SEVENTH FRAMEWORK PROGRAMME

THEME Environment

Grant agreement for: Small-Medium Scale Collaborative Project

WP 5: Integrated modelling of water-related security threats

D 5.2.2: Report on modelling tools and techniques to be applied to each case study for water balancing

Project acronym:	WASSERMed
Project full title:	Water Availability and Security in Southern EuRope and the Mediterranean
Grant agreement no.:	244255
Project starting date :	1/1/2010
Book Captain:	L.S. Vamvakeridou-Lyroudia, D. Savic, and Z. Kapelan (UNEXE)
Authors:	J. Sušnik (UNEXE); L.S. Vamvakeridou-Lyroudia (UNEXE); E Manoli, (NTUA)
Issue:	Final
Deliverable n°:	5.2.2

Document Status Sheet

Issue	**Date**	**Author**	**Comments**
1.0	16/06/11	Janez Sušnik	Initial draft version
2.0	27/06/11	Elina Manoli	Addition of the WSM DSS description, and baseline models for Rosetta and Syros
2.1	30/6/11	L.S.Vamvakeridou-Lyroudia	Review, revision additions

Executive Summary

This report forms Deliverable 5.2.2 in Work Package 5 of the WASSERMed project. It introduces first a list of possible models that could be used in WASSERMed to carry out the water balance modelling for each of the five case studies: Kairouan, Tunisia; Rosetta, Egypt; Jordan River Basin, Jordan; Syros, Greece; Sardinia, Italy. Next, the two modelling concepts that, according to the Description of Work, will be used to characterise the water balances are introduced. The modelling concepts to be used are: System Dynamics Modelling (SDM) and; the Water Strategy Man Decision Support System (WSM DSS). Each modelling concept is described in detail. The theory and practical application are outlined, and strong cases are made for each as to why they are suitable for use within WASSERMed. For the most part, this suitability is due to their respective flexibility and visual interface, allowing for a participatory process and for the development of case-study specific models and model outputs. This flexibility has allowed separate models to be developed for each case study.

The report presents the current state of development (at the time of writing) of the models for each case study. Because all models are still being developed and discussed with the case study partners, their structure and function may change. In general however, the Tunisian and Greek case studies are the most advanced and very near completion, though the Egyptian and Jordanian case studies are also well progressed as shown in this report. The Sardinian case study is poorly developed, and it is hoped that this will change in the coming months. The latest versions of each model for each case study are presented, along with descriptions of their structure and operation. For some case studies, both SDM and WSM DSS are being used. In this case, both models are presented.

Because of the participatory nature of this part of the WASSERMed project and Work Package 5, many people had significant contributions to the production of this report, and special mention is given here. The following contributed heavily to this report, particularly helping with model development: E. Manoli (NTUA); Z. Lili-Chabaane, H. Chakroun and I. Oueslati (INAT, Tunisia), C. Leduc and A. Ogilvie (IRD, Tunisia); M. Roushdi (ECRI, Egypt); M. Saba and G. Al-Nabar (NCARE, Jordan), M.S. Shatanawi (FAUJ, Jordan).

Contents

1. Introduction

1.1 Purpose of the report

The aim of this report is firstly to summarise the potential models that could be used in order to carry out a water balance simulation for each of the five WASSERMed case studies. This is done in the form of a table which gives brief details about many potentially useful models. After this, the report outlines in detail the theory and practical development of the two chosen modelling concepts to be used within WASSERMed: System Dynamics Modelling (SDM) and the WaterStrategyMan Decision Support System (WSM DSS). For each of these two concepts, the background of how modelling proceeds is given, highlighting their suitability in multi-disciplinary studies such as those being undertaken for WASSERMed. By detailing the strengths behind each modelling concept, the rationale for their use in WASSERMed is explored, and a strong case for each is presented. The report then introduces the current state of development with respect to the water balance models for each of the five case studies.

