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Modelling an urban water system on the edge of chaos

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ABSTRACT

Viewing an urban water system as a complex adaptive system provides new opportunities for analysis and avoids some critical simplifications. Taking this perspective, it is possible to explore the inter-related effects of changes to the system. This is particularly important in the developing world where donors providing aid aim to improve conditions but struggle to understand and quantify the systemic impacts of their actions. This is because an intervention aiming to improve condition may also have unintended and undesirable effects. To provide decision support, this paper describes an agent-based model of an urban water system, developed on the basis of ethnographic interviews, and subsequently evaluated by local stakeholders. The paper describes the model design as well as the results of scenarios. The model provides guidance on which system amendments may produce the best outcomes in terms of output variables, and on the basis of sense-checking and sensitivity analysis it is judged that model results are likely to give a good indication about possible real world outcomes. It is clear that no single strategy will solve all problems on its own, but that a combined strategy – with a strong focus on groundwater management and protection – is likely to be most successful.

1. Introduction

Urban water systems are socio-technical systems that are a critical component in the functioning of cities. Traditionally in the developed world, such systems are mostly human-made and operated via centralised collection, distribution and treatment systems. In these traditional systems, households as well as commercial and industrial users receive the water via the tap from large-scale piping systems.

In the developed world the focus has traditionally been on public health and sufficient supply but in later decades also on pollution control and flood control (Brown, 2005). More recently however, there is an increasing consideration of ecosystems and sustainability thinking, as indicated by a growing body of work (Otterpohl et al., 1997; Lundin et al., 2000; Bai and Imura, 2001; Pahl-Wostl, 2002; Bracken et al., 2004; Palme et al., 2005; Panebianco and Pahl-Wostl, 2006). There is also an increasing push towards considering community attitudes and socio-cultural aspects in the urban water planning process, as indicated by the work on incorporating and assessing socio-cultural aspects of an urban water development in the planning processes (Söderberg and Åberg, 2002).This is typically done in the urban water sector within some type of Multi-Criteria Assessment as is described by Hellström et al. (2000). Other approaches to integrated and holistic analysis have also been used but have not yet gained mainstream acceptance in the urban water sector, such as systems dynamics (Proust and Newell, 2006), agent-based modelling (Panebianco and Pahl-Wostl, 2006), and Bayesian networks (Moglia et al., 2009).

In the developing world, the focus is in line with the Millennium Development Goals, and in particular Goal 7, which aims to reduce by half the proportion of people without sustainable access to drinking water (United Nations, 2009). Progress has been slow (UNESCO, 2006), partly because progress is difficult when faced with severe constraints and problems, such as in Tarawa, Republic of Kiribati in the South Pacific region, where a range of constraints have led to over-extraction, conflicts, severe pollution and high levels of water-borne disease (White et al., 1999a; Dray et al., 2007).

We argue that urban systems have a great deal of complexity in the sense of the word used in complex systems science. This complexity is caused by a number of issues: water use behaviour, use of multiple water sources for different purposes, point sources of pollution due to land use behaviour, flows and leaks of water through a complicated technical system, water supply being dependent on somewhat random weather patterns and complicated hydrological dynamics, as well as dependence on pumping

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and allocation schedules, etc. In large-scale urban water systems in developed countries this complexity has been reduced via technical design – but when this is not possible, as in small or developing systems – management enters a different realm in which we need to acknowledge the dynamic and complex nature of the system. It is recognized that in small towns without adequate economy of scale, reliance on centralised systems is not suitable, and consequently the management approach becomes increasingly difficult to define (Pilgrim et al., 2004). This challenge has prompted research by the authors into identifying governance frameworks (Moglia, 2010) that acknowledge and cope with the urban water system as a complex adaptive system (Holland, 1995; Miller and Page, 2007).

2. Case study setting

As part of this larger-scale study, the authors have undertaken field based research and modelling in Tarawa, Kiribati. The Tarawa water system epitomizes the worst-case scenario in terms of urban systems complexity. It is also a distressing situation in terms of related health concerns, water scarcity and environmental problems, and as such it is a suitable case study. The case study location is shown in Fig. 1 – including the outline of the atoll with its string of islands, as well as its location in the central Pacific Ocean. This shows how islands are very narrow with main urban areas towards one end of the atoll, from the high density population in Betio to the island of Bonriki which is more peri-urban – and with islands north of Bonriki being mainly rural. The water resources in Tarawa are predominantly located in freshwater lenses on the largest islands of the atoll. The water table is typically 0.8 to 1.6 m below the ground surface. The use of groundwater is supplemented by the use of rainwater on most of these islands. South Tarawa is the capital and main population centre of the Republic. The water supply for the urban area of South Tarawa is pumped from horizontal infiltration galleries in groundwater protection zones (*water reserves*) located on Bonriki and Buota islands. These currently supply about 60% of the needs of South Tarawa communities. Rainwater, local private wells and a reverse osmosis desalination plant (100 m^3/day) supply the rest (White et al., 2008). The declaration of water reserves over privately owned land has led to conflicts, illegal settlements and vandalism of public assets. Additionally, the water consumption per capita is tending to increase towards standards in developed nations, threatening the sustainability of the system. Finally, pollution generated by the 45 000 habitants of South Tarawa has already contaminated all the freshwater lenses, with the exception of Buota and Bonriki reserves (White et al., 2008).

This research builds on previous work in Tarawa involving computer simulations (Perez et al., 2003) and participatory modelling (Dray et al., 2006, 2007). This paper describes the development and application of an agent-based model (ABM) aiming at supporting better water governance in Tarawa. After describing the structure and input data of the model, we present the different simulated scenarios and their results before discussing the advantages of this type of computer simulation in the context of water governance in small towns.

3. Study context

Because of an increasingly stretched supply-demand balance in South Tarawa, there were plans to set up new water reserves which would add approximately 700 m^3 of freshwater per day (Falkland, 2003). This was set to occur as part of a large- scale infrastructure investment project, but there were concerns due to the already problematic situation on existing reserves. To find a resolution or understanding of the situation, an initial study was carried out by colleagues using a Companion Modelling approach with two iterations: 1) *AtollScape,* where an ABM was developed based on ethnographic knowledge elicitation and knowledge engineering (Perez et al., 2003); and 2) *AtollGame,* where a role-playing game was devised and applied, in conjunction with the *AtollScape* model (Dray et al., 2006, 2007). Through these studies, a process was facilitated in which stakeholders shared viewpoints, and made apparent a number of intricacies in the interaction between migratory pressures, monetized land value, and access to water which had so far been dismissed in the official discourse about the

