# AtollScape: Simulating Freshwater Management in Pacific atolls. Spatial processes and time dependence issues.

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**Abstract:** Groundwater has long been ranked as a high priority research area by small island nations in the Pacific. It is the major source of freshwater on the atoll of Tarawa (Rep.of Kiribati) and its availability, quality, management and allocation are central to the atoll's sustainable development and poverty alleviation. From a modeling perspective, simulating freshwater lens behavior represents a challenge, as it requires sophisticated numerical models. Such models can hardly fit within an integrated management framework taking into account spatially distributed water use (e.g. wells, trees) and social interactions. Simple analytical solutions exist but they apply for steady-state conditions, verified only on an annual basis. Recent advances in the field of Distributed Artificial Intelligence have permitted the development of a Multi Agent System (MAS) approach, closely related to the problem of complexity. AtollScape uses MAS techniques to simulate water management and freshwater lens behavior on the Tarawa atoll. A distributed and nested structure is used to represent local inputs and uptakes, along with freshwater lens adjustments on a 10 day time steps.

***Keywords:*** *Multi-Agents Systems; Freshwater lens; Atoll; Water management; Pacific; Tarawa.*

## 1. INTRODUCTION

Low coral islands are heavily dependent on groundwater for freshwater supplies. The availability, quality, and management of groundwater are central to sustainable development and poverty alleviation in many developing small island nations. Increasing populations, growing per capita demand and restricted land areas limit water availability and generate conflicts (Falkland and Brunel, 1993).

This study was carried out in the Republic of Kiribati, on Tarawa Atoll. The water resources are predominantly located in freshwater lenses on the largest islands of the atoll. The water table is typically 0.8 to 1.6m below ground surface. Groundwater is supplemented by rainwater on most of these islands. South Tarawa is the capital and main population center of the Republic. The water supply for the urban area of South Tarawa is pumped from horizontal infiltration galleries in groundwater protection zones or water reserves on Bonriki and Buota islands. These currently supply about 1300 $m^3$/day, equivalent to about 30L/capita/day of freshwater, 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., 2002).

The declaration of water reserves over privately owned land has lead to conflicts, illegal settlements and vandalism of public assets. Beside, the water consumption per capita tends to increase towards western-like standards, threatening the sustainability of the actual exploitation 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. 1999).

In order to facilitate the dialogue between local actors with conflicting viewpoints, it was decided to build an integrated model that encapsulates social and biophysical complex interactions. The use of Multi-Agent Based Simulations (MABS) enabled us to overcome three major modeling constraints (Bousquet et al., 1999):

- Creating an explicit spatial representation of the simulated processes, distributed along a very narrow strip of successive islands.
- Integrating the daily based soil water balance modeling with much longer-term groundwater balance analytical solutions.
- Representing the individual and space dependent behavior of the water users (consumption, waste, and pollution).

This paper successively describes the structure of the AtollScape model, the soil water balance and hydro-geological dynamics formalisms. Then it describes the social representations, including demographic dynamics. Finally, the first results are compared with available field observations.

## 2. ATOLLSCAPE STRUCTURE

### 2.1. The modeling environment

AtollScape was created with VisualWorks SmallTalk, using the CORMAS platform developed by Bousquet et al. (1998). AtollScape is constituted with:

- Spatial active entities: the Cells, the Lenses (aggregate of Cells) and the Islands (aggregate of Cells and Lenses).
- Social entities: the Households and the Public Utility Board (PUB) that manages water distribution.
- Spatial passive entities: Land-use types (bare soil, crop, tree crop) and Water-use techniques (well, rainwater tank, connection to PUB).

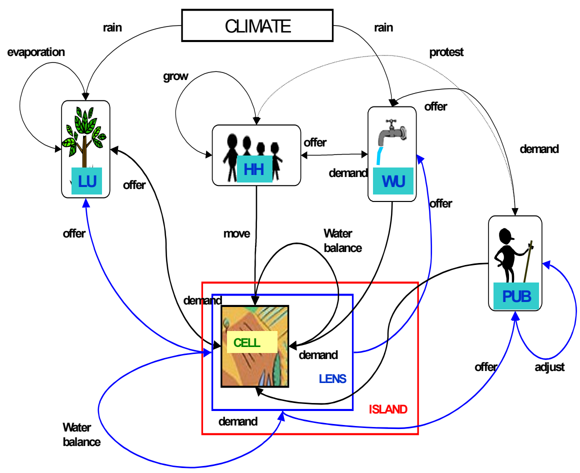



Figure 1: AtollScape entities and interactions.

