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Building climate resilience in deltas amid uncertainty and surprise

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Delta management has been quite successful reducing historical risks. However, climate change and the myriad of other challenges that deltas face involve many uncertainties and unknowns, leading to potential surprises that are currently rarely addressed. I examine how such surprises might arise, and how delta communities can build resilience in the face of them.

Deltas are hubs for human activity. According to the Global Centre on Adaptation, around 500 million people live in deltas and coastal urban regions, with an expected 50% increase by 2050. contributing significant portions of national GDPs.[1] [1] Deltas offer fertile soil, access to marine resources, and trading opportunities with inland and overseas regions and thus contribute significant portions of national GDPs.[1]. They also offer quick access to other places, allowing residents to reap the benefits of many interconnected systems.

Yet life for delta communities is also inherently variable: annual fluctuations in river flow and sedimentation and storms and floods have regularly changed delta landscapes. Seasonal and multi-year changes in rainfall and temperature, whether random fluctuations or oscillations such as El Niño, also lead to natural variability in local climatic conditions. Delta communities have found many ways to cope with this variability, ranging from seasonal proverbs that helped farmers decide what crops to plant and when, to modern delta infrastructure, agricultural systems, and insurance schemes. Delta management has emerged to tame this variability; to make deltas more predictable and management as efficient as possible. Centuries of experience and data have revealed what the 'average' year might bring and the range of variability for river flows, storm surges, rainfall, temperatures, and so on. This means risks can then be weighed and optimal solutions designed. In many developed countries, this 'predict-and-prevent' approach.[4] has led to delta management using 'hard infrastructure', such as levees and canalisation of rivers, technocratic, top-down decision-making based on detailed hydrological and engineering models, and the illusion of control. Developing countries are perhaps historically more attuned to flexible, informal approaches, whether due to culture or necessity, and may be able to teach the developed world some lessons on living with unpredictability. However, many developing countries have also started to adopt this 'predict and prevent' approach Such a transition is particularly likely in situations where the management culture is hierarchical or expert-driven, where institutional culture is impacted by the legacy of colonial rule, or where adaptation is influenced strongly by donor countries or international organisations that still adhere to this predict-and-prevent mindset. This approach is deeply ingrained in current institutional cultures; internal logics, worldviews, values, and power relations.[2] However, it was designed for a relatively stable world, and 'normal', routine problems that can be handled by specialists in their separate departments.

Today, deltas face numerous new challenges, ranging from climate change to land use change, subsidence, biodiversity loss and ecosystem degradation, urbanisation, demographic changes, conflicts, and globalisation. Climate change will contribute to sea level rise, changing rain patterns, river discharge and resulting floods and droughts, more frequent and intense heat waves, the arrival of new agricultural pests, changes in diseases, and so on.[3] Estimates of economic losses range from

9% of GDP-per-capita (Volta Delta) to 19.5% (Bangladesh).[1] Seemingly small changes can also have large consequences. A 0.15m rise in sea level compared to 2020 would increase the population potentially exposed to a 100-year coastal flood by 20%.[3] Each of these changes is inherently uncertain, but they also interact in complex ways; their combined impact on communities living in deltas and their divergent interests is even more fraught with unknowns.[4,5] Current delta challenges are decidedly 'Post-Normal' and action is urgently needed, but decisions are characterised by high uncertainty, and disputed values and goals.[6]

Delta decision-makers seem to be forcing new challenges into old ways of managing deltas. There are many examples of climate adaptation plans that acknowledge and highlight uncertainty but seem to have been developed using conventional mindsets.[2,7,8] For instance, they use only a single scenario, rather than the full range of potential futures, or focus on technocratic fixes while ignoring the deeper societal roots of delta challenges like persistent social inequalities or poverty. Delta management requires a new approach.

Climate-related uncertainty and surprise

Effective delta management and planning is complicated by uncertainties arising in the data and models used to project global change, in the translation from global change to local impacts, and in the effect of specific adaptation measures.[2,3,9] There are knowledge gaps, ambiguities, and inherently unpredictable behaviour in complex systems.