SDM is introduced, following model development from the conceptual phase, where systems are described in qualitative terms in order to get a better idea of their functioning, through to quantitative model development. SDM models are iterative. They tend to start off simply, then as discussions progress between all interested parties, complexity is introduced until the model is believed to accurately represent that part of the system under consideration. Model performance can be tested against real-life data in an attempt to verify that it is mimicking the system well. SDM allows for simply sensitivity and uncertainty analyses to be carried out. In addition, because SDM can take many inputs, the outputs can e tailored to suit the needs of the end user.

WSM DSS simulates water supply and demand, and can prioritise each such that certain water sources remain 'protected' or such that critical infrastructure never runs short of water. Policy decisions can be tested, and the effect upon the water balance can be analysed. Various options can be ranked according to user defined criteria, allowing for rapid assessment of those options deemed the most suitable. Economic analyses may also be carried out. Finally, a GIS interface allows for a participatory modelling process.

Once the models have been introduced, the state-of-development in each case study is outlined, and the latest versions of the water balance models (at the time of writing) are presented. In some case studies, both SDM and WSM DSS are being used. In this case, both models are presented. Tunisia is the most advanced case study in terms in water balance modelling, with Egypt and Jordan also progressing well. For the Sardinia case study, progress has been very slow, and it is hoped that this will change in the coming months.

1.2 Report structure

The section following the introduction provides a summary of potentially useful models that could be used for the water balance modelling in WASSERMed. Section 3 then introduces System Dynamics Modelling as a concept outlining its theoretical and practical development, and at the same time providing rationale as to why it is suitable for use in WASSERMed. The specific software to be used (SIMILE) is also introduced and described. Section 4 presents the WaterStrategyMan DSS in a similar way.

Finally, Section 5 goes through each case study in turn. The current state of model development is detailed, and the latest versions of the models are presented and described in detail. Because the models are not finalised, the structure and focus could change. For some case studies, both SDM and WSM DSS are being used. In these cases, both model are presented and described. Section 6 concludes the report and Section 7 lists the references cited.

2. Comparison of water balance and decision-support tools for the simulation of water systems

This section presents a table summarising some of the available water balance and relevant decision support tools that are available. The table was originally presented in Deliverable 5.2.1, and the reader is referred to that report for further information (WASSERMed, 2010).

In the literature, there are many water balance and decision-support tools for the simulation of water systems. Table 1 gives a brief summary to some of the more relevant ones and provides a comparison between them.

Table 1: **A comparison and brief description of decision support tools (adapted from AQUASTRESS, 2005).**

Name of tool	**Developer**	**Purpose**	**Description**	**Contact/availability**
Aquastress water balance model	Sonja Schmidt	Simulate and assess water stress for a specific test site. Analyses potential and limitation of dealing with water stress at sectoral level: industry, agriculture, etc.	Focus on regional level and indicates water stress. Takes into account amount of water and factors affected this quantity. Not geographically explicit. Hierarchical, allowing for gradually increasing complexity.	Sonja.schmidt@usf.uni-osnabrueck.de
Catchment modelling toolkit	CRC for catchment hydrology, Australia	Repository of hydrologic modelling software to improve efficiency and standard of catchment modelling	Web-based repository of catchment models, data sets, river tools, terrain analysis tools, water quantity models, etc.	www.toolkit.net.au
CORMAS	CIRAD, France	Programming environment for the creation of multi-agent systems, specifically for natural resource management.	Structured into three modules: definition of system entities and interactions; control of the dynamics and; observation of the simulation.	Cormas.cirad.fr/en/outil/outchar.htm
DELFT-FEWS	WL Delft Hydraulics, Netherlands	Collection of modules to build a Flood or Drought Early Warning	Modular data processing and modelling system, complete with validation and interpolation modules	www.wldelft.nl/soft/fews/int/index.html

