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# Integrated System Dynamics Modelling for water scarcity assessment: Case study of the Kairouan region

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ABSTRACT

A System Dynamics Model (SDM) assessing water scarcity and potential impacts of socio-economic policies in a complex hydrological system is developed. The model, simulating water resources deriving from numerous catchment sources and demand from four sectors (domestic, industrial, agricultural, external pumping), contains multiple feedback loops and sub-models. The SDM is applied to the Merguellil catchment, Tunisia; the first time such an integrated model has been developed for the water scarce Kairouan region. The application represents an early step in filling a critical research gap. The focus of this paper is to a) assess the applicability of SDM for assessment of the evolution of a water-scarce catchment and b) to analyse the current and future behaviour of the catchment to evaluate water scarcity, focusing on understanding trends to inform policy.

Baseline results indicate aquifer over-exploitation, agreeing with observed trends. If current policy and social behaviour continue, serious aquifer depletion is possible in the not too distant future, with implications for the economy and environment. This is unlikely to occur because policies preventing depletion will be implemented. Sensitivity tests were carried out to show which parameters most impacted aquifer behaviour. Results show non-linear model behaviour. Some tests showed negligible change in behaviour. Others showed unrealistic exponential changes in demand, revenue and aquifer water volume. Policy-realistic parameters giving the greatest positive impact on model behaviour were those controlling per-capita domestic water demand and the pumped volume to coastal cities. All potentially beneficial policy options should be considered, giving the best opportunity for preservation of Kairouan aquifer water quantity/quality, ecologically important habitats and the agricultural socio-economic driver of regional development. SDM is a useful tool for assessing the potential impacts of possible policy measures with respect to the evolution of water scarcity in critical regions. This work was undertaken for the EC FP7 project 'WASSERMed'.



## 1. Introduction

Water availability for domestic, agricultural and industrial use has become an increasingly important topic of international and interdisciplinary research in response to major water challenges being faced in certain parts of the world, and particularly across the Mediterranean Basin. While in theory there is ample water to supply almost every person on the planet (Savenije, 2000), the spatial and temporal distribution and flow of this water (Oki and Kanae, 2006) combined with increasing demand, particularly in rapidly developing nations, is such that, in practice, more areas and a larger proportion of the global population are facing water shortages and water scarcity conditions. In addition to the already serious problem being posed to water supply caused by an increasing population, future projections of climate-change suggests that not only will the Earth surface temperature increase, but also that rainfall volumes may become less or more sporadic, particularly in the Mediterranean and northern African regions (Arnell et al., 2004; Solomon et al., 2007). Drought frequency is expected to increase in many areas (Solomon et al., 2007). Such changes will only exacerbate an already serious water supply situation, with many more people likely to be plunged into potentially severe, lasting, water shortages.

Water supply and demand challenges, similar to those outlined above, are currently being faced in Tunisia. Here, the combination of improving domestic conditions leading to greater demand for domestic water, changes to local/regional climate and an agricultural sector accounting for about 80% of Tunisian water abstraction (Chahed et al., 2008) coupled with problems in the management of local water resources (Lacombe et al., 2008), are responsible for some of the issues being encountered at present. The main manifestation of this being groundwater over-exploitation, water table decline, water quality and sustainability issues, as well as ecological impacts, particularly to local sebkha regions, which are naturally occurring salt flats with sensitive water balance dynamics that are extremely vulnerable to

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environmental change. This situation also has the potential to significantly impact on agriculture, the main economic activity in the region, and driver of regional development. In addition to this, the Tunisian population, while relatively stable, is experiencing increased wealth, leading to improved lifestyles and as a result, an increase in domestic water demand.

Regarding precipitation, studies throughout the Mediterranean basin and northern Africa have failed to determine any significant historical trends in annual rainfall (Leduc et al., 2007). However, with respect to future changes to the regional climate, various generations of climate model simulations have converged to give similar climate projections over the region (Giorgi and Bi, 2005; Giorgi and Lionello, 2008). The most prominent predicted change is a drying and warming during the spring and summer months, with a decrease in winter rainfall also predicted for the southern Mediterranean basin. Local variations due to complex coastline morphology and mountain ranges are superimposed on this picture, together with an expected increase in inter-annual variability. Such heterogeneity, in space and time, necessitates the application of specialised models, in order to examine a significant number of potential scenarios, and their impact to the water resources. Despite these complex challenges (physical and socio-economic) with respect to water resources, not just in Tunisia but globally, there has been a general shortage of integrated modelling of physical and socio-economic processes (Green et al., 2011). Therefore, this paper goes some way to addressing the critical and pertinent gap in current research, and proposes the System Dynamics Modelling framework as an ideal methodology capable of capturing this complexity.

WASSERMed (Water Availability and Security in Southern EuRope and the Mediterranean) is an ongoing European Commission Seventh Framework (EC FP7) funded interdisciplinary research project (2010–2013). The aim is to analyse, with the participation of local stakeholders, the current and future climate-induced changes to hydrological budgets and extremes in southern Europe, northern Africa and the Middle East, under the frame of threats to socio-economic and human security (WASSERMed, 2011). Impacts on key strategic sectors, such as agriculture and tourism, are being analysed, as well as the macroeconomic implications of changes to water availability across the Mediterranean basin. WASSERMed aims at issuing policy guidelines at the end of the project that will be of generic use for the region. It aims to achieve these goals by examining five case studies in detail: Kairouan, Tunisia (the focus of this paper, with competing pressures on water resources from agriculture, domestic use and tourism); the Greek island of Syros, with strong pressures from tourism; Sardinia, which is affected by intense agricultural requirements and a large tourist sector; the Jordan River, with severe water shortages and competing demands between nations and; the Rosetta region on the River Nile in Egypt, where the water is shared by several water stressed countries.

This paper presents research carried out for the Tunisian case study (Merguellil Valley and Kairouan aquifer) within WASSERMed, and aims to show how the situation of the Merguellil basin/Kairouan aquifer water system might evolve between now and the year 2050 (the horizon year being simulated in the WASSERMed project). The modelling uses available data, reasonable assumptions and information provided from local stakeholders. The Kairouan aquifer is the main focus here as it represents the major stable fresh water supply in the region, and is critical for many local activities. Model predictions aim to facilitate discussion and provoke local policy makers and stakeholders into developing potential policy scenarios aimed at mitigating potential climate impacts rather than giving precise numerical prediction of the volume of water stored in the aquifer (for this, ‘pure’ hydrological models would be more suitable). Actual policy measures/options are beyond the scope of this paper because they will be related to generic conclusions to be drawn at the end of the WASSERMed project, which is still ongoing, and which will be decided with the active participation of local partners and stakeholders. The information presented here may be used to make better-informed decisions for the future development of water strategies not just in the study area, but throughout Tunisia and the wider northern African region.

## 2. System Dynamics Modelling

The water availability scenarios for the Kairouan aquifer have been simulated using System Dynamics Modelling (SDM) concepts (Forrester, 1961; Ford, 1999). SDM is a methodology for studying complex feedback-driven systems in which non-linearity usually plays a key role. SDM is typically used when formal analytical models do not exist, but when simulations can be developed by linking a number of processes (i.e. developing a system structure). Forrester (1961) introduced SDM in the early 1960s as a modelling and simulation methodology for decision-making in industrial management problems. Since then, SDM has been applied to various business and strategy problems (Barlas, 2002; Sterman, 2000) and it has proven useful for the simulation of complex environmental (Ford, 1999; Mulligan and Wainwright, 2004; Mazzoleni et al., 2004; Meutzelfeldt, 2010) and water systems problems (Simonovic, 2003; Chung et al., 2008). SDM has also been used to model environmental systems at a range of scales from local (Stave, 2003; Khan et al., 2009) to global (Simonovic, 2002; Kojiri et al., 2008). Simile (Muetzelfeldt and Massheder, 2003; Simulistics Ltd, 2011) is the specialised graphics/programming environment that was used to implement the SDM water balance model for this case study, mathematically similar and comparable to other SDM environments such as Vensim (Ventana Systems Inc, 2011) and STELLA (ISEE Systems, 2011) in terms of its capabilities and functions, but developed primarily for environmental rather than general purpose/business applications.

Starting from qualitative conceptual models aimed at describing the causal processes operating in a given system, leading to a basic model structure, quantitative models are built, so as to allow the construction of an initial working quantitative simulation model (Atanasova et al., 2006). The initial working SDM is then modified and improved iteratively, sometimes with stakeholder engagement, to show the desired level of detail and complexity (Haraldsson and Sverdrup, 2004). SDM development aims to develop a model that closely mimics the system under investigation to the level of detail required. Such an iterative, cooperative procedure was used here, described in detail in Section 3.

In order to build an SDM, system components are described as interlinked compartments (stocks), flows (directed links) and converters (influences) (Ford, 1999). Stocks can be thought of as storing a quantity of material (e.g. money in a bank, a population of humans, water in a reservoir). If the inflows and outflows to/from a stock are equal or set to zero, then the value of the stock will remain constant. Flows are directed into and out of stocks, and represent the physical movement of material through the stocks (e.g. cash deposits or withdrawals, births and deaths, water supply and consumption). The converters act to influence the rate of the flows. For example, a converter may represent the interest rate on a bank account, which would subsequently influence the amount of cash deposited at the next time step. Likewise, a birth-rate or death-rate influences the number of people entering/leaving a population, with the flow in/out of the stock dependant on the rate itself and the number in the population stock. Thus, converters not only influence the flows, they also act to form feedback loops within a system. Some of these converters may not be simple ratios, but could be calculated from (non-linear) equations, or they may act with a time-delay (e.g. a child cannot be born until the parent has reached maturity). SDM is a structural modelling paradigm, as opposed to other ‘pattern-matching’ modelling approaches e.g. artificial neural networks (Plumb et al., 2005). The ability to model feedback and delay processes present a distinct advantage over Bayesian Network modelling for example, which is inherently acyclic, and thus unable to handle feedback structure (Cain, 2001; Molina et al., 2010).

SDM environments, including Simile (Muetzelfeldt and Massheder, 2003), can also handle many interdependent sub-systems, allowing the breaking down and detailing of small but important aspects of any given study (Meutzelfeldt, 2010). Subsystems may be designed so as to simulate multiple superimposed similar typical elements, which can be hard to implement otherwise. Sensitivity testing and uncertainty analysis can be quickly and efficiently undertaken without the need for changes to model structure. Another advantage of SDM, when compared to other water balance modelling tools, is the flexibility of accepting any kind of variables/parameters as computational elements. In this paper, the inputs and variables, together with specifically required outputs (e.g. revenue), were selected in cooperation with local partners and experts. These outputs should be designed in a way such that their meaning is immediately clear to non-experts, and may facilitate the assessment of scenarios, sensitivity analysis and feedback when stakeholders and non-experts are involved in participatory mode during the development and assessment of the model (Sušnik et al., 2011). The graphical development environment facilitates close cooperation with non-experts, something that was essential for this study, as described in Section 3 (WASSERMed, 2011). This presents an advantage over some more traditional code- or physically-based models which usually require a greater level of *a priori* understanding by the cooperating partner.

Disadvantages include the difficulty of modelling iterative procedures within a single model time step (i.e. processes occurring in time-frames shorter than the model time step). Spatial modelling is not strictly possible. Despite these limitations, it is the ability of SDM to simulate complex, non-linear feedback driven systems that justifies its use here. Additionally, the fact that it is not limited to a specific system type means that physico-socio-economic systems can be incorporated, simulated and analysed within the same model. This benefit allows for truly integrated modelling, something that is lacking in present research (Green et al., 2011).

SDM has been used successfully by the authors of this paper for complex water system simulation, namely in the EC FP6 project AquaStress (Vamvakeridou-Lyroudia et al., 2008; Wintgens et al., 2009; Ribarova et al., 2011). An SDM was used to simulate the upstream hydrological processed of the current study area, focussing on the surface water processes and the operation of a large reservoir (Vamvakeridou-Lyroudia et al., 2008), and also to simulate a complex industrial plant in order to define more efficient rules for the use of (waste) water (Wintgens et al., 2009). Other similar examples exist in the literature, e.g. Simonovic (2002) and Kojiri et al. (2008) to assess global water dynamics. Simonovic (2002), following from the World3 model of Meadows et al. (1974) created a new WorldWater model. It was shown that water use, population, industry and agriculture are very much inter-related, and that global water use is potentially a major barrier for global growth as pollution becomes chronic. Kojiri et al. (2008) also concluded that water availability may also limit future global growth in a number of sectors, particularly agriculture. Stave (2003) made use of the graphical SDM interface to facilitate public understanding of water management in Las Vegas. It was shown that when stakeholders are fully involved and understand a problem, interest and engagement improves, leading to better solutions to a given problem. Tidwell et al. (2004) came to similar conclusions when using SDM modelling principles for planning water resources management in New Mexico. Rehan et al. (2011) used SDM for financially sustainable management of municipal (waste-) water systems, illustrating the applicability of SDM to human systems focussed on socio-economics. These studies illustrate the diversity of problems to which SDM can be applied, and also show that not only can it be used for natural and anthropogenic systems at a variety of scales, but it can be effectively used to further local stakeholder engagement and knowledge.

