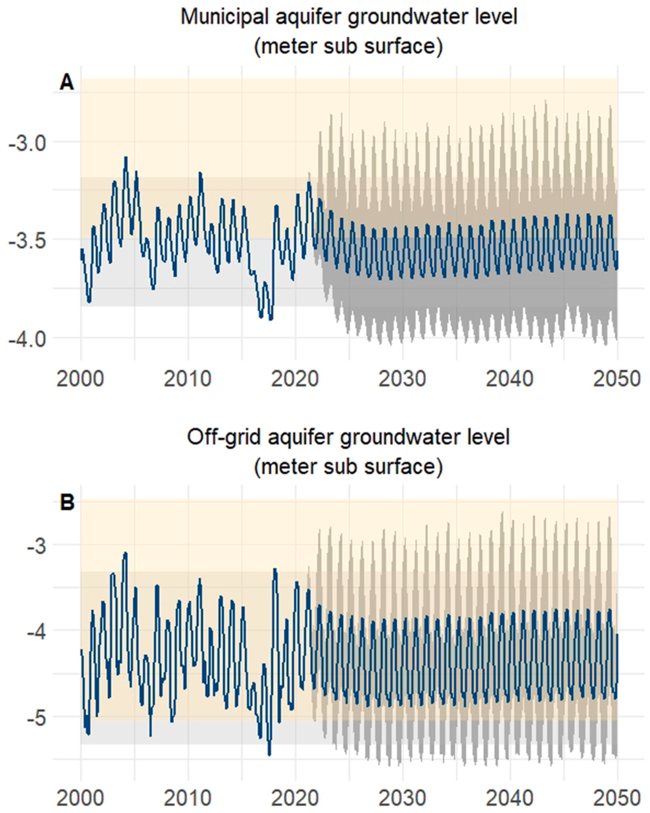

Fig. 11. Simulated groundwater level in the municipal and private aquifers on Fårö (panel A and B respectively). Blue lines are mean groundwater levels of the simulated ensemble, shaded areas represent the 95% confidence intervals, and the yellow and grey bands indicate the normal groundwater range (mean level +/- two standard deviations) for reference period P1 (1961–1990) and P2 (2000–2020), respectively.

Table 2
Frequencies and probability of extreme groundwater levels in the MC ensemble. The frequency columns represent how many times the groundwater table reaches a level equally or more extreme than the lowest level since 1961, or the 2.5th percentile in reference period P1 (1960–1990) and P2 (2000–2020). The probability column shows the probability of a new extreme low occurring at least once between 2020 and 2050.

	Frequency of a new extreme low	Probability of a new extreme low	Frequency of a < 2.5th percentile scenario (P1)	Frequency of a < 2.5th percentile scenario (P2)
Public aquifer	14.7	73.0%	211	31.6
Private aquifers	4.5	59.3%	36.1	10.0

base levels across the island. Accounting for both the spatial and temporal variability in groundwater chloride concentration when issuing new building permits is important to avoid an accumulation of houses in risk zones during periods when chloride levels are low. To mitigate this risk, further studies exploring spatial variation in chloride responsiveness to groundwater fluctuations are needed, so that locations with acceptable and stable groundwater quality can be identified for future building projects.

Table 3
Housing stock, tourist bed capacity and yearly water transports in 2020, and their estimated values in 2050 for the lower bound, mean, and upper bound of the simulated outcome space.

	2020	2050		
	Observed	Lower bound	MC mean	Upper bound
Houses	1300	2300	2650	3100
Tourist beds	800	1050	1220	1340
Water transports (m^3/year)	< 3000	2200	4000	5400

4.3. Socioeconomic impacts

4.3.1. Impacts on the housing sector

Our MC ensemble mean suggests that by 2050, the total number of households on Fårö will be between 2300 and 3100, compared to about 1300 in 2020 (Table 3). Most of the variation arises from uncertainty about future housing demand and about the strength of influence that groundwater chloride levels have on housing construction rates. On average, between 40% and 50% of well sites will have chloride levels exceeding 100 mg/L in the coming decades, but at the extreme of the simulated outcome space, that is during periods of severely low groundwater levels (as described in Section 4.1), the proportion can be as high as 75% for parts of the island. Detailed assessment of the impacts this would have on the housing sector requires further investigation of what areas that are attractive for housing development and how these areas correlate with risk zones for high chloride levels. In lack of this type of detailed spatial information, we make the simplifying assumption that housing development projects are homogenously distributed across the island. If this holds true, elevated chloride levels will pose a constraint for future housing development, increase housing prices, and reduce the number of households in 2050 by 4–11% compared with the unconstrained scenario where chloride levels have no effect on housing development.