		System.	and a user-interface. Can be customised depending on the end-user	
MedWater Model	EC funded FP5 project 'MedWater'	Give a clear understanding of the consequences of policy decisions on all sectors of water chain. Give general concepts on how water can be saved or productivity increased. Analyse water competition in the Mediterranean basin.	MedWater is an MS Excel based model to determine the water balance of a region at the present and in the future. The present year is used as a base for calculating future water balance. Assumptions are easily modified in the regional context.	www.medwater.de/results.html
MIKE BASIN	DHI Software	GIS integrated simulation modelling tool for water availability analysis, infrastructure planning, analysis is multi-sectoral demands and ecosystem studies.	Addresses water allocation, reservoir operation and water quality issues. Easily coupled to ArcGIS.	www.dhisoftware.com/mikebasin/index.html
PCRaster	University of Utrecht, Netherlands	Dynamics System Modelling (DSM) tool for developing distributed simulation models in environmental modelling, hydrology, geography, etc. Examples include rainfall-runoff modelling, and slope-stability models.	A raster modelling environment that includes sophisticated GIS functionality. Uses a scripting language for constructing models describing processes through time. Models are easily constructed using the building blocks and functions.	www.pcraster.nl

POWERSIM	PowerSim Software AS, Norway	Model package to simulate complex models and decision making using Dynamic System Model (DSM) principles	Model can be used in order to experiment and test to find out more about a real system. Initially designed for business applications, but since extended. All variables are run in an integrated and dynamic way. Connects with Excel for input/output	www.powersim.com
SIMILE	Simulistics Ltd., Edinburgh Technology Transfer Centre, UK	Visual modelling software tool for the earth, environment and life sciences using Dynamic System Modelling techniques.	A visual modelling environment allowing you to draw the elements of the model and the relationships between them using system dynamics notation, adding influences between related variables. Code is compatible with C++, so can be used with other programs. GIS-compatible	www.simulistics.com
SIMULINK	The Mathworks, USA	Graphical modelling environment for MATLAB	Platform for multi-domain simulation and model-based design for dynamic systems. Provides an interactive graphical environment and is customisable and extendable.	www.mathworks.com
STELLA	Isee Systems, USA	A DSM tool for modelling the dynamics of highly inter-dependant systems	General purpose, and well-known. Can be used for a wide variety of applications (e.g. hydrological modelling, surface water quality management, hydro-ecological modelling, etc).	www.iseesystems.com
VENSIM	Ventana Systems Inc. USA	DMS tool for building general purpose simulation	Can integrate managerial and technical elements to solve complex problems.	www.vensim.com

		models of dynamic, complex systems	Can construct models of business, scientific, environmental and social systems. Provides monte-carlo sensitivity analysis.	
WaterStrategyMan GIS DSS	EC FP5 funded project WaterStrategyMan	Primary goal is to assess the state of a water resources system in terms of sources, usage, water cycles and environmental quality. The DSS can compare different water management options or single interventions under different scenarios. Different responses can thus be formulated.	An integrated GIS data editor, simulation model and results evaluation tool composed of a base-case editor, water management scheme editor and a results evaluator.	Environ.chemeng.ntua.gr/WSM/Newsletters/Issue5/Editorial_05.htm
WEAP (Water Evaluation and Planning System)	Stockholm Environment Institute, Boston Centre	Allocation of limited water resources between agricultural, municipal and environmental uses requires an integration of supply, demand, quality and ecological considerations. WEAP attempts to incorporate these into a robust tool.	Operates as a water balance database, a scenario generation tool (simulating supply, demand, storage, flows, treatment etc.) and a policy analysis tool (evaluates a range of water development and management options and takes account of multiple, competing uses of water systems).	www.weap21.org

Within WASSERMed some of these tools, namely System Dynamics Modelling (SDM) tool SIMILE, the Water Strategy Man Decision Support System (WSM DSS) and WEAP are of particular interest and they have been selected as the main water balance tools to be used for this project. For WASSERMed the water balance modelling will be undertaken using SIMILE in four of the case studies (Kairouan, Tunisia; Rosetta, Egypt; Jordan River Basin, Jordan; and Sardinia, Italy). The WaterStrategyMan Decision Support System (WSM DSS) is applied for the case studies of Syros Island, Greece and Rosetta, Egypt.