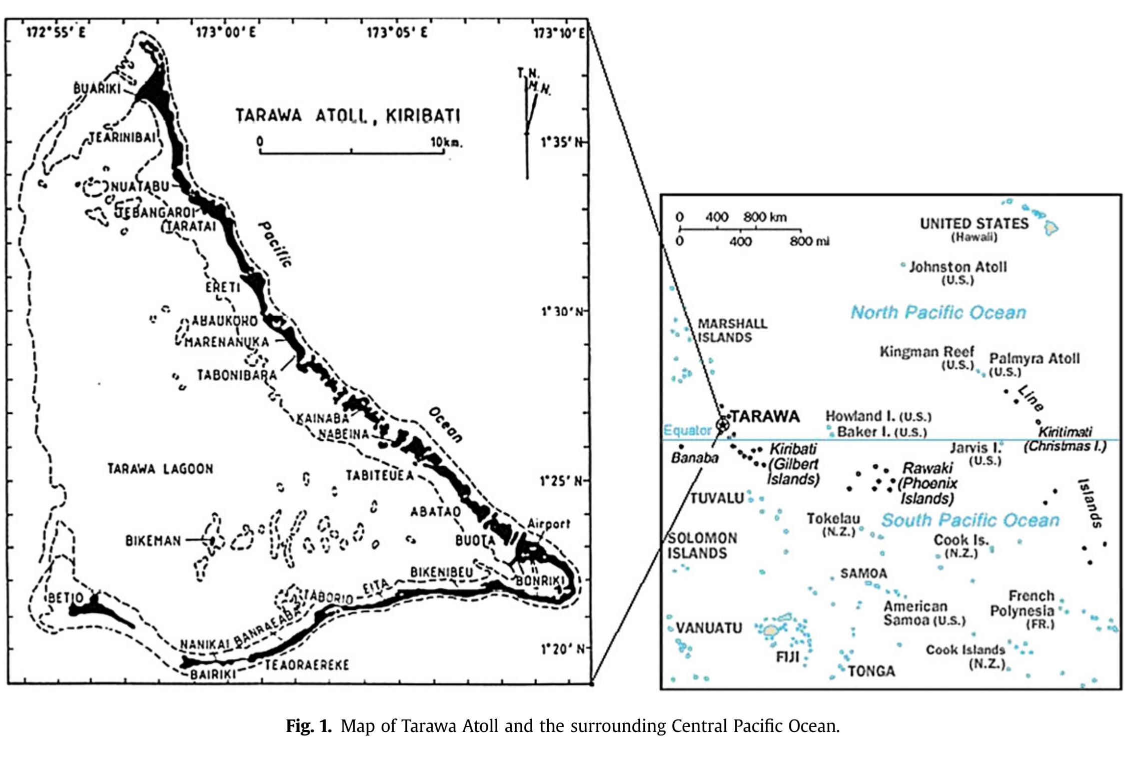

Fig. 1. Map of Tarawa Atoll and the surrounding Central Pacific Ocean.

reserves issues (Dray et al., 2007). A framework for co-management including financial, technical and social solutions was devised. Additionally, recommendations were made in regards to how the process could be continued at a different level, reaching real decision and policy makers, but at the same time keep the direct interaction with communities, families and island representatives (Dray et al., 2007). When plans for extensions of reserves were delayed indefinitely, it was clear that there was a real need for making the current urban water system more efficient, to mitigate undesirable effects of the increasingly critical shortage of water, and to evaluate alternative water supply options.

This is where we entered the process, and as such the current study can be seen as a continuation of the *AtollScape* and *AtollGame* experiences. The ABM described in this paper aims to help improve the water management in the urban part of Tarawa as opposed to the previous studies that have focussed on the water reserves. This is to improve the ability of local agencies to manage the water supply and sanitation despite considerable resource deficiencies, and better acknowledge and take into consideration the complex socio-cultural and behavioural aspects of their community.

4. Methodology

The focus in this study is on understanding the complex interactions of urban water systems, i.e. involving interactions between issues such as water use patterns, health impacts, water sources, groundwater pollution as well as various technologies. The underlying assumption is that this system is a complex adaptive system (CAS), and that we require methods suitable for such circumstances.

The science of CAS concerns those systems that are neither chaotic nor ordered, but that tend to exhibit changing and emergent patterns (Holland, 1995). The use of the term chaos in the title of this article refers to the distressing situation in Tarawa rather than a characterisation of its systems properties. A CAS, it should display most of the following features (Holland, 1995; Perez and Batten, 2006; Miller and Page, 2007):

- Elements of surprise due to the unpredictable nature of the system,
- Emergence of macro-scale properties from micro-scale interactions,
- Irreducibility, or the fact that the system can not be understood by its parts alone but that the system needs to be viewed in its entirety,
- Self-organisation, or the emergence of order/complexity without inputs from the outside, and
- Feedbacks and thresholds; or non-state equilibriums that change over time and which generate dynamic processes with stable and unstable regions.

Socio-technical systems, such as urban water systems, are typical examples of CAS where agents tend to act in response to their environment, the built and natural environment as well as the institutional, normative and cultural settings, as well as the actions of other agents.

Whilst other approaches are available such as Systems Dynamics and Bayesian Networks, ABMs tend to be more suitable for analysing CAS in the environmental research field due to its capacity for supporting inter-disciplinary endeavours, analysing long-term intergenerational issues, uncertainty management, analysing local-global interactions, and being suitable for use in a participatory manner (Boulanger and Brechet, 2005). Others argue that it is particular suitable for modelling behaviour and interactions and for integrating social and spatial aspects – and useful for theorisation and collective decision making support (Bousquet and Le Page, 2004). Heckbert et al. (2010) argue that ABMs particularly suitable are good for quantitatively analysing complex systems that include autonomous entities that each have dynamic behaviour and heterogeneous characteristics with adaptive decision making capabilities – as is the case with water users in a city – but that such models need solid empirical grounding, calibration and validation.

Local stakeholders, including local water utility representatives argue that an ABM may help via:

- Its capacity to embed understanding of human behaviour, which is a critical aspect to consider in the management in the urban water system, but which has so far proven very challenging. Such aspects include the water use behaviour of households, the changing land use on the reserves, and the various pumping and allocation strategies of the water utility.
- Its ability to embed multiple perspectives into a single integrated analysis tool – making it particularly suitable for facilitating discussions between different departments and stakeholders.
- Its ability to allow users to quickly improve their intuition and understanding of the overall water system; something which is critical in a situation where formal education and practical experience is constrained to a small number of individuals.

In particular the last feature is critical to allow efficient communication of results to a wide range of stakeholders, who otherwise may have a limited understanding of the system, and this is critical in order to potentially embed the analysis technique within a more encompassing governance framework. Wider involvement of stakeholders in this context is critical because of the lack of economies of scale which creates reliance on both technical and centrally controlled engineering systems using pipes and other infrastructure, with supplements from typically rural water supply options such as ad hoc groundwater extraction from shallow wells and rainwater collection from roofs.