Some uncertainties, like the historical likelihood of an area experiencing a flood, can be quantified into probabilities.[9] Much of existing delta management focuses on this type of uncertainty, as discussed above. In the context of climate change, historical probabilities are less informative. A second type is scenario uncertainty. Scenarios show ranges of possible outcomes, and they have become a more useful way of exploring an uncertain future. For example, the mitigation and adaptation pathways described in the IPCC reports explore potential future climate scenarios.[3] These indicate ranges of potential outcomes, but cannot be expressed as probabilities. A third type of uncertainties relates to ignorance. Unlike the often gradual trends depicted in climate scenarios, they deal with more 'messy' situations: unknowns, non-linear changes, and the unpredictable. Many surprises are at least partly due to ignorance. For example, oversights in the engineering calculations for the levees in New Orleans (optimistic interpretations of data for known factors, overlooked processes) led to catastrophic failure during Hurricane Katrina. To make them manageable, decision-makers can inventory what unknowns could conceivably lead to policy-relevant deviations from expectation: 'imaginable surprises'[10] (Table 1). Similar tools and concepts include surprise scenarios or wild cards,[4,5,10,11] hinge points and incremental scenarios,[13] and black swan events.[14] In Rotterdam, for instance, policymakers critically re-examined adaptation plans against 'surprise scenarios' including rapid ice-sheet melt, frozen ports, enduring heat and drought, port malaria incidents, and extreme storms. Using structured brainstorms and Group Model Building, policymakers explored which adaptation options held up under various surprise scenarios, which ones might become maladaptive instead, and how local resilience could be improved.[5] Imaginable surprises can be used to assess systemic vulnerabilities and weaknesses in adaptation plans, inventory local information needs,[13] and design options to improve delta resilience.

Some imaginable surprises could lead to an outcome that is worse than expected.[5] For instance, there are still considerable knowledge gaps in the melting processes of the Antarctic icesheet and the associated sea level rise. Surprises could also occur in monsoon patterns, desertification, cascading ecological changes, or distribution of vector-borne diseases and pests. Another example would be a

confluence of events with unforeseen impacts: high river discharge occurring simultaneously with a high storm surge, or a merger of multiple storm systems that then hit a delta (e.g. Hurricane Sandy). Surprises can also be outcomes opposite to those expected. A classic example is a potential shutdown of the Thermohaline circulation, which could result regional cooling in Europe despite global warming. Another example might be a case where adaptation is laser-focused on heat-proofing deltas, while unintentionally increasing vulnerability to cold spells that could still occur due to climatic variability. Finally, surprises may be entirely new issues such as climate impacts new to science, or to the specific delta, unexpected side-effects, or cascades of impacts over multiple systems.

What constitutes a surprise, is highly locally dependent: in West-European countries, there is considerable knowledge on intense rainfall, but knowledge gaps surrounding drought. Work in South Africa observed the opposite: much experience with prolonged drought, but intense rainfall resulted in surprises.[15] Climate-related surprises can come from a variety of sources: knowledge gaps in climate science, extraordinarily bad luck, or the limited awareness or attention span of organisations involved in delta management.

Societal surprise

Other surprises can emerge from societal factors, such as politics, policy, legal aspects, economics, public perception, technological developments, and other non-climatic stresses.[12] For example, in Dordrecht, policymakers, residents, and researchers inventoried potential hinge points for climate adaptation, including societal surprises, such as flood risks resulting in stigma for the city, economic shocks to critical local industries, and adaptation-related urban renewal programs that could threaten community cohesion in disadvantaged neighbourhoods.[13] These were used to reflect on socially robust climate adaptation planning and information needs.

Societal surprises might arise, for instance, when government departments overlook diversity in vulnerability among the population, changes in vulnerability, or potential unintended side-effects of policies. Discussions on resilience and sustainability often focus on ‘the delta’ or ‘the city’, but these are neither homogenous nor static.[7] Adaptation options may benefit some, but hinder others, and this can lead to maladaptation or societal tensions. For example, policies that uncritically upgrade neighbourhoods with costly high-tech climate-proofing or forbid housing in floodplains may work for higher income residents, but lead to gentrification and clearing of informal neighbourhoods in the developing world, exacerbating inequalities.[5] Other surprises might arise from unspoken differences in values and goals among actors, who may frame the challenge of climate resilience or sustainability very differently;[7] with diverging views on the problems, causes, moral judgements, and appropriate solutions. Blind spots on these framings may lead to decision-makers ignoring trade-offs, fixing the ‘wrong problem’, or a breakdown in collaboration with delta actors. Similarly, assumptions in climate-adaptive development might also prove incorrect. For instance, the Global South might not follow a similar demographic transition (declining birth rates as affluence increases) as the North, .[10] The framing and values underpinning adaptation can also change over time. External events, including geopolitical, demographic, economic, or social disruptions, may force us to rethink our approach.[12] Smith & Dubois,[12] for instance, explore strategic wild cards for European spatial planning, such as ‘Gulf Stream stops’, ‘European social security system collapses’, ‘era of energy scarcity’, and ‘dollar collapses’. Such events alter climate vulnerability and the pros and cons of adaptation options. Furthermore, future generations may have different values and challenges than we do today, and decisions that we make may limit or expand their options.[16]