3. System Dynamics Modelling and SIMILE

3.1 System Dynamics Modelling introduction

System Dynamics Modelling (SDM) is a methodology for studying and managing complex feedback systems, typically used when formal analytical models do not exist, but when system simulation can be developed by linking a number of feedback mechanisms. Visualisation of the system components is via specific software. SDM allows for complex differential/integration equations to be simply solved. The visual nature of the interface allows for a user-friendly, participatory process (Ribarova et al., 2011), and can be used effectively as a decision support tool for stakeholders and experts.

Constructing, examining, and modifying System Dynamics Models follows an iterative approach, involving both the modeller and the stakeholder/local expert, and is thus ideal for use in a project such as WASSERMed. Starting from conceptual qualitative models representing the system, simple quantitative models with few feedback loops and little detail are built, so as to allow the construction of an initial working numerical simulation model (Atanasova, 2006). The working SDM model is then be modified and improved to show the desired level of detail and complexity (Haraldsson and Sverdrup, 2004).

Forrester (1961) introduced SDM in the early 1960's as a modelling and simulation methodology for long-term decision-making in dynamic industrial management problems. Since then, SDM has been applied to various business policy and strategy problems (Barlas, 2002; Sterman, 2000). Subsequently it has proven to be very useful for the simulation and study of complex environmental (Ford, 1999; Mulligan and Wainwright, 2004; Mazzoleni et al, 2004) and water systems (Simonovic, 2003; Chung et al, 2008) in an integrated way, and has been applied at a range of scales from local (Khan et al., 2009) to global (Simonovic, 2002; Kojiri et al., 2008).

In order to build a model using standard SDM techniques, system components are described as interlinked compartments (stocks), flows (directed links) and converters (influences) (Ford, 1999). Many specialised SDM software packages have been developed. The most prominent include: SIMILE (Muetzelfeldt and Massheder, 2003; www.simulistics.com), VENSIM (www.vensim.com), STELLA (www.iseesystems.com) and SIMULINK – an add-on to MATLAB (www.mathworks.com). These provide a graphical interface which adds to the participatory process, and is especially useful for those unfamiliar with programming. SIMILE and VENSIM have both been used successfully in previous EU Framework Programs, namely the EU FP6 project 'AquaStress' (Ribarova et al. 2011; Wintgens et al., 2009; Vamvakeridou et al., 2008). Mathematically, most existing SDM visual environments are similar.

SIMILE (Muetzelfeldt, 2010; Muetzelfeldt and Massheder, 2003; www.simulistics.com) has been selected as the primary software platform for implementing the quantitative (numerical) model for the case studies within WASSERMed (see Section 5). There are two reasons for this: (a) it efficiently supports breaking the model into sub-models thus facilitating the participatory development process of very complex systems and; (b) it can automatically produce model documentation in C, thus making the model potentially re-usable for further specialised applications, if necessary.

3.2 SDM application procedure

Within WASSERMed a highly interactive process will be applied between two different groups of participants. The first group consists of “experts”, who define, describe and suggest various technical options to be potentially applied for solving a problem (i.e. mitigating water stress) for each specific case study. It is noted that the group of experts, i.e. WASSERMed partners and researchers, has been deliberately chosen to be interdisciplinary, including non-engineers (i.e. from socio-economic disciplines). This adds to the complexity of the procedure, as far as mutual understanding is concerned. The second group comprises local stakeholders, who present the case study to the experts, together with initial suggestions for solving the problem, listen to further suggestions, and react to them by accepting / rejecting/modifying them, and finally implementing the agreed-upon solution(s). The local stakeholder involvement is crucial, as it is they who are the experts with regard to their individual study areas, and can therefore challenge and modify potentially incorrect assumptions made regarding system structure or operation for example.

SDM will be applied for modelling the complex water system of the various case studies according to the following step-by-step procedure:

- Initially all (case study specific) water security threats will be defined per study area.
- Problem identification then occurs at system-level for the water quantity and quality in the five different water systems, together with the description of a hypothesis explaining the cause of the problems. This step requires interactive cooperation between experts and stakeholders, and will taken place through consecutive meetings, workshops and teleconferences.
- Develop a dynamic hypothesis explaining the cause of the problem (**SDM: Conceptual model**). The conceptual (qualitative) model diagram for each system/case study is built, by combining and linking several technical options, again through an interactive procedure. The conceptual model is not linked to any specific software program and is merely a schematic representation of the system under consideration.
- Development of the computer simulation model (**SDM: Quantitative model**) for each case study. This development will be undertaken primarily by UNEXE, with input from case study partners.
- Test the model. The SDM model will be continually updated and revised by technical meetings, exchange of information and discussions.
- Use the model to produce and assess alternative options. The final SDM models will be aimed at generating alternative scenarios, exploring factors, policies and impacts, aiming at supporting the decision making process.