The behavioural aspects that are considered important for the performance of the urban water system are: water use behaviour which is reactive, situation dependent and based on local culture and norms, as well as rapidly evolving settlement patterns and activities on the protected water reserves, but also to some extent in urban areas, having a considerable impact on the water quality of groundwater. Relating to this are centrally controlled allocation mechanisms that are a critical component of a strategy – impacting critically on interactions between how multiple water sources are utilised for a range of water uses.

4.1. Modelling choices

With the decision to develop an ABM, we also need to specify the characteristics of our model. According to the taxonomy proposed by Hare and Deadman (2004), we assume the following design principles:

1. Space is represented in an explicit but stylized manner,
2. Individual decision-making processes are represented by heuristic rules,
3. Social interactions are described by task-based interactions and local learning,
4. Adaptive behaviour is implemented through multiple strategy selection.

The conceptual model is formally described through Unified Modelling Language (UML) diagrams, which is standard practice in this area, and the simulation model is developed within an Integrated Development Environment (IDE) called Cormas© (Bousquet et al., 1998). This choice is justified by Cormas' capacity to support rapid development, and its open-source nature. Cormas© is also the IDE that was used to develop the *AtollScape* and *AtollGame* simulation models mentioned earlier.

We also note that the model does not include interaction between agents other than through imitation and indirectly through the shared environment, which is in contrast to some of the more novel methodologies for MAS design such as Interaction Oriented Design of Agent Simulations (Kubera et al., 2008).

4.2. Data and design process

It is important in order to develop an understanding of complex environmental problems to collect information and perspectives from a wide range of sources, and this includes both qualitative and quantitative information (Bammer, 2005). In our study, the data is generated from iterative ethnographic interviews with key-informers, reviews of historical documents and data extraction from previous scientific reports (Alam and Falkland, 1997). Ethnographic surveys are based on semi-structured questionnaires or open-ended narratives. The critical analysis of this material is compiled in a review of the water sector in Tarawa (Moglia and Perez, 2007; Moglia et al., 2008) that identifies critical elements of the system. These elements and their dynamics are subsequently translated into conceptual *classes* and *methods* in the UML model (Fig. 2). While the design and implementation of the model are conducted by researchers only, the validation phase includes successive and direct interactions with stakeholders (social validation). UML diagrams are then essential instruments used as 'mediating objects' (Latour, 1986) during semi-structured interviews. Therefore, UML diagrams not only facilitate the conceptual design of the model but also create a bridge towards stakeholders that facilitates iterative validation of the model, according to participatory modelling principles (Van den Belt, 2004).

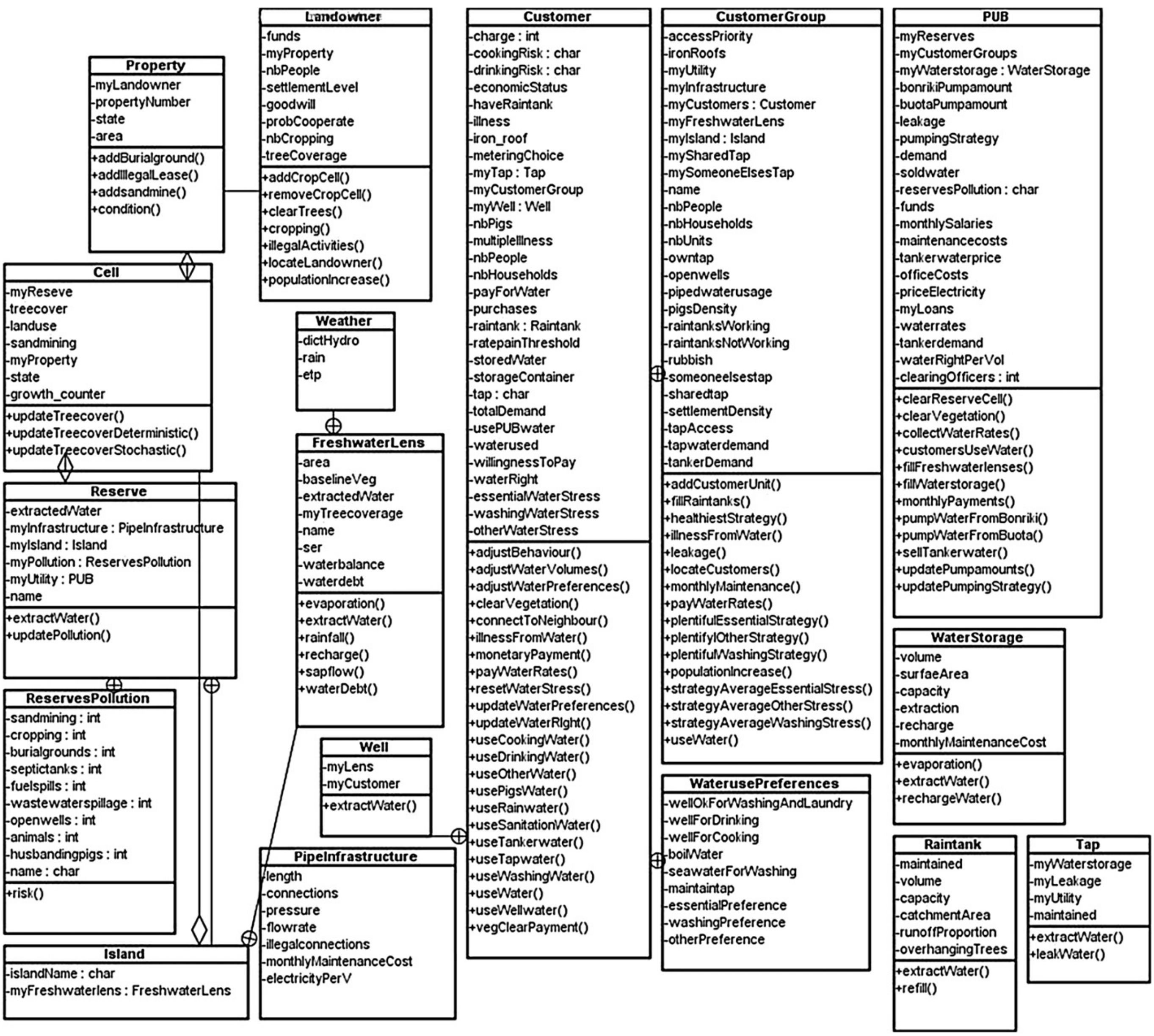

Fig. 2. UML Class Diagram for the Tarawa Waterscape Model. Note: This figure shows the UML Class Diagram with key classes in the Tarawa Waterscape Model, and most methods and attributes. There are classes related to customers, the operation of the water system, as well as classes related to the reserves, and some classes representing infrastructure and the spatial environment.