The South Tarawa islands are represented by 2157 Cells of land. Each hexagonal Cell (7307m²) provides isotropy properties to the modeling and a distance of 75 m separates two Cell centers. The isotropy is used to model freshwater lenses around center Cells. The global error between the actual area of South Tarawa and its computer artifact is 687 m² (less then 1%). The shape of the different islands was broadly respected but their geographical positioning was not respected in order to limit the dimensions of the simulation grid. Nevertheless, the connections between islands and their lagoon/ocean orientations were taken into account. The modeling time step corresponds to a 10 days period and the simulations are limited to 10 years.

Several modeling viewpoints were created, directly accessible during the simulations, in order to represent key features of the system. The SoilDepth viewpoint represents the soil depth gradient from the lagoon shore to the ocean shore. The LandUse viewpoint visualizes the eventual changes between the three Land-use types. The LensDepth viewpoint allows following the depth evolution of each Lens during the simulations. Finally, the PopDens viewpoint represents the evolution of Households/Cell, according to the demographic rate increase.

### 2.2. The water balance model

The recharge of the freshwater lenses is directly controlled by the infiltration rate through the unsaturated soil layers. The water balance is simulated within AtollScape using a slightly modified version of the mass-conservation driven model proposed by Falkland (1992) for South Tarawa. This three reservoirs-based model, called WATBAL, uses rainfall and potential evapotranspiration (PET) as input data. Runoff is not taken into account because of the very high permeability of the coral sand soils. The two basic equations are:

$$P = E - TL + R + \Delta S \qquad (1)$$

$$E = Ei + Es \qquad (2)$$

with:

| | |
|---|---|
| P | rainfall (mm) |
| E | actual evaporation from the soil (mm) |
| TL | actual evaporation from the lens (mm) |
| R | recharge of the lens (mm) |
| ΔS | soil water storage variation (mm) |
| Ei | evaporation from interception (mm) |
| Es | evaporation from the soil (mm) |

The first reservoir intercepts the rainfall at the vegetation level. The second reservoir corresponds to the soil water storage and the water entering the third reservoir corresponds to the recharge of the freshwater lens. Recharge of the lens may occur only after plants have satisfied their water requirements. Tree crops (mainly coconut trees in our case) are able to extract water directly from the lens (Figure 2).

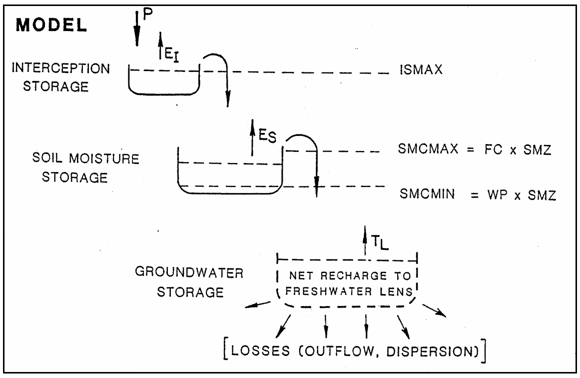



Figure 2: WATBAL Conceptual representation.

This model was adapted to AtollScape by splitting the hydrological calculations between the Cell and the Land-use entities. Each instance of these two classes can operate its specific part of the water balance. Hence, AtollScape takes the spatial heterogeneity of the processes and their time dependence into account. The nested structure allows each Lens to collect the different recharge values coming from each of its constituting Cells. Finally, the Lens aggregates these values into an average recharge/time step.

### 2.3. The hydro-geological model

The shape and the depth of the freshwater lenses are calculated according to the model proposed by Volker et al. (1985). This model predicts the depth of the freshwater lens and the thickness of the transition zone from the recharge and uptake values, according to the maximum length of the lens. Two strong assumptions limit the use of this simple 2D-model: (1) the recharge is constant and (2) the lens is in a steady-state condition. Hence, the model is often used for long-term predictions based on ten years averaged data.

According to Dupuit-Forcheimer assumptions, the lens depth (H) at a distance (x) from the lens center is given by the following equations:

$$H^2 = (q_o - Q_o).(L^2 - x^2) \quad (3)$$

$$q_o = q.[K.\varepsilon.(1 + \varepsilon)]^{-1} \quad (4)$$

$$Q_o = q.[K.\varepsilon.(1 + \varepsilon)]^{-1} \quad (5)$$

$$\varepsilon = (\rho s - \rho f) / \rho f \quad (6)$$

with:

| | |
|---|---|
| q | lens recharge (mm/d) |
| Q | lens uptake (mm/d) |
| L | lens radius (mm) |
| $\rho_s$ | sea water density |
| $\rho_f$ | freshwater density |
| K | hydraulic conductivity (mm/d) |