Importantly, surprises can also be positive.[13] Some might open a window of opportunity to improve delta policy or the quality of life of residents. For example, a radical new technology might decrease the costs of adaptation or offer new social or economic benefits. Similarly, an organisation might come up with an 'out-of-the-box' solution that allows for better integration of adaptation, sustainability, and other concerns.

Table 1. Illustrative examples of imaginable surprises in climate adaptation in deltas.

Type of surprise	Examples	Potential reasons	Potential consequences	Solutions that are especially important
Expected change, but impact surprisingly higher	- Disaster (flood, wildfire, etc.) hits, while long-term drought issues due to climate change had already increased vulnerability. - Flood barriers were heightened to reduce the chance of flooding, but an event (e.g. storm) occurs that is well beyond the design limits. - Upstream country modifies flood risk management (changing downstream risks).	- Short-term shocks and long-term stresses act in concert, amplifying an impact. - Other socio-economic trends increase climate vulnerability. - Estimates of plausible change or vulnerability were too optimistic. - Policy focus too narrow (e.g. only on probability, ignoring vulnerability).	- Higher damage (e.g. economic, structural, health, lives) that was preventable. - Overwhelm of urban systems, leading to potential catastrophic events.	- All resilience-based adaptation options function well: foresight, absorption, recovery, adaptability, community resilience.
Expected change, but unexpected uneven distribution of impact	- Floods or heat waves hit vulnerable groups hard (e.g. disadvantaged communities, elderly). - Drought results in moderate problem for delta in general, but takes out local river fishing industry.	- Climate knowledge didn't take specific local conditions into account. - Climate policy didn't account well for power dynamics or existing inequalities.	- Specific population groups, actors, or systems hit disproportionately. - Challenge to social justice. - Erosion of local resources (e.g. specific industry leaves).	- Community resilience. - Capacity to spot weak signals (early warnings) from delta systems and communities.
Expected change, but impact surprisingly lower	- Impacts of flooding turn out less severe than expected. - Global climate mitigation speeds up.	- Unrecognized source of autonomous adaptation. - Vulnerability less than expected, or reduced through other trend.	- Questions of accountability (didn't we spend too much on adaptation?)	- Flexibility. - Specific options with co-benefits, no-regret.
Opposite of expected change	- Excess focus on swift removal of rainwater to prevent floods in wet season results in droughts in dry season. - Adaptation focus on dealing with heat, while decreasing ability to deal with cold events.	- Feedback loops in climate system result in unexpected change. - Overreaction in policy or operational response. - Policy focus too narrow. - Forgetting variability.	- High impact, if adaptation policy had increased vulnerability to these. - Questions of accountability (who failed to spot that this was possible?)	- Capacity to spot weak signals. - Adaptability & flexibility. - Community resilience.
Novel, change or impact	- Tropical disease hits temperate delta. - Limited, but repeated flood events damage the reputation of the delta as safe and modern place (wealthy residents, companies, tourists leave).	- Novel issue. - Confluence of events (multiple shocks happen at the same time, with unexpected knock-on effects). - Impacts cascade across multiple systems, leading to unexpected effects.	- Government taken off-guard. - High impact due to absent skills, tools to manage this change. - Need for quick and large policy overhaul (expensive; high risk of unintended side-effects).	- Broad capacities for anticipation & foresight and adaptability. - Community resilience.

Building delta resilience in the face of uncertainty

Even if deltas face a future that is full of uncertainty and unpredictability, we may still be able to improve delta resilience.[4,5] Resilience is the ability of a system or community to cope with disturbances (short-term shocks and long-term stresses) while retaining broadly the same structure and identity; for instance through preparing for, absorbing, recovering quickly from, and adapting to disturbances.[7] Rather than trying to 'predict-and-prevent' changes, resilience-based adaptation asks: if something does go wrong, how could the systems and communities in the delta respond? Different approaches can be taken to build resilience (Figure 1).