Table 1
Descriptions of classes in Tarawa WaterScape.

Classes	Representing	Key activities/attributes
Customer	A typical water use unit, i.e. a household	Water use, Illness from water, Pay for water, Update water use strategy
PUB	The public water utility responsible for the provision of urban water services	Pump water, Collect water rates, Sell tanker water, Adjust pumping amounts, Clear vegetation, Maintain infrastructure
Land owner	A land owner on the reserves (i.e. the water catchment areas)	Settlement patterns, Land use, Clear vegetation, Protect land
CustomerGroup (aggregate)	A group of customers with similar access to water. I.e. an urban village or an island	Same as customer
Cell	An area of land, ocean or lagoon	Tree cover, Land use
Property (aggregate)	An aggregate of cells representing the property of a land owner	Land use activities
Reserve (aggregate)	An aggregate of cells representing the catchment area of a freshwater lens	Land use activities, Pollution of the lens, Vegetation cover
Island (aggregate)	An aggregate of land cells joined into an island	For display purposes.
WaterStorage	The reservoir or dam used by the PUB for storing water	Extraction and recharge, Evaporation
Well	A well that a customer can use to access the freshwater lens corresponding to its island	Extraction of water from a freshwater lens.
Rain tank	A tank connected to the roof of a household's house	Extraction of water, Recharge of water from rain.
Tap	A connection point to the pipe network providing access to water	Maintenance, Extraction of water, Leakage of water, Access by customers
ChlorinationPlant	A Plant operated by the PUB for chlorinating the piped water	Chlorination, Maintenance
Weather	The weather changing on a 10-daily time step	Rainfall, Evapo-transpiration
FreshwaterLens	A freshwater bubble sitting in sand and located under islands	Evaporation, Extraction of water, Recharge of water, Sap flow
ReservesPollution	The level of pollution on a water reserve	Sand/gravel mining, Cropping, Settlements, Burial grounds, Septic tanks, fuel spills, etc.
PipeInfrastructure	Transmission or distribution pipes transporting water	Leakage, Electricity use, Illegal connections

5. Model description

The structure and content of the model is described through two major UML components: (1) a *class* diagram and (2) a *sequence* diagram. In order to describe specific dynamics in the model, we have opted for more traditional narrative explanations rather than using *activity* diagrams due to complex interactions between *classes*.

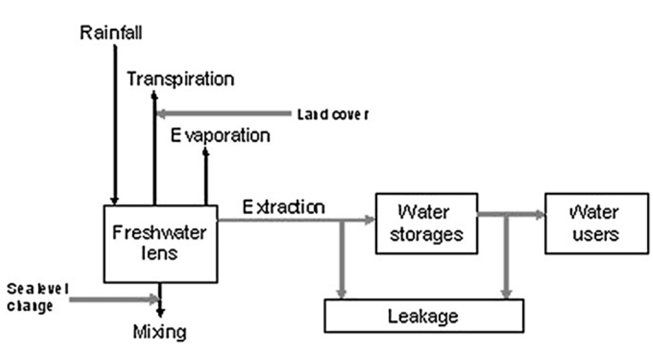

Fig. 3. Water balances of the freshwater lenses under water reserves.

5.1. Class diagram

The *classes* and their interactions are shown in Fig. 2, as well as most of the *attributes* and *methods*. Table 1, provides a brief description of each *class*, while individual behavioural models help agents to perform (when required) water use, land use or vegetation clearing activities. Dynamics of the freshwater lenses are described by a very simple hydrological model derived from Perez et al. (2003). Infrastructure operations and maintenance are also described in the model.

Tarawa WaterScape is a time step-driven model. One simulation time step, described by *t*, corresponds to a 1 day period, but has different activities at different frequencies. For example, population increases occur at a yearly time step, weather changes on a 10 day time step as described by *T*, with subsequent recharge of freshwater lenses and rain tanks, customers' water use occurs daily, as do reserve activities.

5.2. Selected components

As shown in the Table 1, there are numerous components in the model. Some of these are further described below, including descriptions of water flows, water use, reserve activities and financial aspects.

5.2.1. Water flows

Fig. 3 shows the water flows in the model. The *Weather* class of Table 1 controls the inflow of water into freshwater lenses and rainwater tanks via rainfall and evaporation. This is done on the basis of historical data allowing scenarios to be explored, including drought or rainy conditions which is generally governed by El Nino or La Nina events.

As described by Alam and Falkland (1997), in small atolls such as Tarawa, the freshwater lens is essentially a bubble of freshwater that sits in an ocean of salt water, and where the edge is not sharp but rather a transition zone. As can be seen in Fig. 3, the freshwater balances are also affected by factors such as land cover which impacts on transpiration, as well as mixing of the freshwater lens with salt water at its edge. The change in available water is as per Equation (1):

$$V(T+1) = V(T) + A\cdot[R - ETP - S] \quad (1)$$

Where, *V(T)* is the available freshwater volume (in litres) at time *T*, A is the catchment area in m^2, *R* is the rainfall in millimetres, *ETP* is the provided evapo-transpiration potential (in *mm*); and *S* is the sap flow, i.e. the loss of water through vegetation. On the basis of estimated sustainable extraction rates, the area of each lens has been calibrated using Equation (2), based on historical time series of rainfall and evapo-transpiration:

$$A = 1000\cdot SER/\left(\sum_{t=1}^{N}[R(T) - E(T)]/10\cdot N\right) \quad (2)$$

Where, *SER* is the sustainable extraction rate of the lens (in cubic meters per day, *N* is the number of data points in the weather file, *R(T)* is the rainfall at data point *t, and E(T)* is the evapo-transpiration. There is also a scaling factor of 10 because there are 10 days per weather data point, and a scaling factor of 1000 in order to convert millimetres to meters. Sustainable extraction rates of the various islands in the atoll are as much as possible aligned with the work by Falkland (2003) and for the islands where no reliable estimates are available, we use estimates provided by the local water utility.

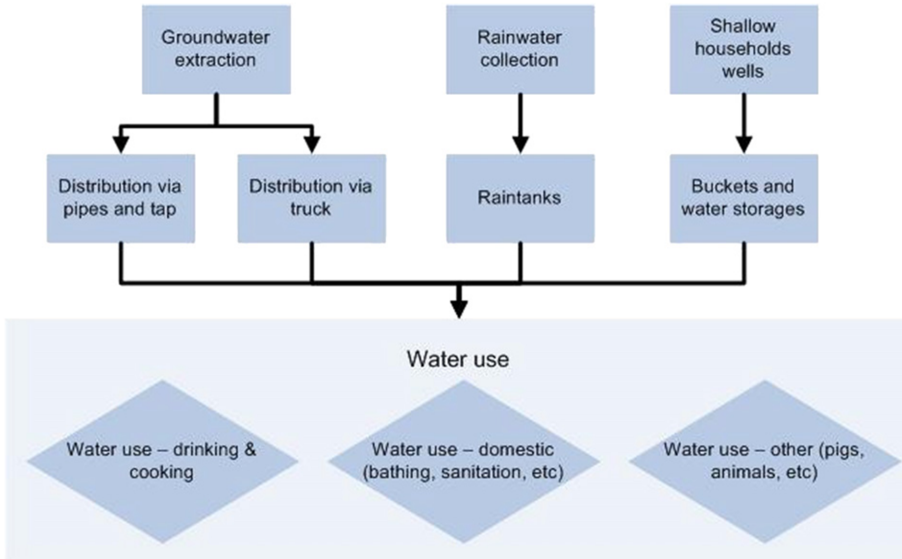

Fig. 4. Water sources and water uses.