Schematically the procedure for the application of SDM is shown in Figure 1.

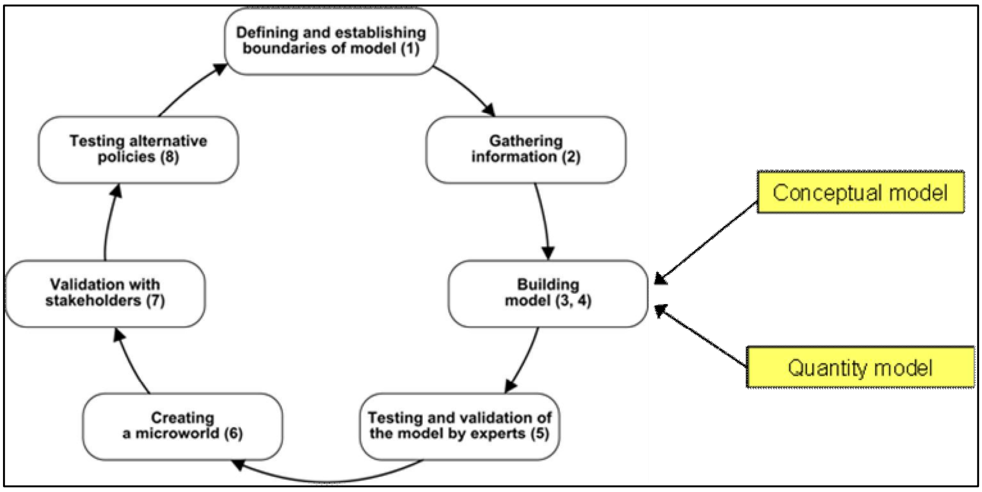


Figure 1: Schematic representation of SDM development.

3.3 Conceptual models

Conceptual models are diagrams of key variables and interactions, representing the dynamic nature of a system, including interconnections, feedback loops and delays. Such graphical tools are generally transparent and easy to understand, especially for non-specialists. Establishing a conceptual model is a demanding task because the processes involved are dynamic, interdependent, complex and non-linear, and these processes may not be completely understood.

Each model must be designed to answer specific questions, and should start by defining the system boundaries, the goal of the model and the key interactions. Only once this conceptual model is well defined should numerical modelling proceed.

The use of a conceptual model leading to formal SDM development offers the advantage of being able to partition a very complex system into number smaller sub-systems describing different elements of the larger system, making the quantitative modelling process more manageable. Conceptual models can be developed for each sub-system, then linked together to form an overall model of the larger system under consideration.

Conceptual models are generally represented as diagrams showing key system components interconnected with directed arrows. It can be drawn without being linked to a specific software tool and/or environment, thus consisting the initial approach to the system and/or problem definition (Figure 1).

In SDM there exist two types of conceptual diagrams (Figure 2; Ford, 1999): a) flow diagrams with arrows representing inputs/outputs to/from system components. These generally tend to be more user-friendly, and; b) causal loop diagrams where directed arrows are signed either positively (+) or negatively (-) depending on whether interconnected variables change in the same or opposite directions when they affect each other.