The water table depth (h) and the thickness of the transition zone (Δ) are given by the following equations:

$$h = \varepsilon.H \quad (7)$$

$$\Delta = A.B \quad (8)$$

$$A = [\lambda^{-1/2}.(L.(q_o - Q_o)^{-1/2}).(L^2 - x^2)^{1/2}/x]$$

$$B = [1-(L^2 - x^2)^{1/2}/L]^{1/2}$$

This vertical, 2D representation had to be adapted to the AtollScape's distributed grid. Hence, some Cells have been selected and designated as lens centers or Nuggets. Using the isotropy property of the grid, each Nugget is surrounded by concentric circles of isopiezometric Cells. The orthogonal distance between the lagoon and ocean shores, crossing the Nugget gives the value of the radius (L). The distance between two Nuggets may be smaller then their respective radius; in this case, a common Cell is given the deepest value calculated at each time step. The global shapes of the Lenses correspond to overlapping bowls (Figure 3).

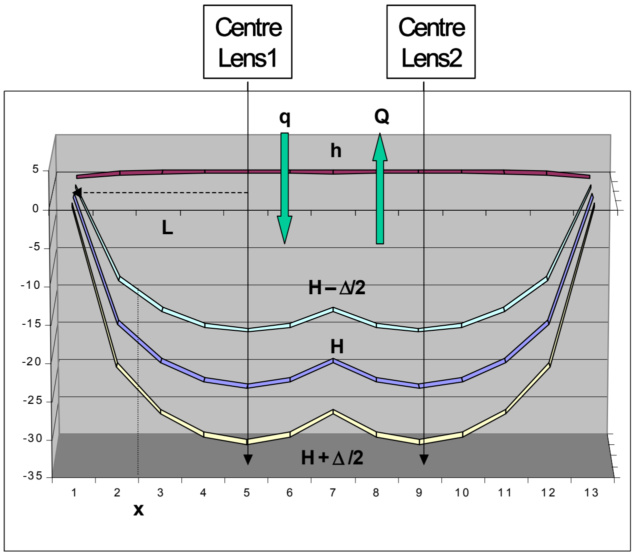



Figure 3: Depth (H) and transition zone thickness (Δ) for a 2 Nuggets Lens (L = 400 m for both).

The main problem encountered was to adapt the model proposed by Volker et al. (1985) to our ten day time step. As a matter of fact, the recharge and the uptake were updated at each time step and could vary in large proportions between two time steps. Thus the steady state assumption was not verified. The following procedure was adopted to update the Lens depth:

- At the initialization, Volker's equations are used to calculate the shape of the Lens, using an array of ten identical values for (q – Q).
- At each time step, the Lens calculates an average net recharge and sends it to its

components. Each Cell updates its Lens depth value by a simple mass conservation equation.

- At the end of each year, AtollScape calculates an average annual recharge (and uptake) for each Lens, updates the corresponding arrays and calculates the new shape of the Lenses accordingly.

### 2.4. The social entities

Two classes of entities were defined. The Households represent the local population and each instance corresponds to one family living on South Tarawa. The PUB class contains only one instance representing the Public Authority Board, in charge of the water distribution among the population. At this stage of the model, social interactions focus only on the competition for water between Households and the PUB's management decisions.

The main attributes of each Household are: the size, the drinking and domestic water requirements, a list of Water-use equipment and a consumption satisfaction index. Theoretical demands are set up to maximum levels of 30 L/d/person for drinking water and 70 L/d/person for domestic water. Water-use equipments have different using priorities, depending on the type of water required. The water availability is updated at each time step according to the type of equipment (direct rainfall, groundwater or PUB pipes). Groundwater extraction from individual wells is limited by a maximum depletion rate in the vicinity of the well.

Creating three new Households (between 2 and 8 family members) every time step simulates the population growth. They are located randomly but a maximum capacity load per Cell limits their positioning.

The PUB entity is characterized by the volume of water pumped from the Buota and Bonriki reserves, and the PUB offer to each island. Buota uptake is initialized at 5000 $m^3$/time step and 10000 $m^3$/time step for Bonriki. The distribution among the different islands corresponds to their ranking along the main PUB distribution pipe. The PUB can modify its pumping rates according to the average recharge rates of both reserves. Later on, the Household's satisfaction index will be used to modify PUB's decisions as well.

## 3. FIRST RESULTS

### 3.1. Recharge of the Bonriki reserve

The model proposed by Falkland (1992) was validated against estimated values of the Bonriki recharge. Thus, we have compared the results given by AtollScape with the one from the original model over the 1990-1999 period.