After water is extracted from the freshwater lenses, it is pumped via water pipes to water storages, and subsequently to households who only have water supply for about 1 h each day. During the transport of water through pipes, there is leakage, which is modelled on the basis of leakage per kilometre of pipe, and the number of customer connections.

Another common source of water is rainwater tanks that collect rainwater from roofs. Not all households have rainwater tanks, and many existing rainwater tanks are in fact either non-operational or unsafe. From a water safety perspective, lack of maintenance and over-hanging trees impact on the quality of the water, and hence water safety.

For the households that do not have sufficient amounts of freshwater, water can be purchased from the water utility at a cost of \$2 per m^3, which is considered rather expensive. The water utility provides 20–30 m^3 per day but this is limited by having only a single truck for deliveries. In times of drought there is often a long queue for receiving water this way. In the model, water users have the option to purchase truck water, which is delivered to their private water container. It is also assumed that 10% of the water is lost in each delivery.

5.2.2. Water use

Behaviour of agents is the main source of complexity in *Waterscape*, and from the urban water system point of view (i.e. ignoring the reserves), in particular because of the way that customers respond to events and conditions in their choice of water source. Customers, i.e. mainly households, can access freshwater from four different sources, i.e. via 1) the tap, 2) domestic wells, 3) water tank trucks, or 4) rainwater tanks. However, the set of options for an individual customer will vary depending on what level of service and water that is accessible, and this was initiated on the basis of a household survey (Asian Development Bank, 2000). However, all customers can purchase water from water trucks, but the amount of water available in this way is limited by the number of water trucks operated by the water utility. Three categories of water use are taken into account: (1) drinking water such as for drinking and cooking, (2) domestic water use such as for bathing, sanitation and washing of clothes, and (3) other use such as for feeding animals and watering gardens. The water use flows are shown in Fig. 4.

Each time step, the customer will decide on what source type to use for each use category. This means that the water use preferences can be described using a three-dimensional vector for which each value can take four discrete values, i.e. specifying the vector ['Tap', 'Rain tank', 'Domestic well'] if the customer uses tap water for drinking and cooking, rain tank water for domestic uses, and domestic well water for other uses.

The way that this decision is modelled is on the basis of the principles applied in the *Consumat* model (Jager et al., 1999; Janssen, 2001). The *Consumat* model is based on social psychology and models a decision based on two dimensions for cognitive processing: firstly the cognitive effort required in the decision, and secondly the social or individual orientation of the process, which depends on the level of certainty or uncertainty involved in the decision situation. This means that there are four situations:

- *Deliberation*: Low level of needs satisfaction and low uncertainty of the decision situation, in which case the customer will essentially maximize its utility of the decision based on its representation of the system.
- *Social comparison*: Low level of needs satisfaction, but high level of uncertainty, in which case the consumer will apply social comparison, i.e. update mental map and subsequently find customers with similar abilities, calculate the potential benefit of their strategy, and change strategy in case the other customer's strategy is found to provide more benefit.
- *Repetition*: High level of needs satisfaction, but low level of uncertainty, in which case the customer will repeat previous decision.
- *Imitation*: High level of needs satisfaction, but high level of uncertainty, in which case the customer will imitate the behaviour the customer which he/she last compared herself with (in social deliberation).

For the water use situation in our study, the level of uncertainty is always high, which means that the customers will base their decisions on *social comparison* or *imitation* depending on the level of needs satisfaction. The way that this happens is based on triggers, i.e. model parameters subject to sensitivity analysis, and further described in Fig. 5. To describe this, the level of needs satisfaction depends on three types of occurrences: 1) water