For a region like Fårö, a 4–11% reduction in housing development is significant. For many years, RG has been striving towards increasing the number of permanent residents on the island through initiatives to enhance the availability of affordable housing. Despite these initiatives, reports by RG suggest that the high demand for summer houses, primarily by financially strong consumers from other regions of Sweden, have contributed to driving up house prices beyond what is affordable for the majority of the local community (Brunner, 2014). This effect has been confirmed by previous studies, showing how tourism intensification can lead to increase in local house prices (Paramati and Roca, 2019) and limit the availability of affordable housing for the local community (Mikulić et al., 2021). Our results suggest that future constraints in water availability could enhance these effects as the decline in housing availability that this would cause could contribute to further escalation of house prices.

4.3.2. Impacts on the tourist sector

The tourist sector is expected to grow from about 800 beds in 2020 to between 1000 and 1300 beds by 2050 (Table 3). The rate of growth is constrained by sustained low water self-sufficiency on the public grid, causing current restrictions on new connections to be maintained (see section 4.2.3.). This restraint leads to the establishment of a growing number of tourist accommodation sites relying on water from private wells instead of the municipal grid. The growth rate of these off-grid facilities experiences the same water quality constraints as the housing sector (described in section 4.2.1). Controlling for other factors, water supply limitations cause a 10–30% reduction in tourism growth compared with the unconstrained scenario.

As a whole, the proportion of tourist facilities relying on the municipal water system declines but, counterintuitively, in absolute terms the tourist sector demand for water from the municipal grid continues to increase. This is due to a significant share of tourism water consumption resulting from activities not associated with accommodation. For example, tourism water use arising in restaurant kitchens, spas and laundry facilities accumulates to on average 10–30 liters per guest night according to studies by Gossling et al. (2012). On Fårö, these facilities typically are connected to the public water grid and therefore continues to tax the public water system despite the accommodation facilities having their own wells. These spillover effects will cause an increase in the absolute municipal water use by the tourist sector, despite a growing number of tourist facilities having their own water supply. We argue that this is a challenge that is not unique to our case study. Introducing alternative water supply solutions (e.g. private wells) on top of an already existing centralized water supply system (e.g. the public grid) is likely to increase water use in the centralized system in the long run if it leads to an increase in the total number of consumers, and the water use of the new consumers is not confined to their private taps.

4.3.3. Impacts on the municipal water system

Persistence of the low groundwater regime experienced in the past 20 years will continue to limit groundwater extraction from the

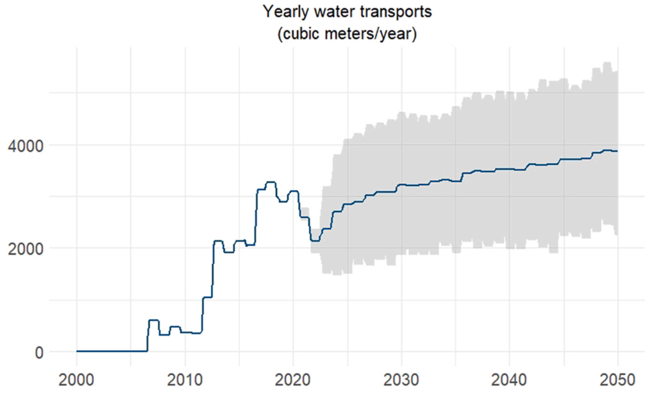

Fig. 12. Yearly municipal water transports. The blue line is the simulated mean and the shaded area represents the 95% confidence interval of the MC ensemble.

municipal aquifer and result in continued dependence on summertime supplementary water transports. As described in section 4.2.2, growing water use in the tourist sector, combined with higher summer water use due to warmer temperatures, causes water transports to increase steadily throughout the simulation (Fig. 12). By 2050 yearly water transports on average reach close to 4000 cubic meters per year (compared with the hitherto highest observed value of 3000 cubic meters), with a confidence bound ranging from 2200 to 5400 cubic meters (Table 3). A remarkable aspect of these results is that the local municipal water supply is insufficient to meet demand for the entire outcome space. This suggests that, even in the most optimistic climate scenario from a water supply perspective, maintaining the current trajectory of socioeconomic development will cause sustained reliance on supplementary water transports. Additionally, the high proportion of households with permanent or periodically elevated chloride levels is likely to result in increased pressure on the municipality to expand the borders of the municipal water management area and provide water services to more communities on the island. This would require substantial investments in infrastructure and further increase the reliance on supplementary water transports.