## 3. The Kairouan System Dynamics Model

The integrated model presented here partially builds upon a preexisting model which was developed for the EC FP6 project 'AquaStress' (Vamvakeridou-Lyroudia et al., 2008). Both for the previous Aquastress model and the current model, development was carried out in close cooperation with INAT, the local Tunisian project partner. INAT assisted in ensuring that the model boundaries and structure were appropriately representative of the system being studied (i.e. the Merguellil/Kairouan hydrological–social system), and that model results were representing observations. INAT also provided access to essential data when required. Thus, INAT were constantly involved in all stages of the model development, and as such, the model itself went through several iterations before a final structure was agreed upon. Briefly, both the AquaStress model, the focus of which was to model in detail the upper Merguellil Valley, with very little focus on the Kairouan aquifer, and the detailed Kairouan model developed within WASSERMed consist of nine interlinked subsystems:

(a) upper Skhira, which models the very upper part of the catchment;
(b) middle catchment, which models in detail the processes in the mid-Merguellil catchment, including the influence of 35 small dams;
(c) El Haouareb, which simulates the water balance in the large El Haouareb reservoir;
(d) surface water input, which estimates the volume of water infiltrating to the Kairouan aquifer from rainfall (rainfall-recharge in Fig. 1);
(e) subsurface water input which models the direct subsurface transfer of water from adjacent aquifers to the Kairouan aquifer (recharge from adjacent aquifers in Fig. 1);
(f) coastal pumping which simulates water pumped out of Kairouan to satisfy coastal city demand;
(g) domestic demand;
(h) industrial demand; and
(i) agricultural water demand.

The aforementioned sub-models contribute to a central water balance component which uses all the inputs and outputs to estimate the Kairouan aquifer water volume at each time step. For each simulation, the initial volume of the aquifer is set to $59.7 \times 10^6$ m$^3$ (Lili-Chabaane, 2010). A basic schematic overview of the model interconnections is shown in Fig. 1. More details for some of the sub-models are given in this section and in Figs. 2–4.

The entire SDM consists of 155 nodes. The Upper Skhira submodel contains ten nodes, the middle catchment sub-model 29 nodes and the El Haouareb sub-model contains 33 nodes. With respect to the newly developed model components, the rainfall submodel has two nodes, the surface water input sub-model 11 nodes, the infiltration (subsurface) input sub-model nine nodes, the coastal pumping demand sub-model six nodes, the industrial demand submodel 11 nodes, the domestic demand sub-model 16 nodes, the agricultural demand sub-model 19 nodes, and the main Kairouan waterbalance component has nine nodes. The model is run continuously for 480 time steps at monthly resolution (i.e. 40 years), taking the simulation to 2050, which is a requirement of the WASSERMed project. Simulations generally take just over a minute to complete on a desktop PC with an 8-core Intel Core i7 processor and 6 GB RAM. In Simile, a results-reporting window is set initially and saved for future use. This window can be recalled for every simulation. Thus, viewing and saving results (graphical or tabular as csv files) for each simulation is simple once the reporting window has been generated and saved.

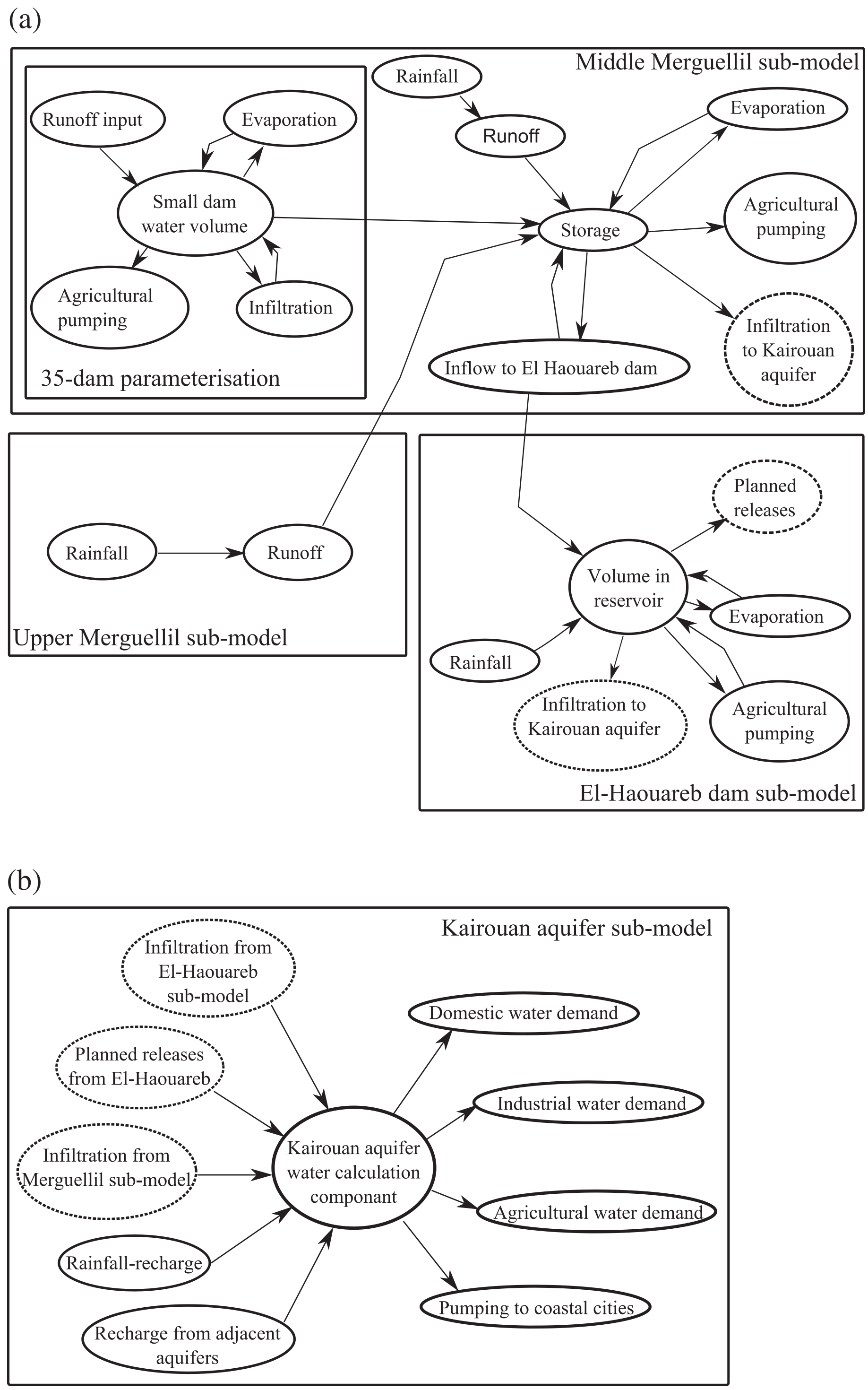


**Fig. 1.** Schematic showing the main interconnections in the SDM developed for this study. (a) illustrates the upper (Merguellil) part of the SDM, while (b) shows the connections between the elements in the newly developed Kairouan aquifer sub-model. This schematic is greatly simplified for clarity here and does not represent the full complexity of the model. Figs. 3–5 detail the causal loop structure of some of the Kairouan demand-side sub-models and of the El-Haouareb sub-model to illustrate the true complexity of the model, and further details are provided in Section 4.

The simple Upper Skhira sub-system models the upper Merguellil catchment, with runoff from rainfall contributing to the second sub-system. The main purpose of separating it as an independent sub-system was the existence of flow measurements at its downstream end, which have been used for calibration (Vamvakeridou-Lyroudia et al., 2008).

The second sub-system models in detail the middle Merguellil catchment, and includes an encapsulated sub-system describing the water balance of the 35 small dams built for irrigation water supply and groundwater recharge. Infiltration and runoff from the 35 dam sub-system, plus runoff from the rest of the middle catchment region (once evaporative losses and agricultural demand have been accounted for) then feed into the El Haouareb dam sub-system. Some infiltration is routed to small aquifers which in turn recharge the Kairouan aquifer. The middle Merguellil is the most complicated sub-system in computational terms. The characteristics of the

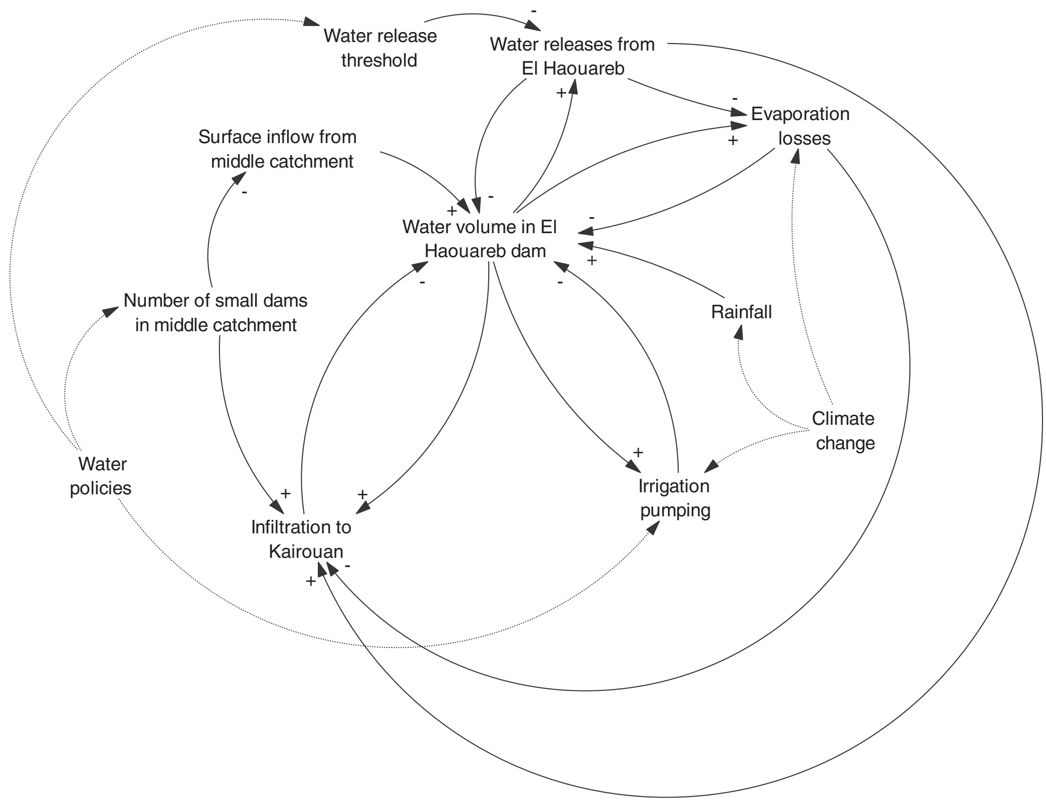


**Fig. 2.** Causal loop diagram for the El-Haouareb sub-model. Polarity of feedback loops is indicated with a '−' for negative (self-stabilising) polarity and a '+' for positive (reinforcing) polarity. Indirect influences are shown as dashed arrows.

encapsulated sub-system have been defined after careful consideration of detailed data on the small dams (Lacombe et al., 2008) and calibration (Vamvakeridou-Lyroudia et al., 2008). At each time step, the volume of water in the reservoirs is updated, accounting for inflowing water, evaporation, pumping and infiltration losses. This approach includes a varying number of small dams in the model in

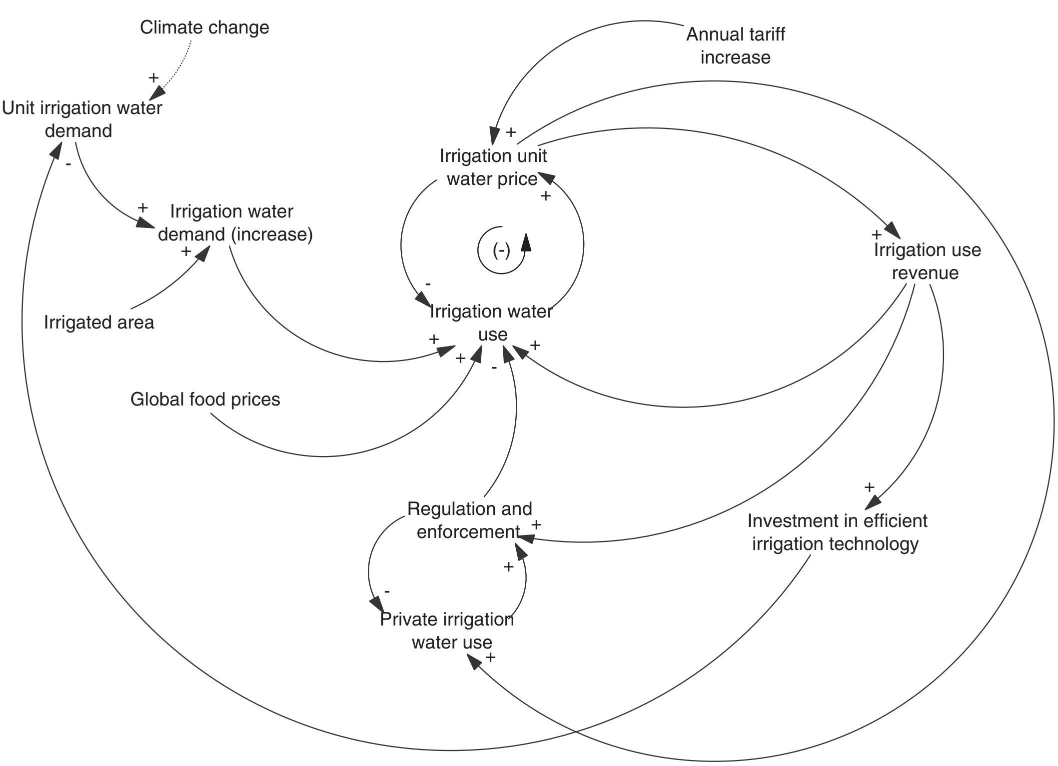


**Fig. 3.** Causal loop diagram for the agricultural demand sub-model. Polarity of feedback loops is indicated with a '−' for negative (self-stabilising) polarity and a '+' for positive (reinforcing) polarity. Indirect influences are shown as dashed arrows.