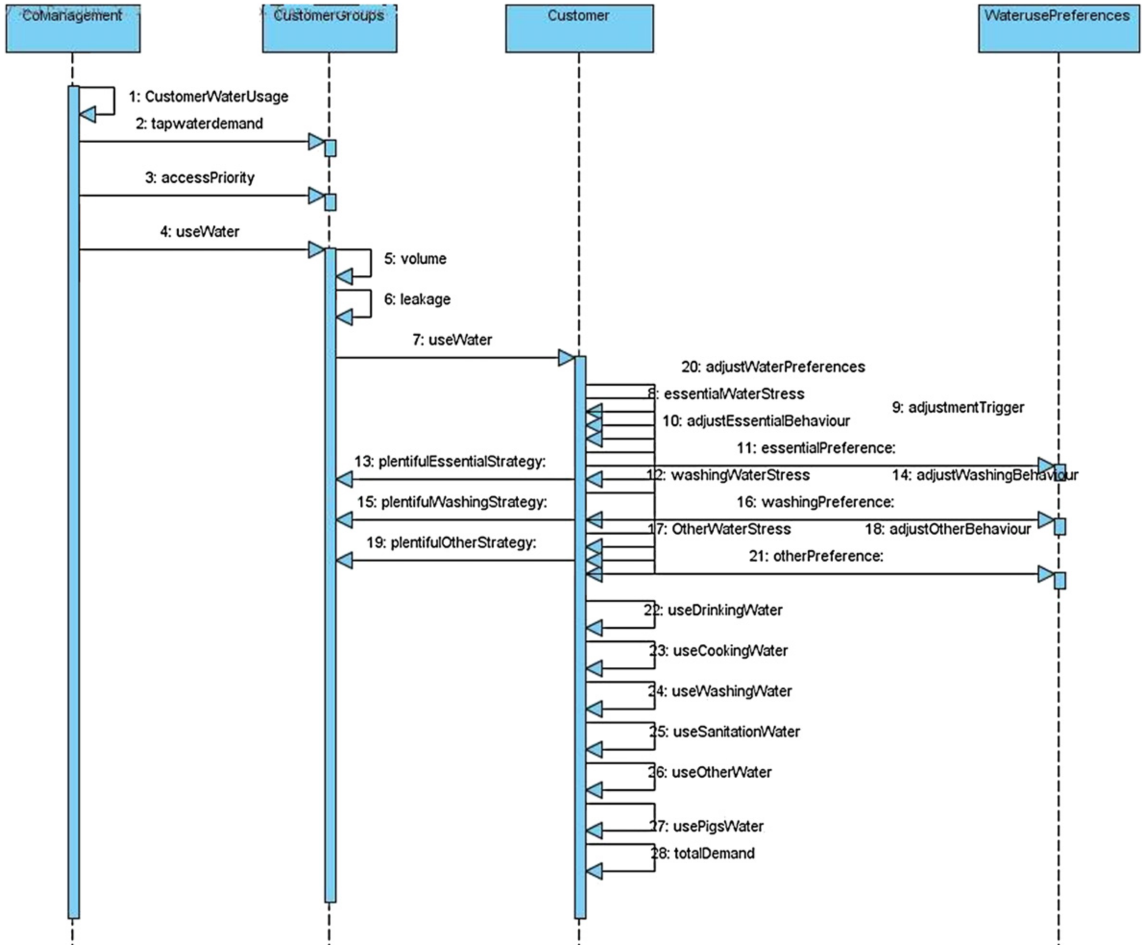

Fig. 5. UML Sequence diagram for customer water use at a daily time step. Note: This diagram shows the methods being called in the various classes whenever water is being used by customers. The sequence of events is essentially as follows: Firstly the access priority for tap water will be given to each CustomerGroup (i.e. village), and then the CustomerGroups (i.e. villages) will start to use water in sequence based on their priority. Secondly, each Customer will evaluate the type of preferences for each of the water use types; and will then evaluate whether there are any triggers (i.e. health, financial or access related) that go off; and update preferences if this occurs. Thirdly, each Customer will use water for each Water use type, using water from various water sources on the basis of their preferences.

scarcity (not being able to get enough water to cover needs), 2) health concerns (incidents of water-related health problems), and 3) payment difficulties (having to pay more than what the customer is willing to pay). These are defined via trigger levels for each of the types of needs. These are used to switch the decision from imitation to social comparison. In other words, if there are too many health incidents for a customer in a given period of time or the customer has to pay more than he is happy to pay, or he does not receive enough water, the customer will switch from *imitation* to *social comparison* as a mode for decision making. In the *social comparison* mode, the customer will find another customer in the same village (i.e. customer group) which is perceived as equivalent of finding a customer with similar abilities.

Another factor that influences a household's access to water is the allocation of water to various urban villages. Under the current regime, there is a difference in the water per capita provided. The amounts of water pumped to different areas vary, ranging from 55 L per person per day down to a meagre 22 L per person in the village with least supply. We also explore other allocation strategies in the model, such as having the allocation to villages proportionally based on their population sizes. Considering the limited tap water access, local wells and rain tanks are critical complements for households, and some hospitals and hotels have alternative water supplies, such as desalination.

5.2.3. *Water reserve management*

The freshwater used in the distribution system is extracted from the two islands with freshwater lenses that have the largest sustainable extraction rates. These two islands are located in the peri-urban part of Tarawa and villagers have been displaced on the outskirts of these islands due to the declaration of water reserves (White et al., 1999a). As mentioned earlier, this situation has led to considerable social disruption and vandalism. In fact, a number of illegal activities occur on the water reserves, such as cropping, gravel mining and illegal settlements (Moglia et al., 2008). Such activities impact on the water quality of the groundwater, and even though there is chlorination before distribution, this is a cause for serious health concerns.

In fact *Land owners* are faced with a situation of bounded rationality, where insufficient information and computational capacity is available when deciding on an appropriate strategy. Therefore, in accordance with the *Consumat* model, we have a decision situation in which the land owners change from *imitation* to *social comparison* depending on their needs satisfaction which is calculated by using utility function. Based on a definition of high and low levels of returns, calculated based on the utility function, each land owner changes their decision making approach as follows, 1) High return => *Imitation (*repeating behaviour, or in fact copying the behaviour of the last *Land owner* compared with),

Table 2
Land owners' decision variables and their effects.

Decision variable	What does it affect?	Impact on utility function
treeCoverage	It impacts on what level of tree coverage that the land owner aims to have on the reserve part of his land. This means he will remove trees and bushes to reach this level.	There is only an impact if the Land Division links the reimbursement for reserve land lease to the level of tree cover on properties.
cooperate	This impacts on whether or not the land owner accepts illegal activities on the property such as gravel mining, burial grounds or illegal leases as households rent land.	Illegal leases generate an income based on the value on the current property market. Gravel mining also generates an income. Non-cooperation increases the probability of failure for water extraction from reserves, which impacts in a probabilistic sense on the expectation value of the utility for land owners; and at each point in time this is calculated as the probability of failure in management, multiplied by the value of the discrepancy between the real estate prices for the property, and the lease payments.
nbCropPlots	This dictates how many crop plots that the land owner has on his property.	Cropping generates an income by allowing land owners to sell produce at the South Tarawa markets.

and 2) Low return => *Social comparison* (copying the behaviour of an individual that is perceived as successful). The decision variables available to *Land owners* are shown in Table 2 and what they affect and the impact on the utility function. The behaviour of *Land owners* has been the focus of previous studies as described in more detail in (White et al., 1999a; Perez et al., 2003; Dray et al., 2006, 2007).

In other words, the utility function of the land owners has three components, income from legal activities, such as legal cropping which is gained on a per plot (i.e. cell) basis and the number of cropping plots is a decision variable, income from illegal activities, and an incentive to undermine the Public Utility Board because of the potential gain by land owners if water reserve declarations fail as a strategy.

6. Results

As discussed by Moglia et al. (2008), there are considerable water related problems in Tarawa, such as: endemic water-borne diseases contributing to one of the highest infant mortality rates in the world, over-extraction of freshwater from groundwater sources, especially at times of drought, social disruption and conflict due to displacement of traditional land owners from water reserves, and inability to finance water services by charging customers for water.

There are trade-offs to be made when attempting to mitigate or minimize such problems – for example there is likely to be serious water contamination and health consequences if all households have to pay for water services. Similarly, there would be serious health problems if land owners were allowed back on water reserves. Other strategies, such as minimizing leakage, or increasing the utilization of rainwater tanks may be more beneficial, but are difficult to implement without adequate funding.

The ABM described in this paper has been used to explore the trade-offs that can be made between multiple goals. To illustrate the type of scenarios that can be run, and the reasoning that this can support, we have explored two weather based scenarios. The normal climate scenario involves using a historical weather file based on a time period with what is considered as normal rainfall and evaporation. This scenario is described by an average monthly rainfall of 195 mm, which is roughly the 60% percentile of rainfall in Tarawa (White et al., 1999b). The drought scenario involves using a historical weather file based on a time period with what is considered as drought, i.e. the 10% percentile of 30-month averages of approximately 100 mm per month (White et al., 1999b). We have also explored management options as shown in Table 3.