Resilience can be built into the way that delta infrastructure and systems are designed, so that the potential impact of surprises is reduced, and responses are mobilized quickly. They can be developed with 'resilience principles' in mind, such as redundancy, omnivory, buffering, high flux, and homeostasis.[4,5] For example, redundancy in connections or critical systems means that if one fails, others are still available. Omnivory involves diversification of critical resources, such as reducing the dependence of the local economy on a single industry, or multiple types of electricity generation (gas, solar, wind). Rainwater buffers such as cisterns or bioswales can limit the potential impact of intense rainfall. High flux involves the ability to quickly mobilize resources, such as information, funds, or equipment to respond in case of an emergency and recover afterwards. Homeostasis relates to stabilizing feedbacks that can be built into the system, for example flood barriers that automatically close under certain weather conditions or forecasts. Such principles work particularly well with short-term shocks and applications such as critical infrastructure design.

Resilience can also be improved through rethinking delta management and planning, so that surprises are spotted earlier and new information is acted upon.[7] Anticipation can be improved by investing in local knowledge networks, developing monitoring networks for key issues (water levels, pollution, socio-economic variables, etc.), and improving information management. Preparedness could be improved through emergency planning and training, public risk communication, and providing stress tests for local businesses. Intentional focus on learning is key to adapting successfully, and includes establishing processes for learning from policy mistakes, retaining and sharing knowledge in organisations, stimulating critical thinking and reflexivity among decision-makers, and experimentation. Flexibility can be included in institutions, spatial planning, and specific policy interventions. For example, Rotterdam invested much in building collaborations with local universities and knowledge institutes, developing uncertainty awareness in its organisation, flexible use and planning of public spaces, and climate-sensitive urban design.[7]

Finally, and crucially, community resilience should be improved. It is the people living in deltas who experience the daily struggles with shocks and stresses. Communities might spot the first signs of things going wrong and will often need to develop an initial response well before government aid arrives. It is meaningless to develop resilient infrastructure and planning, but ignore the needs of residents and risk leaving communities degraded after a disturbance. Therefore, it is important to strengthen the social basis of resilience.[7] This means improving the capacity of delta residents, neighbourhood organisations and local business to spot and respond to disturbances, equitable access to resources, social connectedness, local partnerships and leadership, public engagement, and counteracting deeper determinants of vulnerability, such as inequality, poverty, and a lack of rights, health, sanitation, and education. For example, New York's resilience planning emphasises public communication, education, and urban identity,[7] and Dordrecht emphasised involving disadvantaged communities in adaptation and strengthening the role of local social entrepreneurs as mediators between residents and government.[13] In the Global South, organisations such as the Red Cross and UNDRR spend much effort on awareness raising and local capacity-development among community

actors. Such efforts should enable communities to have agency: a voice and an active hand in navigating surprises and building a resilient delta.

Need for new imagination

Surprises are unavoidable when adapting deltas to climate change and the many other challenges that communities face. Preparing delta communities for such a 'Post-Normal' future, characterised by high uncertainty and disputed values, will require new imagination to foster resilience.

To overcome blind spots, challenge ingrained assumptions, and ensure that the full range of local values and goals is included in decision-making, delta policymakers need to significantly expand the circle of actors involved in delta research and policy. Local communities –residents, social entrepreneurs, local businesses and organisations– should have greater roles. They are less confined by departmental silos and narrow disciplines, live their daily lives in the delta and experience the changes taking place. Therefore, they may spot potential problems earlier and can come up with creative, integrated solutions. This enables delta management to rethink what it means to live in and manage deltas, and to strengthen anticipation & foresight, adaptability, and community resilience. Reimagining delta management requires more open, bottom-up approaches and unconventional collaborations: enabling delta communities to take leading roles in adaptation, from setting the policy agenda to designing options. It also includes improving their involvement in delta research, for instance through community-led citizen science, or developing climate services based on community interests, goals and concerns. While this can be uncomfortable, it helps build capacity for proactive adaptation and societal learning, and places agency back into the hands of delta communities.

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Declaration of Interests

The author declares no competing interests.

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Figure Titles and Legends

Figure 1. Different approaches to resilience-building*. They can take a top-down (engineering, planning & governance) or bottom-up (strengthening the social basis) approach and focus on short-term shocks or long-term development. While not mutually exclusive, they involve different mindsets, adaptation options and decision-making tools. Figure adapted from Wardekker (2021).*[7]