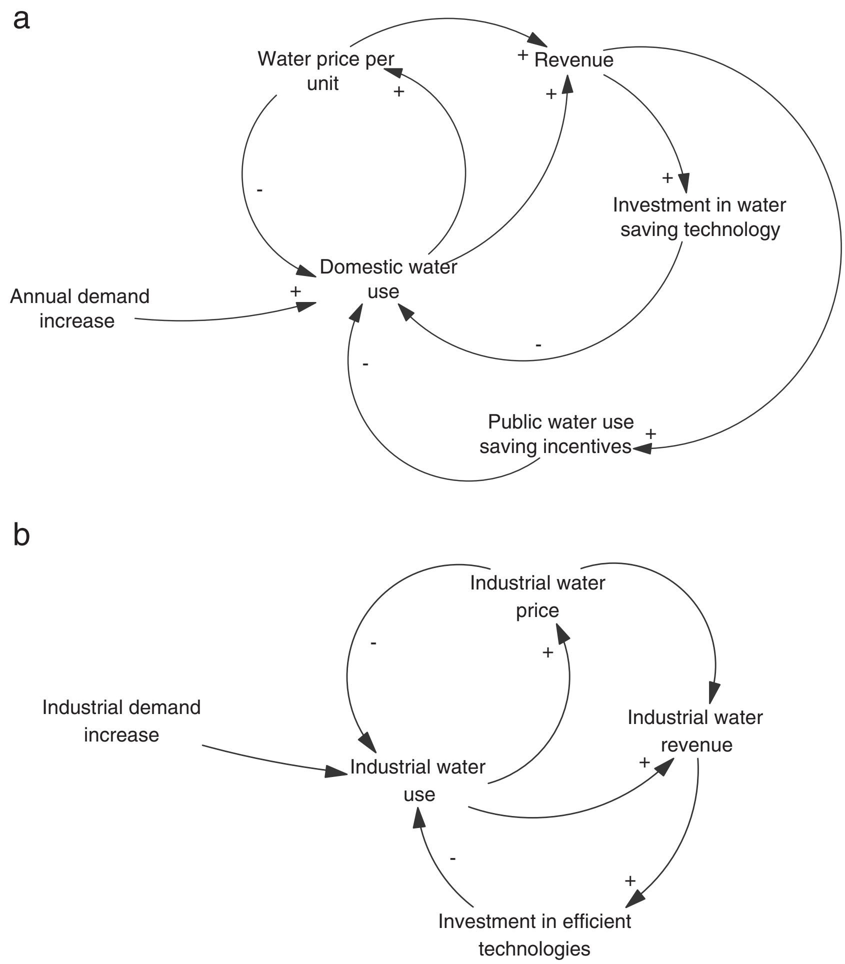


**Fig. 4.** (a) Causal loop diagram for the domestic demand sub-model. (b) Causal loop diagram for the industrial demand sub-model. Polarity of feedback loops is indicated with a '−' for negative (self-stabilising) polarity and a '+' for positive (reinforcing) polarity.

a parametric way, in the guise of a "typical computational small dam subsystem", so as to enable the users to examine different scenarios and policies for the future (e.g., by changing the number of small dams in the future).

The El Haouareb sub-system includes rules to estimate evaporation based on lake surface area, water releases based on threshold water levels to be applied (this is a reservoir operational control rule to maintain safe water levels, although in practice these happen only very rarely), and a function to represent infiltration into the Kairouan aquifer down the recently opened fissure. Fig. 2 shows the causal loop structure in order to illustrate the feedback that is involved within this single sub-model: reservoir volume influences the amount of evaporation and infiltration, but these latter two parameters then feedback (with negative polarity, i.e. self-stabilising loops) to affect the volume of water in the reservoir. Also the number of small dams from the Middle catchment subsystem interact with, and affect the water volume in El Haouareb, as well as infiltration to the aquifer. Indirect influences, i.e. climate change, and water policies are presented as dashed lines. More details about the Aquastress model structure, data and derived relationships, especially for the small dams can be found in Vamvakeridou-Lyroudia et al. (2008).

The main Kairouan aquifer sub-model, which is the focus of this study, comprises a water-balance model which brings together the calculations performed in each of the six sub-models to simulate the behaviour of the water reserves held in the aquifer. Two of the sub-models represent inputs to the aquifer, including rainfall and the other four represent outflows or abstractions.

The two input sub-models represent surface water recharge and direct aquifer transfers. The surface water sub-model uses continuous monthly rainfall time-series data to estimate the volume of water infiltrating over the area of the Kairouan plain per month from rainfall events. At each time step, the rainfall depth (m) is multiplied by the catchment area ($m^2$). This is then multiplied by 0.05 to represent the fact that rainfall only falls over a very small fraction of the catchment area. Of this rainfall, c. 70% is lost to evaporation (Besbes et al., 1978), with the rest recharging the aquifer. In addition, some water released from El Haouareb dam infiltrates to the Kairouan aquifer. The volume of water released from the dam is output from the El Haouareb sub-system and used here as input, thus providing a link between the sub-systems. Again, of any water released, 70% is lost due to the high evaporation rate in the study area (Besbes et al., 1978). The sum of the rainfall infiltration and water-release infiltration comprises the surface water input to the Kairouan aquifer. For the direct transfer sub-model two sources are taken into account. The first is water that infiltrates directly beneath El Haouareb dam, as well as water that infiltrates through the small dams in the middle catchment. The second source is direct water transfer from adjacent aquifers, the data for which comes from the literature (Table 1).

There are four outflow/abstraction sub-models: a coastal pumping model; a model to represent agricultural demand, and models to represent domestic and industrial abstractions. Each sub-model (except the coastal pumping model) uses a series of feedback loops in order to estimate the respective demands at each time step. The initial conditions are set to present days values for each of the parameters

**Table 1**
Details of model parameter values used in the newly developed Kairouan aquifer sub-system.

| Data type | Data source/references | Values used/notes |
|---|---|---|
| Rainfall time series | Centro Euro-Mediterraneo per i Cambiamenti Climatici (CMCC), Italy | Continuous monthly data from 2010 to 2050. Based on data from a regional climate model forced by ECHAM5 with the IPCC A1B emission scenario. Output resolution is 25 × 25 km. A 19% reduction is observed in 2050 compared to 2010 values. |
| Area of catchment over which rain falls | Assumption — agreed with INAT. | Rainfall is not evenly distributed over the catchment. Initial value set at 5%. |
| Evaporation coefficient | Estimate, and Besbes et al. (1978) | A value of 70% evaporation loss was used. |
| Annual volume of water entering Kairouan aquifer from adjacent aquifers | Leduc et al. (2007) | Value of $5 \times 10^6$ $m^3$ $a^{-1}$ was used. Assumed even distribution through the year. No change to 2050 due to a lack of data. |
| Annual volume transferred out of Kairouan to sebkha | Vamvakeridou-Lyroudia et al. (2008) | Value of $7.5 \times 10^6$ $m^3$ $a^{-1}$ was used. Assumed even distribution through the year. No change to 2050 due to a lack of data. |
| Water lost from El Haouareb Dam down a recently opened fissure | Leduc et al. (2007) | 50% of total volume held in the reservoir is routed to Kairouan aquifer. |
| Total volume stored in Kairouan aquifer | Lili-Chabaane (2010) | Initial value of $59.7 \times 10^6$ $m^3$ is used at the start of all simulations. |
| Annual water deficit in Kairouan aquifer | Luc (2005) | Value of $17.4 \times 10^6$ $m^3$ $a^{-1}$ is reported. |
| Evaporation coefficient | Estimate, and Besbes et al. (1978) | A value of 70% evaporation loss was used. |
| Parameterisation of 35 small dams | Vamvakeridou-Lyroudia et al. (2008) | See Section 3 for detail. |
| Domestic demand: population increase | CIA world factbook | 1% per year increase |
| Domestic demand: per-capita demand | INAT | 2.28 $m^3$ per month |
| Domestic demand: price elasticity of demand | Assumption | −0.3 |
| Domestic demand: annual demand increase | INAT | 0.55% per year |
| Domestic demand: annual tariff increase | Belhaj Jrad (2000) | 6% per year increase |
| Domestic demand: proportion of revenue re-invested | Etat (2006) | 55% of revenue is re-invested |
| Domestic demand: proportion of re-investment in infrastructure upgrades | Assumption | 70% |
| Domestic demand: proportion of re-investment for publicity campaigns | Assumption | 30% |
| Domestic demand: water savingsresulting from infrastructure upgrades | Logarithmic relationship assumed. Equation used: if (Investment_in_dom_water_technology == 0) then 0 elseif (last(Investment_in_dom_water_technology) − var_delay(Investment_in_dom_water_technology,2)) > 0 then ((0.2173 * log(Investment_in_dom_water_technology) − 1.8423)/100 * last(Dom_demand)) else 0 | Data from Wessex Water UK water company suggest potential 15% savings from infrastructure upgrades. It was assumed that this is the maximum possible saving, that a logarithmic relationship links investment to the saving made and that if investment decreases, there is no improvement. |
| Domestic demand: water savings resulting from publicity campaigns | Logarithmic relationship assumed. Equation used: if (Dom_water_saving_intiatives == 0) then 0 elseif (last(Dom_water_saving_intiatives) − var_delay(Dom_water_saving_intiatives,2)) > 0 then (0.0614 * log(Dom_water_saving_intiatives) − 0.421)/100 * last(Dom_demand) else 0 | Lee et al. (2011) show a 20% saving from PR initiatives over 4 years (5% per year) from a study in the USA. It was assumed that this is the maximum possible saving, that a logarithmic relationship links investment to the saving made and that if investment decreases, there is no improvement. |
| Industrial demand: monthly increase | INAT | 11.45% per year |
| Industrial demand: tariff increase | Belhaj Jrad (2000) | 6% per year increase |
| Industrial demand: price elasticity of demand | Assumption | −0.3 |
| Industrial demand: proportion of revenue invested for water savings | Holt et al. (2000) | 1% per year |
| Industrial demand: water savings from investment | Assumed relationship, with level of saving based on information in Holt et al. (2000). Equation: (if (last(Money_spent_on_efficiency) − var_delay(Money_spent_on_efficiency, 2)) > 0 then min((0.000000902884 * last(Money_spent_on_efficiency) − 0.0006), 0.00416) else 0.000416) | Annual cap set at 5% saving. |
| Coastal pumping: change in volume restrictions over time | INAT | Table 2 |
| Agricultural demand: annual demand change | Chahed et al. (2008) | 5% over 28 years |
| Agricultural demand: global food price increase | www.fao.org | 11.3% per year increase |
| Agricultural demand: tariff increase | Chenini et al. (2003) | 15% per year |
| Agricultural demand: price elasticity of demand | Assumption | −0.3 |
| Agricultural demand: proportion of revenue invested for efficiency savings | Assumption | 10% |
| Agricultural demand: potential water saving from improving efficiency | Unlu et al. (2011) | 20% per year |
| Agricultural demand: influence of regulation and enforcement | Assumption | Limited to 10% per year |
| Agricultural demand: farmer uptake of efficiency technology | Lower limit (21%) from INAT. Upper limit (70%) assumed. Relationship assumed. Equation: 0.5886 * log(Investment_in_efficient_irrigation) − 4.4977 | |
| Agricultural demand: savings from efficiency measures | Saving is the potential (20%) multiplied by the uptake. It is limited to 20% * 21% at the lower end and 20% * 70% at the upper end. Equation: Investment_in_efficient_irrigation > last(Investment_in_efficient_irrigation) then max(min(((Proportion_of_farmer_take_up * Potential_total_water_saving)/12), 0.011667), 0.0035) else 0 | If no increase in investment is simulated, no savings are made. |

that require an initial value (e.g. demand, tariff). Over the course of the simulation, the system of feedback loops results in the demand/tariff/etc. being re-estimated at every time step. For the industrial, agricultural and domestic demands, the demand itself is influenced both by 'external' factors such as tariff, or predicted annual demand increases, and 'internal' factors such as savings from investment in infrastructure, regulation and water saving campaigns. Tunisia currently has policies in place that relate to water saving campaigns and increasing regulation for water demand (Kharraz et al., 2012). Due to the feedback-driven structure, demand is influenced by many factors, but, in turn influences these factors in subsequent iterations.