Table 3
Water management options explored in the ABM.

Name of scheme	Description
1. Current management approach	This involves a groundwater pumping and water allocation scheme, current population and state of rain tanks in the community, current levels of leakage as well a situation of stalemate and considerable pollution on water reserves.
2. Relocation and clean-up	Relocating all the land owners on the water reserves to Kiritimati island, and clean-up all sources of pollution on water reserves. This involves taking out all the land owners from the model, and to change the status of cells in order to remove sources of pollution from the reserves.
3. Reduce leakage	This means reducing the current leakage rates from pipes and connections. In terms of the model, it involves reducing the leakage from illegal connections from 80 L per day per meter pressure to 10 L per day per meter pressure, and leakage from legal connections from 40 L per day per meter pressure to 5 L per day per meter pressure, and leakage from distribution pipes from 220 L per kilometre per day, to 40 L per day per kilometre per meter pressure. The pipe pressure is assumed to be at 20 m head. The calculation also takes into account that there is water supply for approximately 1 h per day.
4. Proportional allocation	This involves providing the same amount of water per capita to each village, i.e. choosing the pumping volumes to each area/island's water storage as proportional to their populations. Currently this is not the case, and instead the allocation varies between 25 L per person per day in the less dense areas, and up to 55 L per person per day in the most densely populated area (Public Utility Board, 2008).
5. Recovery pumping	Reduce pumping rates from water reserves to 80% of sustainable extraction rates at times of drought in order to preserve water. Sustainable extraction during normal times.
6. Clearing of vegetation	This involves the land division, i.e. a government department, clearing all the vegetation on the reserves, on a monthly time step.
7. Repair and double the size of all rain tanks	This involves increasing the capacity of all existing tanks from 2 m^3 to 5 m^3 as well as to increase the percentage of tanks that are maintained to 100%, and reducing the amount of tanks that have over-hanging trees to 0%.

The first five were first explored separately, and then a combined strategy was explored which incorporates strategy 2, 3, 5 and 6. Scenario and management options have been evaluated on the basis of two criteria: the extent of over-extraction of the main freshwater lens (water debt), and the percentage of the community at severe health risk due to the source of water used for cooking and drinking (high health risk).

Table 4 shows the results of simulations and we note that water debt is only being generated under drought conditions – as is expected considering the default pumping strategy applied in the model. In terms of the water debt under drought conditions, the combined strategy outperforms all others, but clearing of vegetation on its own can achieve almost two thirds of the improvement of the combined strategy. In terms of the second output variable,

Table 4
Description of variables used for exploring outcomes of scenarios using the Tarawa Waterscape model.

Name	Description
Water debt (WD)	This is calculated on the basis of water flow calculations, where 1 day is equivalent of the daily sustainable extraction rate, which in the case of the largest freshwater lens in Tarawa (i.e. Bonriki) is 1,350 m^3/day. Hence if an amount of water is pumped from this freshwater lens that exceeds the sustainable extraction rate, this adds to the water debt. For example, the entry of 300 days in column 2 in Table 4 refers to a freshwater deficit of 300 times the daily sustainable extraction rate which is calculated to 405 000 m^3. For illustration purposes, in this article we use the Bonriki lens to calculate the water debt.
% at high health risk (HHR)	The water-related health risk is calculated using a risk function on the basis of a broad brush risk assessment, according to guidelines by the Australian aid agency AusAID (2005), on the basis of the path of the water from rainfall to household water use. The function is a scoring function where incidents of different types of pollution adds to the total pollution function by an amount equal to the number of incidents multiplied by the particular score for that type of pollution. The total value on the function is then translated into low, medium or high levels of pollution risk. For example, the tap water is exposed to a number of pollution sources on its way to households, i.e. on the basis of the following risk factors: fuel spills, septic tanks, waste water spillage, pigs husbandry on reserves, open wells, animals, settlements, burial grounds and sand mining, Back flow of groundwater into pipes that have only intermittent supply, as well as water storage and the possible contamination that can occur because of this.

proportional allocation actually worsens the situation (increases the health hazard), whilst relocation and clean-up of the reserves achieves the best outcomes (reduces the health hazard by the greatest amount). The combined strategy achieves close to the best outcome as well (reduces the health hazard), but it is very clear that the greatest impact on health hazard outcomes relates to the condition of the reserves.

Furthermore, to explore the sensitivity of the ABM to uncertainty in parameter values, the two key output variables, Water debt and Health hazard risk; have been evaluated for a large range of parameters. These parameters range from the specification of rain-tank properties, to population increase dynamics, to real estate prices and land lease amounts for land owners on reserves, to the triggers that customers use for changing water use behaviours due to health incidents or financial difficulties. Simulations have been run with default values on parameters. Each parameter in the sensitivity analysis has been evaluated for 5 different values that were perceived to be plausible. The range was chosen as the default value plus/minus a chosen one or two step changes from this default. Based on these sensitivity analysis simulations it is found that there are only modest changes to the health hazard risk in response to plausible changes in parameter values, but for most parameters, there is a trend with changes in parameter values. The sensitivity analysis also consistently shows a water debt of zero for all simulations, but this is hardly surprising because this is expected in 'Normal' climate conditions. Further details on the sensitivity analysis will be available in the forthcoming PhD thesis which has recently been submitted (Moglia, 2010). As a whole, standard deviations are in most cases relatively small ($<$5% of the empirical mean), indicating some level of predictability of the model.

The outcomes of the combination of scenarios and management options, shown in Table 5, have been calculated as the empirical mean of these performance variables, as well as the standard deviations (shown in brackets). The 95% confidence interval for the theoretical mean values, based on the assumption that the output

Table 5
Outcomes of each scenario and management option, as per runs in the Tarawa Waterscape model.

Management option	Climate scenario	Water Debt	Health Hazard Risk (%)
Current management	Normal	0 ($\pm$ 0)	52 ($\pm$ 1)
Relocation and clean-up	Normal	0 ($\pm$ 0)	20 ($\pm$ 2)
Reduce leakage	Normal	0 ($\pm$ 0)	68 ($\pm$ 8)
Proportional allocation	Normal	0 ($\pm$ 0)	69 ($\pm$ 10)
Recovery pumping	Normal	0 ($\pm$ 0)	51 ($\pm$ 1)
Clearing vegetation	Normal	0 ($\pm$ 0)	51 ($\pm$ 0.4)
Combined strategy	Normal	0 ($\pm$ 0)	24 ($\pm$ 2)
Current management	Drought	1639 ($\pm$ 13)	53 ($\pm$ 1)
Relocation and clean-up	Drought	1663 ($\pm$ 15)	20 ($\pm$ 2)
Reduce leakage	Drought	1616 ($\pm$ 14)	71 ($\pm$ 10)
Proportional allocation	Drought	1435 ($\pm$ 7)	68 ($\pm$ 8)
Recovery pumping	Drought	1073 ($\pm$ 2)	51 ($\pm$ 1)
Clearing vegetation	Drought	1091 ($\pm$ 1)	53 ($\pm$ 1)
Combined strategy	Drought	767 ($\pm$ 2)	23 ($\pm$ 2)

varies randomly according to a *Normal* distribution, is the empirical mean $\pm$ (1.96/2.24) multiplied by the empirical standard deviation. Because of the relatively small values on the standard deviations, 5 replicates were considered appropriate in most cases, but because of the relatively higher standard deviation in a handful of cases the number of replicates was increased to 10 for the "Reduce leakage" and "Proportional allocation" strategies.