For Fårö to become water self-sufficient, a fundamental change in water supply solutions, growth strategy, and water use efficiency is needed. For instance, the current water supply system is completely reliant on groundwater, making it vulnerable to declines in both groundwater levels and groundwater quality (Schramm and Felmeden, 2012). Diversifying the portfolio of local water sources can reduce this vulnerability by making the system more resilient to unexpected climate events, and the large fluctuations in groundwater availability that our simulations project (Daigger and Crawford, 2007; Leigh and Lee, 2019). Rainwater, stormwater, and graywater are all potential sources of usable water that are not leveraged in most municipalities across the Nordic region. Utilizing these as alternatives for non-potable purposes can reduce water demand from conventional sources by an estimated 30–60% (Biggs et al., 2009; Zadeh et al., 2013). These solutions can improve overall resource efficiency, and increase redundancy by not wasting drinking quality water on uses with lower quality requirements (e.g. irrigation and toilet flushing). Reducing groundwater extraction also serves to maintain environmental flows that are critical for the health of freshwater dependent ecosystems (Leigh and Lee, 2019) and it can significantly reduce energy demand for water treatment and transfer (Xue et al., 2016). Several studies have concluded that because of their low energy costs, short construction times, and low capital intensity, decentralized solutions making use of alternative water sources are compatible, and often economically superior to conventional centralized alternatives (Brown et al., 2011; Leigh and Lee, 2019). On the other hand, a cost-benefit analysis conducted by Sjöstrand et al. (2019), comparing different water scarcity abatement measures in the Gotland region, concluded increased centralized groundwater extraction to be the most cost effective solution for the region. However, the analysis by Sjöstrand et al. (2019), like most conventional approaches for both economic and sustainability policy assessment, are based on a static view of the system (Lindqvist et al., 2019). That is, the system is assumed not to evolve or change over time and factors such as resilience to climate variability, effects of synergies and interactions between interventions, and socioeconomic feedbacks, are not accounted for in the assessment. Our simulation results clearly show that such a static assumption is misleading and, based on previous studies, can compromise the sustainability and resilience of future water systems (Leigh and Lee, 2019; Lindqvist et al., 2021). We call for further studies, on Fårö and elsewhere, to reassess alternative water supply solutions, some of which we have briefly mentioned, utilizing the type of feedback rich, dynamic, socio-hydrological system models we have developed in this study to identify sustainable and resilient pathways to mitigate future water scarcity.

5. Conclusions

We present a combined social and hydrological model using multivariate MC simulations to explore the effects of future climate and socioeconomic mechanisms on local supply and demand for drinking water on the Swedish island of Fårö. Our results suggest, given the available projections of future climate for the region, that the period with historically low groundwater levels experienced in the last decades will be sustained, and the probability of recurring periods with the groundwater table reaching lower levels than hitherto ever experienced is high. The low groundwater levels will limit water availability and increase the risk of saltwater contamination of drinking water wells. This will constrain growth in the housing sector (by 4–11%) and the tourist sector (by 10–30%), and maintain municipal reliance on supplementary water transports in summer months. The tourist sector will become increasingly reliant on private wells to support growth, but spillover effects will continue to increase consumption of municipal water and yearly municipal water transports.

To our knowledge, this is the first study to explore local impacts of future climate using an integrated social and hydrological model in the Scandinavian region. As in many other studies (Rusli et al., 2021; Tegegne et al., 2017), poor availability of local hydrological and water use data poses a challenge to model development for the region. For instance, limited data on historical groundwater levels and lack of spatially referenced water quality samples make spatially disaggregated modeling of future groundwater levels impossible. This necessitates a more exploratory modeling approach, investigating broad parameter ranges and presenting results in terms of outcome spaces rather than narrow predictions (Bankes, 1993). These limitations aside, our results provide important insights about the range of plausible futures that should be accounted for in local to regional water resource management and planning. Ensuring water self-sufficiency across the full outcome space will require investments targeting resilience in the water supply system. This can be achieved by leveraging alternative water sources, improving water use efficiency, and by accounting for socio-hydrological dynamics in the planning and management of future water system. We believe that the work presented here can support this necessary transition on Fårö and serve as a steppingstone for further climate impact and adaptation research in the Nordic region.

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CRediT authorship contribution statement

Andreas Nicolaidis Lindqvist: Conceptualization, Methodology, Formal analysis, Data curation, Writing – original draft. **Rickard Fornell:** Conceptualization, Methodology, Validation, Writing – review & editing. **Thomas Prade:** Writing – review & editing. **Sammar Khalil**: Supervision, Discussion. **Linda Tufvesson:** Supervision, Writing – review & editing. **Birgit Kopainsky:** Conceptualization, Methodology, Validation, Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ejrh.2022.101066.

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