The agricultural sub-model is described here in detail in order to give an idea of the complexity involved, and to show how SDM principles have been exploited. The causal loop diagram for the agricultural demand sub-model is shown in Fig. 3. It is noted that there is an 'Irrigation water use' node representing the public (regulated) supply and a 'Private irrigated demand' node representing unregulated (sometimes illegal) water use. The initial 'Irrigation water use' value is modelled as constantly decreasing based on the findings by Chahed et al. (2008) that state that the agricultural water demand is predicted to decrease by c. 5% (0.05) to 2030. We assume that the 5% decrease by 2030 is maintained to 2050. 'Irrigation water use' is influenced by the tariff, which subsequently feeds back to alter the demand at the next time step. The change in demand due to tariff alterations is controlled by the equation for the price elasticity of demand (Lipsey and Chrystal, 1999):

$$\Delta D = D_{t-1} \times \{PeoD_t \times (\Delta P / P_{t-1})\}, \quad (1)$$

where $D_{t-1}$ is the demand at time step $t-1$, $P_{t-1}$ is the tariff at time step $t-1$, $PeoD_t$ is the price elasticity of demand at time step t. $\Delta D$ and $\Delta P$ represent the change in water demand and tariff from the previous time step respectively.

A constant value was chosen to represent an inelastic water market (−0.3) for PeoD. Generally, the industrial, tourist and lower-demand domestic users, who dominate in this area of Tunisia, have low demand elasticity (Kharraz et al., 2012). This value was changed in model testing to test sensitivity of results to different elasticity. The tariff itself is increased by 1.25% per month (Chenini et al., 2003). Acting alone, this would cause a drop in demand, but this is not the case here. Change in 'Irrigation water use' (i.e. agricultural water demand) is also influenced by 'Global food prices'. The logic is that farmers exploit increases in global food prices to grow more crops for sale abroad, with some of the price increase due to the farmers themselves increasing wholesale costs to recover increased expenditure due to water tariff rises. Thus, tariff increases may not decrease demand as much as expected due to the influence of other feedback loops in the system.

Average global food prices have increased by 11.3% annually from 2000 to 2012 (www.fao.org). It is assumed here that the increase is linear and that this rate of change remains constant through the model simulation. Such a simple relationship was chosen in the absence of better available data, but since the model aims at simulating trends, rather than numerical precision, it is considered adequate; implementing more elaborate formulae would introduce uncalled-for uncertainties.

The 'Irrigation use revenue' node is simply the 'Irrigation water use' multiplied by the tariff per unit consumed. Of the irrigation water use revenue, 10% is invested for improving irrigation efficiency, a reasonable assumption in the absence of more specific data, and was tested with the use of the model. The water efficiency saving from improving irrigation techniques is set at 20% which is very close to the 22% reported by Unlu et al. (2011) when using drip irrigation compared with more traditional irrigation methods. However, it is assumed that a 20% saving of the total agricultural demand can only be achieved if every farmer in the region takes up the technologies. If not, it must be scaled proportionally by farmer take-up. This proportional uptake relies on the investment increasing at each time step. If no increase is calculated, then it is assumed that no 'new' farmers take up the better technology and uptake is the same as during the last time step. If it does increase, then farmer take-up is calculated according to an assumed logarithmic relationship with the amount of investment (Table 1). At present, 21% of farmers use drip irrigation in the Kairouan region (INAT, pers. comm.) and thus at initial conditions the 20% potential saving is multiplied by the 21% of total farmer uptake (=0.042). This proportion is currently being increased due to government led campaigns (Kharraz et al., 2012). The proportion of farmers using drip irrigation was not permitted to drop below 21% (it was assumed that once taken up, a technology will not be sacrificed for a poorer performing technology). Uptake was also capped at 70% of the farmer population because it was assumed that there will always be some farmers who either cannot afford better technology or who resist change to newer technologies. Any water saving calculated is deducted from the total agricultural demand at the next time step.

Finally, irrigation water use is influenced by regulation and enforcement (a feedback structure currently built into Tunisian water policy; see Table 2 in Kharraz et al., 2012), which is in turn governed by the revenue generated. As with the water efficiency savings loop, if revenue increases, there is greater scope for regulation development and for policing water use/extraction. Thus, the unregulated (private) demand will tend to fall with respect to the value at the previous time step, with a concomitant increase in the regulated water use, and vice-versa. The change in regulation is represented as equal to the proportional change in revenue from the last time step, but is capped at 10% per year (Table 1). This relationship, and the cap, was assumed in absence of data.

The causal loops for the domestic and industrial demand are shown in Fig. 4. The logic is similar to the processes described above for agricultural demand, but with various changes made which are specific to each case (e.g. annual percentage change in demand, tariffs, etc.). These figures illustrate the complex nature of this multi sub-model SDM. Specific equations are given in Table 1. Policies aimed to controlling water demand pertaining to water saving campaigns, increasing utilities' network efficiency and introducing more robust regulation are currently employed in Tunisia (Kharraz et al., 2012). These sub-models thus reflect some of the current policy arena in Tunisia.

The exception is the coastal pumping sub-model. Again, data was provided by INAT that lays out how the Tunisian government aim to reduce this pumped volume over time to 2030. This sub-model reduces the pumped volume in a step-wise manner according to the data, creating a downward stepping demand profile over time (Table 2). Once the 2030 level is reached in the simulation, it is maintained until the end of the simulation.

Table 1 outlines the data and parameter values used in the Kairouan aquifer part of the model together with any sources and references.

**Table 2**
The current (baseline) policy to reduce pumping to coastal cities by 2030 (note the initial increase in volumes, data from INAT) and the profiles used for Tests 31–33. Pumped volumes are in $m^3$ $year^{-1}$.

| Year | Baseline | Test 31 | Test 32 | Test 33 |
|---|---|---|---|---|
| 2011 | 2,050,000 | 2,050,000 | 2,050,000 | 2,050,000 |
| 2012 | 2,168,333 | 2,000,000 | 2,100,000 | 2,100,000 |
| 2013 | 2,141,667 | 1,800,000 | 2,000,000 | 1,900,000 |
| 2014 | 2,102,500 | 1,600,000 | 1,900,000 | 1,750,000 |
| 2015 | 2,075,833 | 1,400,000 | 1,800,000 | 1,600,000 |
| 2020 | 2,036,667 | 1,200,000 | 1,700,000 | 1,450,000 |
| 2025 | 1,826,667 | 1,000,000 | 1,600,000 | 1,300,000 |
| 2030 | 1,550,833 | 800,000 | 1,500,000 | 1,150,000 |
| >2030 | 1,209,167 | 600,000 | 1,400,000 | 1,000,000 |

Details of the data and parameters used for the Aquastress model components, which have also been used in this study can be found in Vamvakeridou-Lyroudia et al. (2008). It is noted that the model does not explicitly deal with environmental flow considerations. There is a very small component of aquifer leakage which is relevant for the sustainability of the sebkha regions. However this volume is negligible (INAT), and is not monitored. INAT therefore felt it unnecessary to include it in the model formulation.

## 4. Study area and current water related issues

This study focuses on the Merguellil Valley and Kairouan aquifer (Fig. 5) case study of the WASSERMed project. The ephemeral Merguellil river is the second largest in Tunisia. The relatively hilly upper part of the Merguellil catchment (area c. 1200 $km^2$) ranges from 200 to 1200 m in altitude, and contrasts with the flatter, lower Kairouan plain (area c. 3000 $km^2$), on which the city of Kairouan is located. Rainfall is variable with means of 300 mm $a^{-1}$ and 500 mm $a^{-1}$ over the plain and upper catchment respectively, with extremes of 108 and 703 mm $a^{-1}$ recorded in the city of Kairouan. Rain does not fall evenly over the catchment, but usually falls in highly localised cells. Aquifers are the only stable water supply in this region, with Kairouan aquifer being the largest. Kairouan aquifer is split into two layers: a shallow phreatic aquifer storing c. $28.8 \times 10^6$ $m^3$ water and a deep Plio-Quaternary layer storing c. $30.9 \times 10^6$ $m^3$, giving total volume of c. $59.7 \times 10^6$ $m^3$ (Lili-Chabaane, 2010). From mass balance assessments given by Le Goulven et al. (2009), the average (1994–2003) input to the aquifer represents 32% of the total volume, while abstractions represent 61.8% of the total aquifer volume. Le Goulven et al. (2009) estimate that there is currently a c. $17.4 \times 10^6$ $m^3$ $year^{-1}$ shortfall in the water balance. This situation is mirrored across Tunisia which has a national average renewable water resource extraction rate of 99% (Kharraz et al., 2012).

Water resources in the region are fragile and demands are high, leading to recent groundwater overexploitation resulting in a falling water table (Feuillette et al., 2003; Poussin et al., 2008; Le Goulven et al., 2009). Merguellil Valley hydrological processes are complex and have been extensively modified by anthropogenic activity in the last 40 years. The large El Haouareb dam (capacity c. $95 \times 10^6$ $m^3$, Fig. 5) was constructed in 1989 in order to provide a reliable source of clean water. However due to extensive evaporation loss, extraction for agricultural use and due to basal leakage (Kingumbi et al., 2004) down a recently opened fissure at the downstream of the reservoir (Institut National Agronomique de Tunisie (INAT), pers. comm., February 2011), El Haouareb has been totally, or nearly totally empty for most of the last 10 years. About 50% of the stored water (Leduc et al., 2007) enters the Kairouan aquifer via the fissure, resulting in lower evaporative loss in recent years and higher recharge to the aquifer.

Water and soil conservation measures have been developed since the 1960s. Thirty-five small dams (Fig. 5b) and numerous hillslope retention terraces have been constructed in the upper and middle Merguellil catchment, with the aim of decreasing erosion, providing flood protection and improving crop yields through enhanced irrigation. Such structures, however, negatively impact on the hydrology by significantly reducing runoff through the dams. Runoff, stored

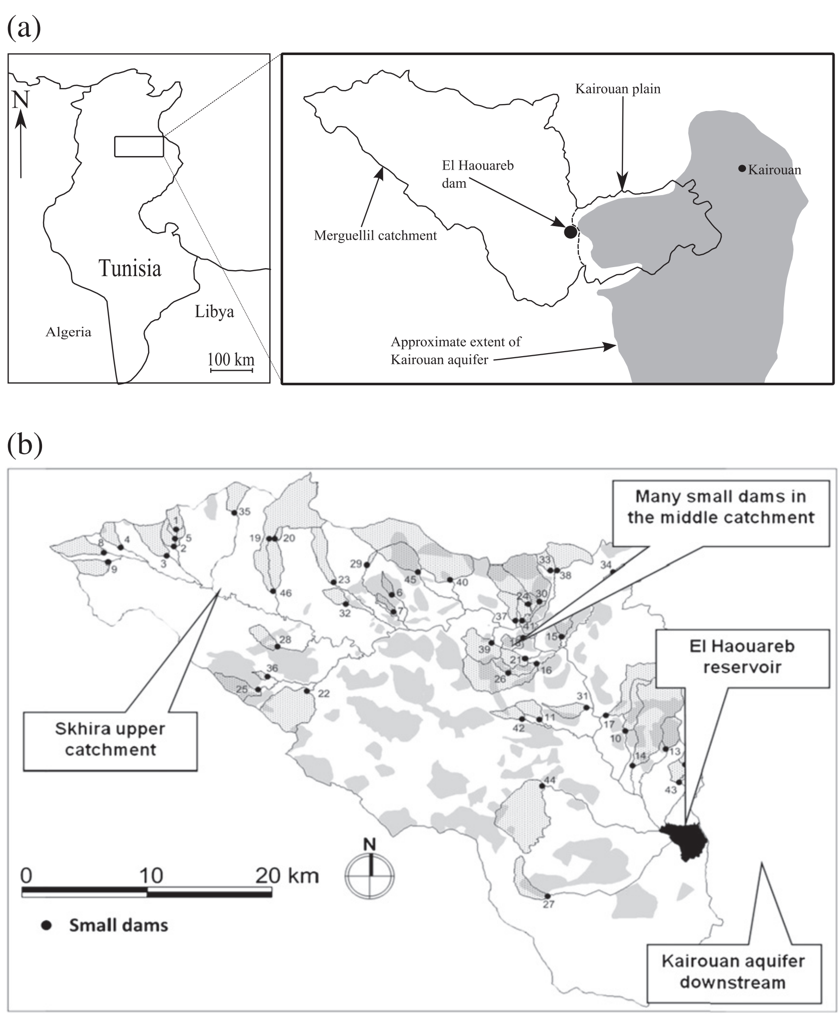


**Fig. 5.** (a) Map of the Merguellil/Kairouan study area in Tunisia; (b) showing the parts of the Merguellil catchment, the location of the small dams and the El Haouareb reservoir.