The average annual recharge calculated by AtollScape (1250 mm) slightly underestimated the one coming from WATBAL (1273 mm).

### 3.2. Depth variations of the Bonriki lens

The adaptation of Volker's model presented more challenging issues in terms of modeling consistency. As a matter of fact, the annual adjustments of H and Δ values were expected to disrupt the mass conservation driven evolution of the freshwater lens depth.

First, the calculated depth values, ranging from 15.5 m to 24.2 m, cover relatively well the estimated depths coming from piezometric and electric conductivity monitoring in Bonriki (White et al., 1999). Beside, during the first five years of simulation, the Lens depth (H) increases dramatically and the annual adjustments generate instantaneous jumps of 1.0 to 1.5 m. This modeling behavior disappears at the end of the fifth year. Obviously, the choice of the values of (q - Q) stored in the initial array tends to underestimate the depth of the freshwater lens. After five years simulation, the moving average calculation gives a more consistent estimation of the net recharge (Figure 4).

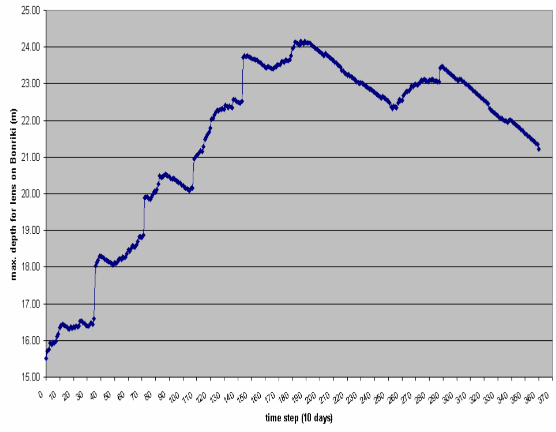



Figure 4: Depth evolution of the Bonriki Lens. Ten years simulation (1990-1999).

At this stage, the initial value of 600 mm/year corresponding to the generally admitted rate of net recharge for Bonriki (Volker et al., 1985) has not been subjected to any sensitivity analysis.

## 4. DISCUSSION AND CONCLUSION

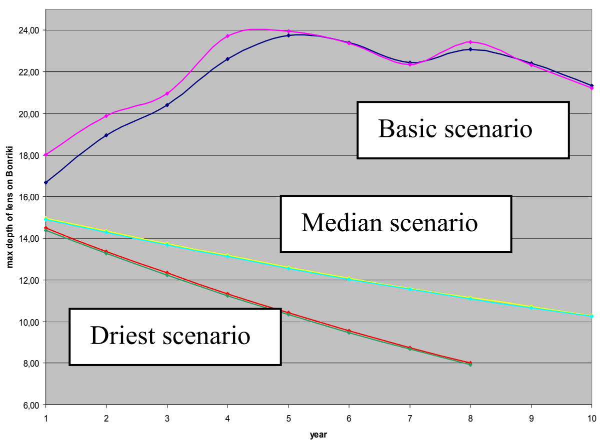
The actual version of AtollScape represents a first attempt to integrate spatial and time dependent processes involved in water management on South Tarawa. The authors have tried to keep the structure as simple as possible, according to a general stand shared by the MABS community (Bousquet et al., 1999).

Nevertheless, AtollScape is able to reproduce the main features of the system reasonably well. We have seen that the average values of lens recharge and depth match the actual estimations coming from fragmented field observations. Moreover, the calculated volume of the Bonriki lens ($3.2 \times 10^6$ $m^3$) is very close to the most accurate estimation given by the experts ($3.6 \times 10^6$ $m^3$) despite the over-simplistic shape given to the lenses in AtollScape (White et al., 1999).

The social dynamics though embryonic reproduce the observed population growth and its influence upon the water consumption. In particular, AtollScape shows evidence of an increasing user's discontent with the PUB in the bottom-end islands of Bairiki and Betio.

Finally, the actual version of AtollScape is already useful for implementing different climatic scenarios. Beside the actual rainfall series (1990-1999), two other series were used: (1) 10 times repetition of the median annual series (average annual rainfall: 1300 mm), (2) 10 times repetition of the driest annual series (average annual rainfall: 600 mm). Figure 5 shows that only the actual scenario is sustainable in terms of management of the freshwater reserve on Bonriki. Any further deterioration of the climatic conditions due to the Global Change would have result in a continuous depletion of the lens. In the worst scenario, the lens would disappear after 8 years.

Figure 5: Depth evolution of the Bonriki lens in




the case of three contrasted scenarios.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