Whilst the hypothesis that strategies are equivalent can not be disproven when evaluating the water debt in normal non-drought conditions; all strategies can be shown to be statistically different in terms of the water debt performance in drought conditions, using a traditional *t-test* for testing hypotheses. For the health hazard, most strategies can be shown to be statistically different using the same *t-test*. The general trend is also that drought increases the health hazards, but this is in most cases not a statistically significant effect.

7. Discussion

In terms of the results, firstly we note the poor performance of the strategy of proportional allocation of water – this was not expected. This effect however can be attributed to the variable access to water sources across the islands, and therefore the vulnerability and needs of various community segments varies. In particular, the area that is currently given the highest priority by the water utility – the island of Betio – is an area which is essentially an informal settlement with severely polluted groundwater and very limited access to rainwater collection.

Secondly, we note that the strategy of relocation of land owners to Kiritimati Island has almost no beneficial impact on water safety unless combined with environmental clean-up of all the existing sources of pollution on the water reserves. However, there are significant health benefits to be gained by doing so, with a significant reduction in water-related health risks.

Thirdly, we also note that there are essentially only two efficient methods for reducing the risk of over-extraction in the case of droughts, reducing the pumping volumes (as may be expected), but perhaps more importantly clearing vegetation from reserves. Fourthly, we note that the impact of leakage reduction is very small unless combined with cleaning up the reserves. This is because leakage reduction only increases access to tap water, but tap water is not a safe source of water in Tarawa unless pollution is minimized. Lastly, the combined strategy leads to significantly reduced health impacts, but remains susceptible to over-extraction in times of drought. This reflects the fact that the water supply in Tarawa is at its limit and there are no other options other than to add new water supply sources in order to sustain a growing population.

The results show that there is a need for a tailored portfolio of actions and interventions rather than just individual strategies. While experts may be able to roughly predict the results of a portfolio of strategies, in order to use their assessments, they in turn need to ask decision makers and stakeholders to trust them. An ABM as described in this paper, if developed in a transparent and participatory fashion, may overcome such problems by providing transparency in the assessment methodology, and the underlying assumptions.

This ABM may allow decision makers to explore the results of a portfolio of interventions, and use such results in a multi-criteria optimisation or decision making framework where financial and other constraints can be embedded. By doing this, local decision makers may find the most efficient and suitable strategy within the constraints under which they operate. They will also be in a position to show the benefits that can be achieved by any extra funds given to them by funding agencies.

With these results, it is clear that application of ABM for integrated systems analysis has been useful in the context of urban water management. The situation that has been explored is messy and at least complicated – as they typically are in small towns in developing countries. It has been shown that the performance of water supply options can be evaluated in an ABM – but we acknowledge that the model is very data hungry and should be approached with a healthy level of scepticism. On the other hand, sensitivity to parameter values is relatively small, showing that the model can produce results that give a reasonable indication of real world outcomes. As such, the model can be useful as a means of initial assessment of water supply options – but noting that the ABM in itself is not sufficient to make a fully informed choice. In other words, the main value of the ABM is that it provides opportunity to undertake integrated assessments that provide good indications of real world outcomes and that include consideration of behavioural aspects.

Furthermore, we note that how the steady-state changes that occur in response to changes in drivers and conditions is not unpredictable but sometimes counter intuitive – showing that the model can be used to improve understanding of the system. Also, we note that while steady-state behaviour is achieved in most cases, occasionally very different steady-states occur, and sometimes they also have sudden shifts that occur for diverse and unexpected reasons – which would need further sense-checking and investigation to be fully understood. This leads back to our initial assumption that the studied system may be described as a complex adaptive system, but if so where does the complexity come from? It appears that such features occur in particular in relation to how the adaptive and often unpredictable dynamics of water use preferences which are at the core of determining outcomes. It is also noted that steady-state behaviour is often observed, but that variability in steady-states does occur given same initial and boundary conditions. In other words, given a certain set of conditions, the pattern of system behaviour is somewhat predictable, at least in a probabilistic sense, leading us to identify the system as path-dependent. On the other hand, whether the system is truly a complex adaptive system is not important as long as the ABM is useful and provides insights that can not be gained using current methods. As such, ABM may be a step forward in helping urban water managers in their jobs.

Furthermore, due to the ever-changing nature of the system, an ABM may be used to understand the system at a certain point in time, but the evolution of events and changes in conditions means that the model brings into question its value into the future. We argue that it is only when it is kept relevant and up to date that it remains useful. Therefore, for ongoing validity purposes, the modelling exercise needs to be embedded in an ongoing and local learning process. Unfortunately, there are a number of difficulties to be overcome before the approach can become an operational part of the urban water management regime. Firstly it is a new approach for which there is currently not enough skills, neither locally at departments or the water utility, nor internationally within key agencies such as development banks, consultants or donor agencies, and secondly it requires efficient and systematic knowledge creation and management, which is currently lacking.

8. Conclusion

This model has been developed on the basis of an ethnographic survey. It has been used to show that the ABM methodology (at least in the case of a small town water system that is perceived as extremely complex and dynamic) can provide guidance on how to manage a distributed and adaptive system, and perhaps more importantly, provides opportunities for incorporating into the analysis a fundamental understanding of the processes, such as those relating to water safety and human behaviour, at a micro-level rather than having to probabilistically describe causality at a macro-level (something which has previously proven difficult). In this context, ABM provides a strong alternative to traditional economic and engineering perspectives. Whilst it shows strong promises in terms of its usefulness in the operation of the water system, there are also difficulties that need to be overcome before the methodology can become a mainstream tool. These difficulties are not impossible to overcome, but their resolution requires political and financial support.

9. Software availability

This Agent-Based Model has been developed in the Cormas development platform, which is available for download from http://cormas.cirad.fr/indexeng.htm. Furthermore, this web site also contains a section with the model described in this paper, http://cormas.cirad.fr/en/applica/tarawaWaterScape.htm. Here, the software code can be found as well as UML diagrams, and a brief model description.

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