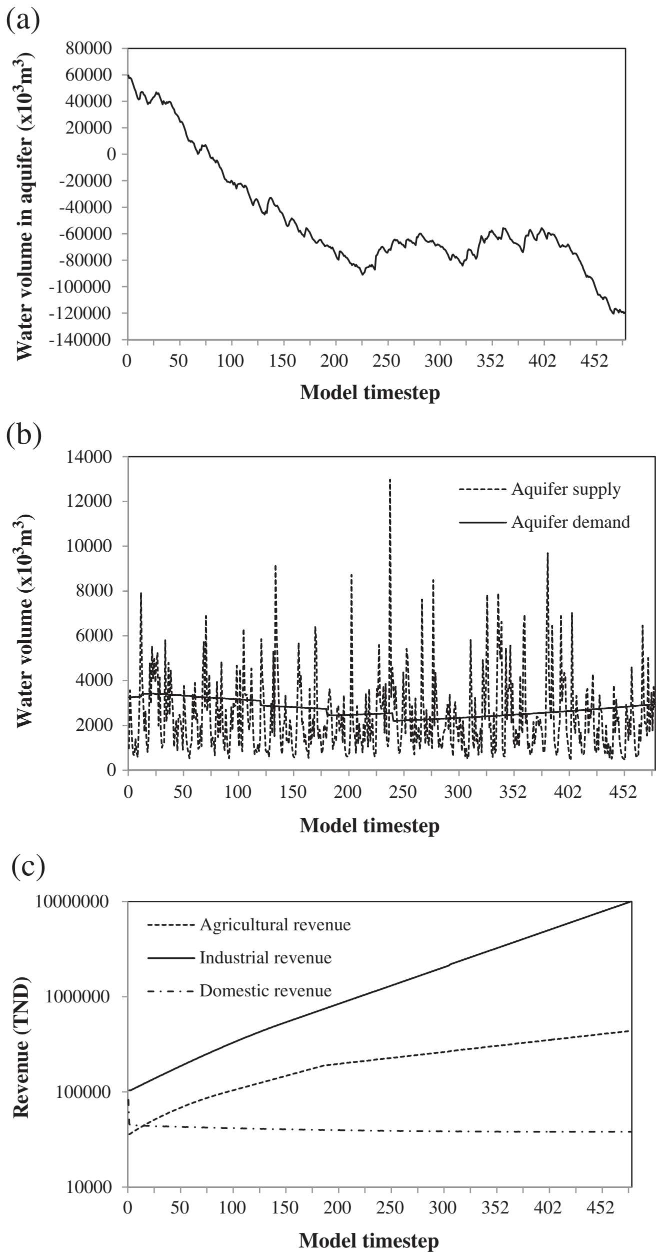


**Fig. 6.** (a) Showing the simulated stored water behaviour in the Kairouan aquifer under baseline conditions; (b) showing the volumes of water input to and abstracted from the aquifer during the standard run; (c) revenue generated in each sector in Tunisian Dinars (TND) during the standard run.

behind retention terraces on hillslopes, primarily aiming at groundwater recharge, mostly evaporated (Lacombe et al., 2008). This leads to lower volumes of water recharging the Kairouan aquifer. Most terraces silted up soon after development, leaving them all but redundant. On the other hand, water retention in the small dams increased, though only by a small amount. Some of this retained water infiltrates and ultimately ends in the Kairouan aquifer (Kingumbi et al., 2004; Vamvakeridou-Lyroudia et al., 2008).

Intense agricultural development (using c. $9\times10^6$ m$^3$ year$^{-1}$ in 2006 according to data from INAT, although this may be an underestimate as Le Goulven et al. (2009) estimate $21\times10^6$ m$^3$ year$^{-1}$), increasing living standards ($7\times10^6$ m$^3$ year$^{-1}$ in 2006, data from INAT), and an increasing demand from the tourist sector ($0.18\times10^6$ m$^3$ year$^{-1}$, data from INAT) are the major factors contributing to the increasing water withdrawal from the Kairouan aquifer. These factors, combined with problems in water management strategies, have led to large increases in pumping, some of which is illegal and unregulated. Recently, a large volume of water is pumped from the aquifer to coastal cities to satisfy demand (mainly tourism). Volumetrically, this represents the largest abstraction from Kairouan aquifer. There is currently an effort to reduce this volume in a stepwise manner over time.

Unsustainable overexploitation of the Kairouan aquifer has impacts for the local population, who are likely to experience a reduction in per-capita water availability or less water for irrigated agriculture, leading to potential socio-economic threats (UN-WATER, 2006). It also has subsequent impacts on the local and regional economy and on farmers' livelihoods, while negative environmental impacts are also likely. Environmental impacts will probably manifest in two main ways: (a) the impact on the nearby sebkha region (naturally occurring salt flats with sensitive water balance dynamics, which are extremely vulnerable to environmental change), where lower inflow may alter the delicate ecosystem, potentially causing irreversible environmental degradation, and (b) impacts related to aquifer water quality. If less water is stored in the aquifer, there is less capacity for dilution of pollutants and salts, leading to increased pollutant levels.

An integrated systems approach is required that can analyse these conflicting, interacting factors as a whole. A long-term view that considers the likely behaviour mode of the aquifer is required such that useful conclusions can be drawn about the probable future for the Kairouan region. Accurate prediction of levels and volumes is not the main aim. More important is understanding of how the system interacts and is likely to respond in the future under a range of physical and socio-economic scenarios, including a do-nothing or business-as-usual scenario. This will lead to better understanding of the system dynamics, and will hopefully give policy makers a better idea as to where to focus water-saving, conservation efforts and adaptation measures.

## 5. Results and discussions

The SDM was run continuously using a temporal resolution of one month for 480 time steps (i.e. 40 years), taking the model from 2010 to 2050, the time horizon for the WASSERMed project. The aim is to reproduce credible behaviour characteristics that pertain to the aquifer water volume. Previous studies of water table levels (Kingumbi et al., 2004; Leduc et al., 2007), which can tentatively be used as a proxy for determining general aquifer volume behaviour, are used to verify that the model behaviour is generally sensible. It is noted again that model behaviour patterns are more important than absolute numbers, and in fact accurate prediction of stored aquifer water volumes is not the aim. Rather the aim is to show which, if any, alterations to the baseline parameters may lead to favourable aquifer behaviour in the future (i.e. potential water volume recovery, and an end to over-exploitation). Such results can then be used as a guide by policy makers to make their efforts more directed towards those options that will likely have the greatest impact in preserving this precious resource, and with it, the social, environmental and economic wellbeing of the surrounding area. A baseline run was conducted first, followed by a suite of parameter tests to observe the impact on aquifer behaviour, and to identify potential options to reverse the current trend of over-exploitation.

### 5.1. Baseline run

The baseline run was conducted using the data and parameters as described in Tables 1 and 2. Fig. 6 shows the results. According to this simulation, the aquifer is being over-exploited, with aquifer supply being lower than demand through most of the run, with intermittent periods of increased supply due to climate (rainfall) variability. The rate of over-exploitation is c. $10\times10^6$ m$^3$ year$^{-1}$, which is lower than the $17.4\times10^6$ m$^3$ year$^{-1}$ estimated by Luc (2005) based on rudimentary mass balance calculations. The overall pattern is one of aquifer stored volume decline, which closely mimics observed water table patterns since the 1960s (Le Goulven et al., 2009), other model simulations of the depth to the Kairouan aquifer water table (Feuillette et al., 2003) and more recent field observations (Leduc et al., 2007). Based on the baseline run, assuming that the model is representing the system reasonably well, assuming that the parameter values are close to representative, and assuming that current social and policy behaviour continues, the model shows that the aquifer undergoes significant depletion (becoming virtually 'empty' in 7 years). It is predicted that industrial and agricultural revenue will both increase from the initial value, whereas revenue from domestic water use will decrease. This is unlikely to be case after the water supply becomes critical or runs out and water use falls sharply. The revenue increases are mainly due to increasing tariff, which in the case of agriculture offsets the predicted decline in demand. For revenue from domestic water use, the decrease is due to the demand falling over time as a result of the impacts of the savings from improving infrastructure (i.e. reduced water losses) and from public water saving measures. Negative simulation values signify "deficits" in the stocks (the storage computational elements in system dynamics). In reality this means that there is not enough water to fulfil the required demands, that there is no viable supply. If this situation occurred in reality, abstraction would be significantly curtailed and restricted, and the energy costs would increase dramatically. We retained the negative values instead of substituting them with a simple "zero" status in order to analyse the full future development of aquifer behaviour in response to various potential policy implementations which we feel is more useful for mid-term policy planning, especially if comparing/ranking various potential options. By retaining the values, aquifer behaviour can be properly assessed.

### 5.2. Sensitivity analysis

During these tests, only the value under investigation was changed in order to observe the impact on model response. All other values were as in the standard run. Table 3 details all the simulations that were carried out for the scenario testing. Test numbers given here refer to those in Table 3, which also details which sector each test number is relevant to. Although mostly hypothetical, it is noted that at present, Tunisia has active policy procedures aimed at reducing water demand in various sectors through a combination of public awareness campaigns, tariff structures, increasing regulation and investment in more efficient irrigation technologies (Kharraz et al., 2012).

These tests aim to identify which parameters in which sectors have the greatest impact on aquifer behaviour and therefore may act as a future guide or focus for policy decisions. It is also assumed that those parameters will also have knock-on implications for local ecological conservation, particularly for the delicate sebkha regions, and for local socio-economic development. It is noted that the behaviour, once the water volumes become 'negative' in the model, is indicative only, and should be seen as an indication/trends of collateral problems (e.g. occurrence of 'hypersalinity', environmental degradation, severe water scarcity) rather than something that could occur in reality. For example, it is infeasible for revenue to keep increasing if there is no water left to extract and exploit (in the model, revenue can increase because water is still extracted from the stock even as the virtual 'volume' falls below zero — i.e. there is no rule in place to limit water extraction, or revenue generated, as the stock volume falls to or below zero). In reality, the opposite would probably happen — as the water limit is approached, sanctions on pumping would likely be put in

**Table 3**
Outline of the 33 Tests carried out. See Section 5 for the results.

| Test number | Tested parameter | Relevant sector | Baseline value | Value tested | General result — water volume trend |
|---|---|---|---|---|---|
| 1. | Per-capita demand | Domestic demand | 2.28 $m^3$ $month^{-1}$ | Baseline × 0.5 | Declining |
| 2. | Per-capita demand | Domestic demand | 2.28 $m^3$ $month^{-1}$ | Baseline × 2 | Declining |
| 3. | Population increase rate | Domestic demand | 0.00083 | Baseline × 0.5 | Declining |
| 4. | Population increase rate | Domestic demand | 0.00083 | Baseline × 2 | Declining |
| 5. | Annual domestic demand increase | Domestic demand | 0.0004583 | Baseline × 0.5 | Declining |
| 6. | Annual domestic demand increase | Domestic demand | 0.0004583 | Baseline × 2 | Declining |
| 7. | Price elasticity of demand | Domestic demand | −0.3 | −1 | Declining |
| 8. | Price elasticity of demand | Domestic demand | −0.3 | −1.5 | Declining |
| 9. | Fraction of revenue invested for infrastructure upgrades | Domestic demand | 0.385 | Baseline × 0.5 | Declining |
| 10. | Fraction of revenue invested for infrastructure upgrades | Domestic demand | 0.385 | Baseline × | Declining |
| 11. | Fraction of revenue invested for public water saving initiatives | Domestic demand | 0.165 | Baseline × .5 | Declining |
| 12. | Fraction of revenue invested for public water saving initiatives | Domestic demand | 0.165 | Baseline × 2 | Declining |
| 13. | Monthly demand increase | Industrial demand | 0.0095416 | Baseline × 0.5 | Declining |
| 14. | Monthly demand increase | Industrial demand | 0.0095416 | Baseline × 2 | Declining |
| 15. | Price elasticity of demand | Industrial demand | −0.3 | −1 | Declining |
| 16. | Price elasticity of demand | Industrial demand | −0.3 | −1.5 | Declining |
| 17. | Fraction of revenue invested to improve efficiency | Industrial demand | 0.01 | Baseline × 0.5 | Declining |
| 18. | Fraction of revenue invested to improve efficiency | Industrial demand | 0.01 | Baseline × 2 | Declining |
| 19. | Price elasticity of demand | Agricultural demand | −0.3 | −1 | Recharge |
| 20. | Price elasticity of demand | Agricultural demand | −0.3 | −1.5 | Recharge |
| 21. | Monthly change in demand | Agricultural demand | −0.00015 | Baseline × 0.5 | Declining |
| 22. | Monthly change in demand | Agricultural demand | −0.00015 | Baseline × 2 | Declining |
| 23. | Monthly global food price increase | Agricultural demand | 0.009416 | Baseline × 0.5 | Recharge |
| 24. | Monthly global food price increase | Agricultural demand | 0.009416 | Baseline × 2 | Declining |
| 25. | Tariff increase | Agricultural demand | 0.0125 | Baseline × 0.5 | Declining |
| 26. | Tariff increase | Agricultural demand | 0.0125 | Baseline × 2 | Declining |
| 27. | Proportion of revenue invested to promote efficient irrigation | Agricultural demand | 0.1 | Baseline × 0.5 | Declining — stable |
| 28. | Proportion of revenue invested to promote efficient irrigation | Agricultural demand | 0.1 | Baseline × 2 | Declining — stable |
| 29. | Potential water saving from efficient irrigation | Agricultural demand | 0.2 | Baseline × 0.5 | Declining |
| 30. | Potential water saving from efficient irrigation | Agricultural demand | 0.2 | Baseline × 2 | Declining — stable |
| 31–33. | Reduction in pumped volume over time | Coastal pumping demand | See Table 2 | See Table 2 for tested values. | Tests 31 and 33 — recharge. Test 32 — declining |

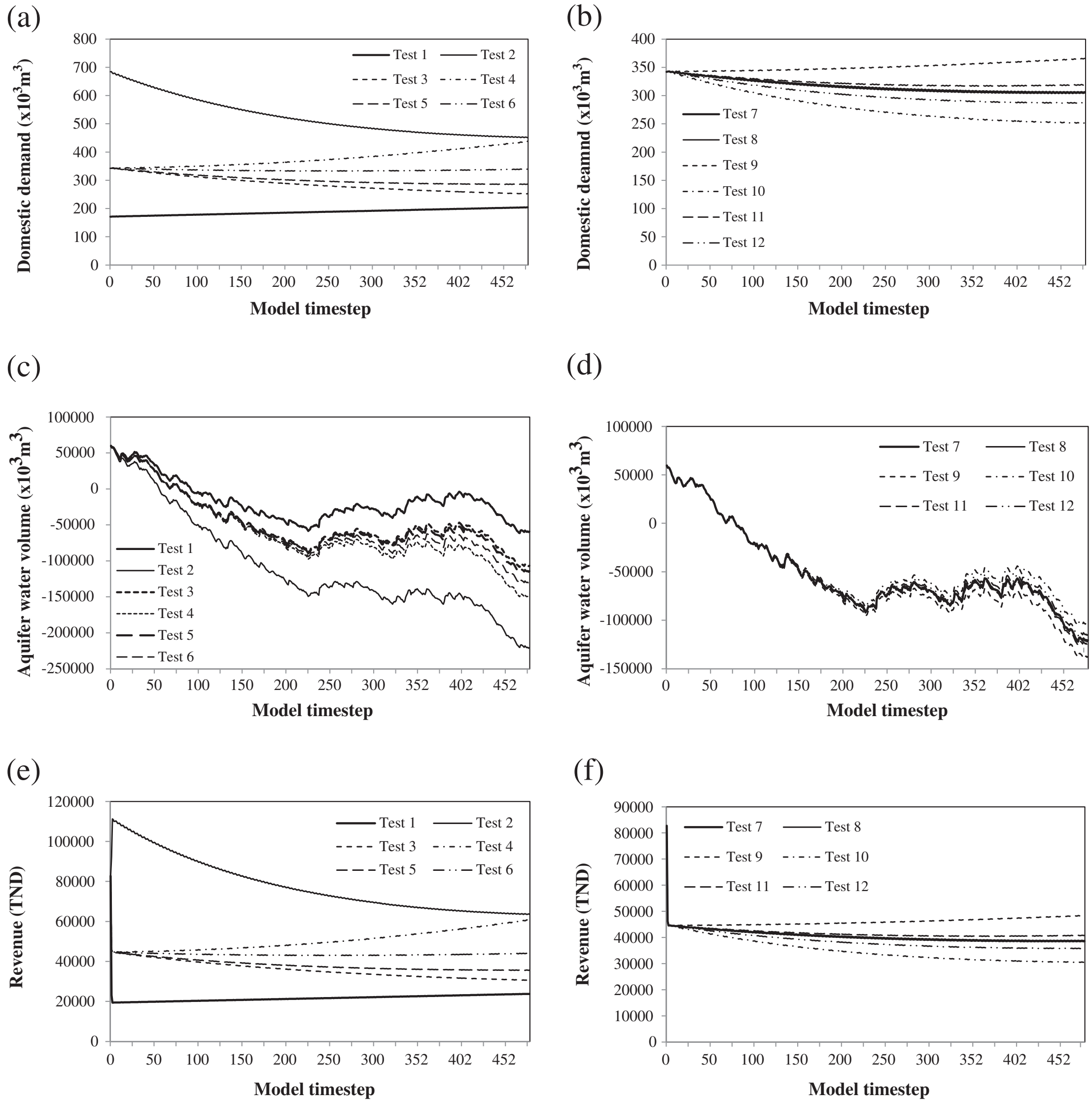


**Fig. 7.** Results for the domestic demand series of tests (Tests 1–12) showing (a) domestic demand for Tests 1–6, (b) domestic demand for Tests 7–12, (c) the aquifer water pattern for Tests 1–6, (d) the aquifer water pattern for Tests 7–12, (e) the domestic revenue generated for Tests 1–6 and (f) the domestic revenue generated for Tests 7–12.

place to curb demand, leading to lower revenue. However, the simulated results are intended to show behaviour patterns rather than give accurate numerical prediction of the future state of the aquifer (also see Section 5.1).

### 5.2.1. Domestic demand sub-model tests (Tests 1–12)

Fig. 7a shows the domestic demand over the model simulations for Tests 1–6, Fig. 7b shows the demand for Tests 7–12, while Fig. 7c shows the Kairouan aquifer water volume behaviour for Tests 1–6 and Fig. 7d for Tests 7–12. Fig. 7a and b clearly shows the non-linear response to changes in the parameters during these tests. For example, Test 1, which halved the per-capita demand shows a gradually increasing demand pattern, while Test 2, in which the per-capita demand was doubled shows an exponentially decreasing demand profile (Fig. 7a). These changes subsequently have significant impacts on the aquifer volume profiles (Fig. 7c and d). Despite this, water in the aquifer is still projected to decrease (virtually 'emptying'), with the time at which this occurs varying from 7.5 years (Test 1) to 4.5 years (Test 2). The revenue generated from domestic water charges (Fig. 7e and f) have the same profiles as for demand. This is because the revenue is calculated from 'demand × tariff'. Therefore, the tests that give the lower demand, also give the lower revenue.

Changes to various domestic demand parameters (such as doubling or halving the tariff increase rate, doubling or halving the per-capita demand, altering investment fractions for the purposes of lowering demand, etc.) have, when acting alone, relatively little impact on the simulated behaviour, with all the tests resulting in net over-exploitation and eventual 'emptying' of the aquifer. For example, even if per-capita demand is reduced to half that of present levels, which is unlikely due to a) improving lifestyles and b) an already low per-capita demand, then the time at which the aquifer may become empty is only delayed by about 2 years. The main reason for the relatively small impact observed is that these sectors consume the least water in the Kairouan region. Despite this, given the current state of the aquifer behaviour, it would be unwise to neglect any potentially fruitful water-saving policy aimed at these sectors. In terms of policy-realistic actions, changes to water-efficiency/saving investment rates and/or campaigns to change social behaviour and promote better water use efficiency, together with more aggressive tariff increases (though this would prove less popular) could be targeted in an effort to reduce overall demand.

*5.2.2. Industrial demand sub-model tests (Tests 13–18)*

Fig. 8a shows the industrial demand evolution for Tests 13–18, while Fig. 8b shows the evolution of the Kairouan water stored water volume for the same tests. As with Fig. 7, these results show highly non-linear response to changes in the model parameters, with Test 14 showing an exponential increase in demand (note the logarithmic scale on Fig. 8a), leading to an exponentially decreasing aquifer behaviour (Fig. 8b). It is recognised that this is inherently unrealistic, but again, it is the behaviour mode that is more important than the numerical result. In all model simulations, the aquifer becomes virtually 'empty' in about 7 years. Fig. 8c shows the revenue profiles for these tests. Unlike the domestic revenue profiles, they do not follow the same pattern as the demand curves. This is explained here by the fact that the industrial tariff increases faster than the rate of decline in demand for some of the tests (e.g. Tests 13 and 16).

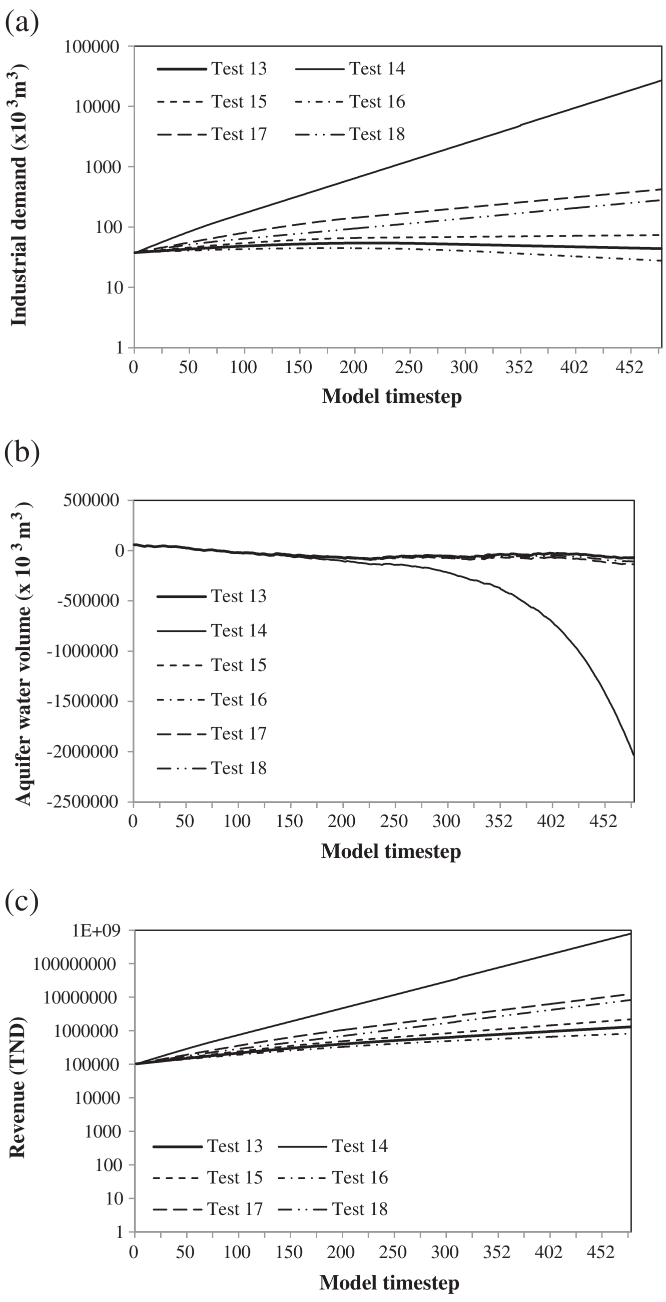


**Fig. 8.** Results for the industrial demand series of tests (Tests 13–18) showing (a) industrial demand for Tests 13–18, (b) aquifer water pattern for Tests 13–18 and (c) the revenue generated for Tests 13–18.

For the industrial sector, like with the domestic sector, all tests resulted in net over-exploitation and eventual 'emptying' of the aquifer. As with the domestic sector, this is mainly due to the very small volumes of industrial demand having a negligible impact on the overall regional water budget. But again, it would not be prudent to neglect any potential water-saving policy aimed at the industrial sector. In addition, water quality policy is also just as important, given the current declining aquifer volume.

*5.2.3. Agricultural demand sub-model tests (Tests 19–30)*

Fig. 9a shows the agricultural demand evolution for Tests 19–24 and Fig. 9b for Tests 25–30, while Fig. 9c shows the aquifer stored water volume evolution for Tests 19–24 and Fig. 9d for Tests 25–30. Test 24 results in exponentially increasing demand (note logarithmic ordinate) with concomitant exponential decrease in the aquifer water volume (Fig. 9c). The kink in the demand profiles at time step c. 186 is a result of the tariff being capped at ten times the present day value. After this has taken effect, the other feedbacks dominate the behaviour, leading to the renewed increase in demand. In these tests, Tests 19, 20 and 23 allow for aquifer recovery, and by the end of the simulation, there is a substantial quantity of stored water in Kairouan aquifer (Fig. 9c). Test 30 also hints at the potential for recovery. This is due to a decrease in agricultural water demand through the simulation period in response to increased demand elasticity (Tests 19 and 20) and halving of the rate of food price increases (Test 23). The time at which the simulation suggests that the aquifer will become virtually 'empty' ranges from 5 years (Test 24) to 15 years (Test 20), although this is only temporary, as this simulation suggests significant recharge later in the model run. Fig. 9e and f show agricultural revenue profiles. Initially, as the tariff increases, demand drops while revenue increases (the tariff increase is greater than the demand decrease). Once the tariff reaches the cap set at ten times the current tariff, the effects of irrigation efficiency measures, regulation/enforcement, the interplay between public and private water use and the effects of global food price changes dominate the water demand and revenue profiles. This change is marked by kinks in profiles, particularly noticeable for example in Tests 19, 25 and 26. It is feasible that if the cap was removed, that demand would keep declining through the simulation.

The tests conducted on the agricultural sector had more of an impact on aquifer behaviour. Agricultural water demand is by far the main local stress on the aquifer. Some tests, particularly 25–30, which relate to alterations to the tariff increase, the amount of revenue invested and the potential saving from water efficiency measures, all had relatively negligible impact, and none prevented depletion of the aquifer, although Tests 28 and 30 are more encouraging. Tests 19–24 had a greater impact on simulated behaviour. For example, Test 24 shows exponentially increasing demand as a result of doubling the average historic global food price increase. The impact on behaviour is as follows: the extra increase in global food price acts to alter farmers' behaviour such that they either use water more intensively to produce more crop or expand their cropped areas in order to take advantage of the increase in prices and make more profit. As more water is used, the tariff rises (to the limit), and in turn, farmers increase food prices to offset this increase. This in turn generates exponentially increasing revenue for water companies as a result of the feedback effects built into the model structure. Of course, in the real world this behaviour is grossly unsustainable in the long term. Once aquifer yields begin to decline, water demand must fall (to the limit of zero if the aquifer were actually allowed to become empty, which is unlikely). As such, the revenue will never increase in an exponential manner indefinitely. However, the point here is to illustrate that such a real-world change would be an unfavourable scenario, as it could bring about a change in the Kairouan aquifer system that brings about severe water shortage much

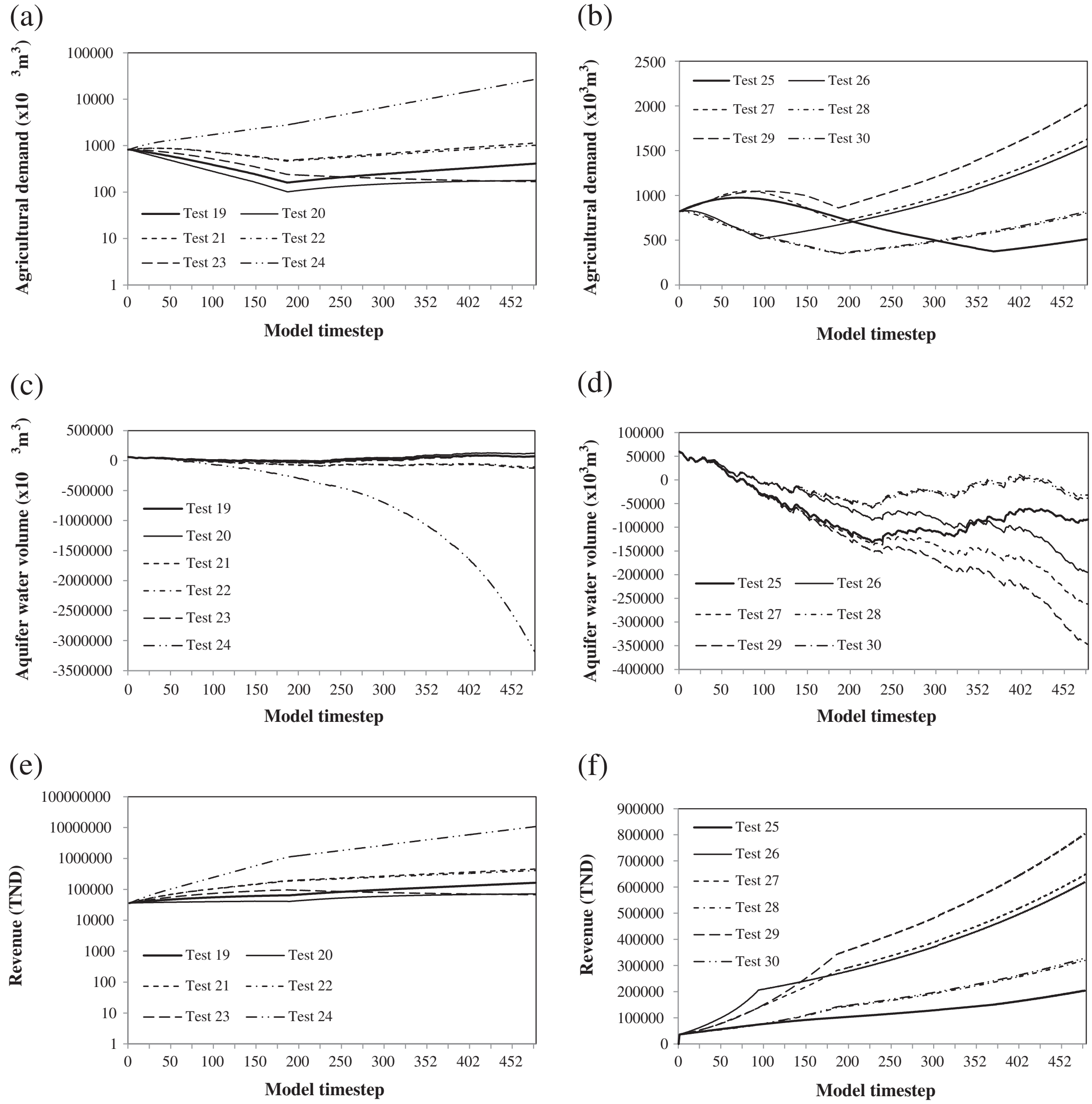


**Fig. 9.** Results for the agricultural demand series of tests (Tests 19–30) showing (a) agricultural demand for Tests 19–24, (b) agricultural demand for Tests 25–30, (c) aquifer water patterns for Tests 19–24, (d) aquifer water patterns for Tests 25–30, (e) revenue generated for Tests 19–24 and (f) revenue generated for Tests 25–30.

faster than expected, reducing the timeframe to initiate mitigating or adaptation measures. Such a scenario as in Test 24 would, in the long term, likely lead to rapid environmental degradation, drastic reduction in aquifer water quality, and hinder socio-economic development in the region as agricultural activity suffered due to the water shortages.

Conversely, Tests 19 and 20 indicate that the aquifer would initially be overexploited, but then demand drops sufficiently to allow for net recharge, especially in the second half of the simulations. These two tests pertain to altering the value for the price elasticity of demand, which was initially set at −0.3, representing fairly low elasticity (demand does not change much in response to price changes). The tests both assumed greater elasticity — unitary elasticity and elastic demand response for Tests 19 and 20 respectively. While these changes altered the behaviour in the most encouraging way with respect to aquifer water volume, demand elasticity is probably one of the parameters least ably controlled by local policy decisions as it can depend on many socio-economic and psychological factors (e.g. amount of income spent on the commodity, brand loyalty and necessity). Furthermore, demand elasticity would probably be slow to change and difficult to directly influence through policy changes.

#### 5.2.4. Coastal pumping sub-model tests (Tests 31–33, Table 2)

Fig. 10a shows the pumping profiles over time, while Fig. 10b shows the evolution of the aquifer stored water. The three tests performed here represent more or less stringent caps on the volume of water that would be allowed to be pumping out of the Kairouan aquifer to cities on the coast then the currently proposed regime of downward-stepping limits. Test 31 represents a significant decrease to pumping volumes relative to the proposed regime, Test 32 represents an initial improvement over current proposals but achieves lower reductions in the later years, and Test 33 is a case intermediate between the two, but with the limits being lower than are currently proposed. Both Tests 31 and 33 indicate that the aquifer never becomes 'empty' (all other parameters held constant), while Test 32 shows 'emptying' of the aquifer in approximately 8 years.

The coastal pumping tests had significant impacts of recharge behaviour due to the substantial volumes of water involved. These tests showed that, by altering current policy to reduce pumped volumes by greater amounts than presently committed to, but not by so much as to be unrealistic or unobtainable (Test 33), net recharge behaviour is simulated for the Kairouan aquifer. However, if the targets are missed by only a relatively small amount, then aquifer overexploitation,

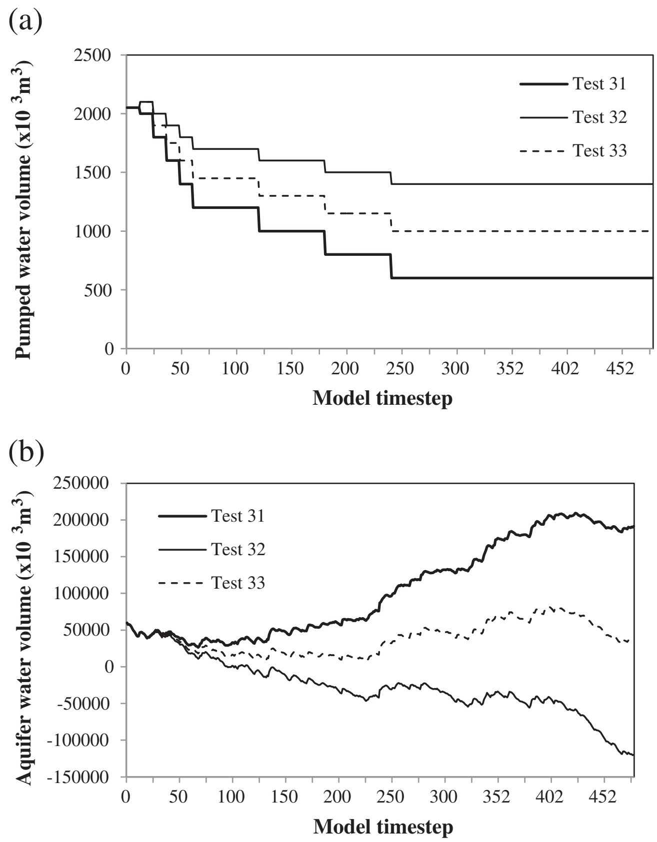


**Fig. 10.** Results of the coastal pumping series of tests (Tests 31–33) showing (a) the pumping patterns over the simulation period and (b) aquifer water patterns for Tests 31–33.

environmental degradation and negative impacts to socio-economic development are still probable.

All the above tests were carried out in isolation, whereas in reality it is likely that many policies will be implemented in parallel, which may have the effect of damping or amplifying each other. For example, if agricultural water demand elasticity could be affected through policy, and this was implemented together with a more aggressive programme to reduce pumping to the coast, it is likely that substantial aquifer recharge will occur. This will in turn lead to the continued development of agriculture in the region, safeguarding socio-economic activity, and would encourage environmental rehabilitation. However, if the demand of elasticity policy were coupled with a policy to improve domestic lifestyles, thus doubling domestic demand, the two policies, while well-meaning, would offset each other, and probably lead to aquifer depletion and worsening the water scarcity situation, even if this was not the initial aim.

From the results and the above discussion, the parameters that have the most impact on aquifer behaviour, and those that are probably most policy-realistic (in terms of the effectiveness of policy to effect changes in the parameters) are:

- changes to domestic demand (e.g. through various campaigns/incentives); and
- changes to the volume of water pumped to the coast.

While the agricultural tests showed significant alterations in aquifer behaviour, these results came from parameters not easily changed through local policy. This does not suggest however that other policies to save water/improve efficiency should not be sought. Indeed, given the current situation in the Kairouan aquifer, every possible measure that is likely to reduce the over-exploitation should be considered, and as many as practicably possible should be implemented in parallel to amplify savings made and promote a water-secure future.

## 6. Summary and conclusions

This paper presents a complex, feedback-driven SDM that represents the Kairouan aquifer system in north-central Tunisia. The model builds on an earlier SDM that simulated the upper Merguellil catchment, but greatly improves on this through the characterisation of the Kairouan aquifer in detail, linking six feedback-driven submodels in order to simulate the behaviour of the Kairouan water supply over time. The model consists of over 155 nodes, and numerous feedback loops which either dampen or amplify behavioural patterns depending on their polarity, and many feedback loops also interact, thus making the resulting model response unclear. The Kairouan model accounts for supply from surface and subsurface sources, and also demand from four sectors: domestic, industry, agriculture and pumping of water to coastal cities. This is the first time that such an integrated physico-socio-economic SDM has been developed for the Kairouan region. The model focus for this paper is to simulate the behaviour of the evolution of the Kairouan aquifer water supply between 2010 and 2050, which is the timeframe specified by the EU FP7 funded project 'WASSERMed' for which this work was undertaken. Once the behaviour using standard parameters was established and found to agree closely with observed patterns of water level decline in the aquifer, a suite of demand-side parameters were altered in order to observe the impacts on aquifer behaviour, and to identify those which have the most favourable effect on the potential future evolution of the aquifer system (i.e. lead to long-term recharge).

The results obtained in the baseline run indicated a behaviour of over-exploitation, with the simulation suggesting potential 'emptying' (in reality this represents a significant depletion. Negative aquifer values were retained so that the behaviour could be properly analysed, Section 5.1) of the aquifer in about 7 years assuming no change to demand or policy behaviour, which is unlikely. The behaviour pattern closely matches locally observed patterns, and suggests that mitigating measures to prevent serious water scarcity are required. From the sensitivity tests, it was found that some parameters have significantly more impact than others, and the sign of the impact varies as the multiple feedback loops in the sub-models take effect. Most responses were observed to be non-linear, meaning that the impact of changing a single parameter could not be (easily) predicted. Some parameters led to negligible change, while others greatly impacted aquifer behaviour leading to either significant recharge, or even quicker decline of the reserves, depending on which parameters were changed, and in which direction. The parameters found to a) have the greatest impact on aquifer behaviour whilst b) being policy-realistic were the parameter controlling the per-capita domestic water demand and the parameter controlling the regime of reducing pumping to coastal cities. This latter parameter may prove a key to securing water supply in the future for the region due to the volumes of water involved. Pumping water to coastal cities is currently the main water stress on the aquifer. A policy does currently aim to reduce this volume in a step-wise manner, however, this policy still leads to over-exploitation when acting alone. However, it was found that by being more aggressive in the level of reduction, though not unrealistically so, recharge, and thus sustainability of the water resource, could be achieved.

Despite the importance of these two parameters, given the current situation being faced in the Kairouan region (reductions in water quality, environmental degradation and potential impacts to socio-economic activity as farming may be forced to cut-back due to water shortages), it is not suggested that only these two options are considered. Indeed, it is suggested that all viable policy options for reducing water demand should be considered, and that as many as practicably possible should be implemented in parallel. In this way, the effects of many beneficial policies could amplify each other. This is the path that will most likely ensure a secure, clean water supply for Kairouan, and with it, environmental protection such as maintaining water quantity and quality, preservation of the delicate Sebkha ecosystems, and the continuation of core socio-economic activity and development. As part of the final stage of the WASSERMed project, potential policy realistic mitigation measures will be discussed with local partners such as INAT. These measures can then be tested within an integrated SDM environment such as that developed here. As a result, local policy makers will get a better sense of the full impacts of their potential actions, and will thus be better informed and be in a better position to select those measures which are likely to have the best environmental, economic and social outcomes.

It is shown that SDM may be a useful tool for integrated water systems modelling, incorporating socio-economic elements, and using results to draw wider conclusions about the potential environmental and socio-economic impacts of changes to key system parameters which may represent changes to policy. Such integrated modelling is critically missing in current water resources research, and as such this work represents an early attempt to fill this gap.

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## References

Arnell NW, Livermore MJL, Kovats S, Levy PE, Nicholls R, Parry ML, et al. Climate and socio-economic scenarios for global-scale climate change impact assessments: characterising the SRES storylines. Global Environ Change 2004;14:3-20.

Atanasova N, Todorovski L, Dzeroski S, Kompare B. Constructing a library of domain knowledge for automated modelling of aquatic ecosystems. Ecol Modell 2006;194: 14–36.

Barlas Y. System dynamics: systemic feedback modelling for policy analysis in knowledge for sustainable development — an insight into the encyclopaedia of life support. Paris France, Oxford UK: UNESCO Publishing, Eolss Publishers; 2002.

Belhaj Jrad MK. La tarification de l'eau d'irrigation en Tunisie. Republique Tunisienne: Ministere de l'Agriculture, Direction Generale du Genie Rural; 2000. In French.

Besbes M, Delhomme JP, de Marsily G. Estimating recharge from ephemeral streams in arid regions: a case study at Kairouan, Tunisia. Water Resour Res 1978;14:281–90.

Cain J. Planning improvements in natural resources management. Wallingford, UK: Centre for Ecology and Hydrology; 2001.

Chahed J, Hamdane A, Besbes M. A comprehensive water balance of Tunisia: blue water, green water, virtual water. Water Int 2008;33:415–24.

Chenini F, Huibers FP, Agodzo SK, van Lier JB, Duran A. Use of wastewater in irrigated agriculture. Country studies from Bolivia, Ghana and Tunisia. Volume 3: Tunisia. Waganingen: WUR. ISBN: 90-6754-703-4; 2003.

Chung G, Lansey K, Blowers P, Brooks P, Ela W, Stewart S, et al. A general water supply planning model: evaluation of decentralized treatment. Environ Modell Softw 2008;23:893–905.

Etat. Defis Majeurs et Axes Strategiques du secteur de l'eau en Tunisie. Republique Tunisienne: Ministère de l'agriculture et des ressources hydrauliques; 2006. Rapport National de "Ministère de l'agriculture et des ressources hydrauliques"; in French.

Feuillette S, Bousquet F, Le Goulven P. SINUSE: a multi-agent model to negotiate water demand management on a free access water table. Environ Modell Softw 2003;18: 413–27.

Ford A. Modeling the environment: an introduction to system dynamics modeling of environmental systems. Washington DC, U.S.A: Island Press; 1999.

Forrester J. Industrial dynamics. Waltham, MA, U.S.A.: Pegasus Communications; 1961

Green TR, Taniguchi M, Kooi H, Gurdak JJ, Allen DM, Hiscock KM, et al. Beneath the surface of global change: impacts of climate change on groundwater. J Hydrol 2011;405:532–60.

Giorgi F, Bi X. Regional changes in surface climate interannual variability for the 21st century from ensembles of global model simulations. Geophys Res Lett 2005;32: L13701. http://dx.doi.org/10.1029/2005GL023002.

Giorgi F, Lionello P. Climate change projections for the Mediterranean region. Global Planet Change 2008;63:90-104.

Haraldsson HV, Sverdrup HU. Finding simplicity in complexity in biogeochemical modelling. In: Wainwright J, Mulligan M, editors. Environmental modelling: finding simplicity in complexity. West Sussex, England, UK: John Wiley & Sons Ltd; 2004. p. 211–23.

Holt CP, Phillips PS, Bates MP. Analysis of the role of waste minimisation clubs in reducing industrial water demand in the UK. Resour Conserv Recycl 2000;30:315–31.

ISEE Systems. www.iseesystems.com 2011.

Khan S, Yufeng L, Ahmad A. Analysing complex behaviour of hydrological systems through a system dynamics approach. Environ Modell Softw 2009;24:1363–72.

Kharraz JE, El-Sadek A, Ghaffour N, Mino E. Water scarcity and drought in WANA countries. Procedia Eng. 2012;33:14–29.

Kingumbi A, Besbes M, Bourges J, Garreta P. Evaluation des transferts entre barrage et aquifères par le méthode de bilan d'une retenue en zone semi-aride. Cas d'El Haouareb en Tunisie centrale. Rev Sci Eau 2004;17:213–25.

Kojiri T, Hori T, Nakatsuka J, Chong T-S. World continental modelling for water resources using system dynamics. Phys Chem Earth 2008;33:304–11.

Lacombe G, Cappelaere B, Leduc C. Hydrological impact of water and soil conservation works in the Merguellil catchment of central Tunisia. J Hydrol 2008;359:210–24.

Le Goulven P, Leduc C, Salah Bachta M, Poussin J-C. Sharing scarce resources in a Mediterranean river basin: Wadi Merguellil in central Tunisia. River Basin Trajectories: Societies, Environments and Development; 2009. p. 147–70.

Leduc C, Ben Ammar S, Favreau G, Beji R, Virrion R, Lacombe G, et al. Impacts of hydrological changes in the Mediterranean zone: environmental modifications and rural development in the Merguellil catchment, central Tunisia. Hydrol Sci J 2007;52: 1162–78.

Lee M, Tansel B, Balbin M. Influence of residential water use efficiency measures on household water demand: a four year longitudinal study. Resour Conserv Recycl 2011;56:1–6.

Lili-Chabaane Z. Tunisia case study. Presented at the First WASSERMed Workshop, 1–3 June 2010, Tunis, Tunisia; 2010.

Lipsey RG, Chrystal KA. Principles of economics. 9th ed. New York (USA): Oxford University Press; 1999.

Luc JP. Blue and green water accounting: the Merguellil River basin. Report for the comprehensive assessment of water management in agriculture. International Water Management Institute; 2005. www.iwmi.cgiar.org/assessment/files_new/research_projects/river_basin_development_and_management/bluegreenwater_rapport_luc.pdf (last accessed November 2010). 78 pp.

Mazzoleni S, Rego F, Giannino F, Legg C. Eco-system modelling: vegetation and disturbance. In: Wainwright J, Mulligan M, editors. Environmental modelling: finding simplicity in complexity. West Sussex, England, UK: John Wiley & Sons Ltd; 2004. p. 171–86.

Meadows DL, Behrens III WW, Meadows DH, Naill RF, Randers J, Zahn EKO. Dynamics of growth in a finite world. Cambridge, Massachusetts: Wright-Allen Press, Inc.; 1974. 670 pp.

Muetzelfeldt R, Massheder J. The Simile visual modelling environment. Eur J Agron 2003;18:345–58.

Meutzelfeldt R. Extended System Dynamics modelling of the impacts of food system drivers on food security, livelihoods and the environment. Report for the CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS); 2010. 27 pp.

Molina JL, Bromley J, García-Aróstegui JL, Sullivan C, Benavente J. Integrated water resources management of overexploited hydrogeological systems using Object-Oriented Bayesian Networks. Environ Model Software 2010;25:383–97.

Mulligan M, Wainwright J. Modelling and model building. In: Wainwright J, Mulligan M, editors. Environmental modelling: finding simplicity in complexity. West Sussex, England, UK: John Wiley & Sons Ltd; 2004. p. 7-73.

Oki T, Kanae S. Global hydrological cycles and world water resources. Science 2006;313:1068–72.

Plumb AP, Rowe RC, York P, Brown M. Optimisation of the predictive ability of artificial neural network (ANN) models: a comparison of three ANN programs and four classes of training algorithm. Eur J Pharm Sci 2005;25:395–405.

Poussin JC, Imache A, Beji R, Le Grusse P, Benmihoub A. Exploring regional water demand using typologies of farms and production units: an example from Tunisia. Agric Water Manage 2008;95:973–83.

Rehan R, Knight MA, Haas CT, Unger AJA. Application of system dynamics for developing financially self-sustaining management policies for water and wastewater systems. Water Res 2011;45:4737–50.

Ribarova I, Assimacopoulos D, Jeffrey P, Daniell K, Inman D, Vamvakeridou-Lyroudia LS, Melin T, Kalinkov P, Ferrand N, Tarnacki K. Research-supported participatory planning for water stress mitigation: Journal of Environmental Planning & Management 2011;54:283–300.

Savenije HHG. Water scarcity indicators: the deception of the numbers. Phys Chem Earth Part B 2000;25:199–204.

Simonovic S. World water dynamics: global modelling of water resources. J Environ Modell 2002;66:249–67.

Simonovic S. Assessment of water resources through system dynamics simulation: from global issues to regional solutions. Proc. 36th Hawaii International Conference on System Sciences IEEE (HICSS'03), Hawaii: USA; 2003.

Simulistics Ltd. http://www.simulistics.com/2011.

Solomon S, Qin D, Manning M, Alley RB, Berntsen T, Bindoff NL, et al. Technical summary. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL, editors. Climate change 2007: the physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press; 2007.

Stave KA. A system dynamics model to facilitate public understanding of water management options in Las Vegas, Nevada. J Environ Manage 2003;67:303–13.
Sterman JD. Business dynamics, systems thinking and modeling for a complex world. New York, USA: Irwin/McGraw-Hill; 2000.
Sušnik J, Vamvakeridou-Lyroudia LS, Savić DA, Kapelan Z. System Dynamics Modelling applied for the integrated simulation of complex water systems. Proc. 8th IWA Symposium on Systems Analysis and Integrated Assessment WATERMATEX 2011, 19–22 June, 2011, San Sebastian, Spain; 2011. p. 535–42.
Tidwell VC, Passell HD, Conrad SH, Thomas RP. System dynamics modeling for community-based water planning: Application to the Middle Rio Grande. Aquatic Sciences 2004;66:357–72.
Unlu M, Kanber R, Koc LD, Tekin S, Kapur B. Effects of deficit irrigation on the yield and yield components of drip irrigated cotton in a Mediterranean environment. Agric Water Manage 2011;98(4):597–605.
UN-WATER. Coping with water scarcity, a strategic issue and priority for system-wide action, UN Water Scarcity Initiative. www.unwater.org 2006.
Vamvakeridou-Lyroudia LS, Leduc C, Savić D. System dynamics modelling: the Merguellil valley water system. Report No.2008/04, Centre for Water Systems, Univ. of Exeter, UK; 2008. accessible at www.ex.ac.uk/cws. 96p.
Ventana Systems Inc. www.vensim.com 2011.
WASSERMed. Water Availability and Security in Southern EuRope and the Mediterranean. at www.wassermed.eu 2011. (last accessed 20 July 2011).
Wintgens T, Dimova G, Ribarova I, Druzynska E, Caruk M, Vamvakeridou-Lyroudia LS, et al. Industrial water management as a water stress mitigation option. In: Koundouri P, editor. The use of economic valuation in environmental policy. Oxon UK: Routledge978-0-415-45323-3; 2009. p. 125–95.