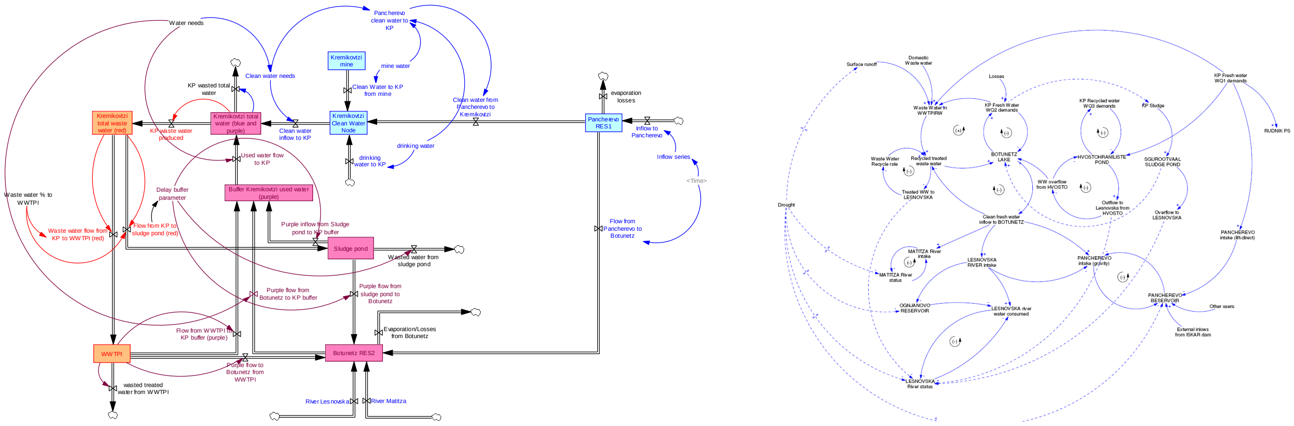


Figure 2: Example of a flow diagram (left) and casual loop diagram (right) conceptual model (from AQUASTRESS, 2008).

The conceptual modelling that will be applied on WASSERMed is independent from algorithmic or software specifications, but it does allow for the subsequent implementation of an SDM. According to SDM terminology, each system comprises three components:

- Stocks. These represent nodes in the system where water is stored/accumulated, and in real life may be lakes, reservoirs, etc.

- Flows. These are shown as arrows in conceptual diagrams, and represent links and connections between system components. There can be no storage or alteration or mass or volume within a flow.

- Converters. These are system components that modify storage at the stocks or the flow between two components. Converters may be thought of as inflows to a system (e.g. precipitation), losses from a system (e.g. evaporation) or water users. Other converters may also exist that are specific to a system under consideration.

One of, if not the main advantage of SDM, as compared to any other water balance modelling tool, is the flexibility of accepting any kind of parameters as stocks, converters, flows etc. In this way it is possible for the user to define input/output forms specifically suited to the aims and purposes of the simulation. It is therefore possible to develop water balance models that will automatically give as output to the decision maker suitable values related to water security issues. All other types of water balance modelling offer a limited choice in this respect, restricting input/output formats to hydraulic/hydrological parameters and time series, which will need to be transformed by the user to the desired form.

3.4 Quantitative models and SIMILE

As noted above, SIMILE (Muetzelfeldt, 2010; www.simulistics.com) will be the main software package to be used in this WP to construct and develop the System Dynamics models for the project case studies. SIMILE is a visual modelling environment which has been designed to overcome various problems originally associated with agro-ecological modelling but is also applicable to other areas of study. These problems include the skill required to program a model, the lack of transparency and the lack of re-useability of existing models (Muetzelfeldt and Massheder, 2003) and the inability of some models to be able to handle many interconnected sub-systems simultaneously (Muetzelfeldt, 2010). SIMILE combines System Dynamics and object orientated paradigms, which allows for multiple levels of disaggregation to be handled, as well as spatial modelling. The visual environment makes it accessible to non-programmers, while more competent users can develop their own visualisation tools (Muetzelfeldt and Massheder, 2003). Moreover SIMILE is a SDM tool that has been developed specifically for ecology applications and/or environmental systems, and not the business applications as with many of the other SDM tools.

The main features in SIMILE are (Muetzelfeldt and Massheder, 2003; Muetzelfeldt, 2010):

- A visual modelling environment split into two phases. The first phase represents the model and its components, while the second attributes these components with suitable values and equations.
- Use of System Dynamics terms and components, such as stocks, flows etc.
- Disaggregation. SIMILE allows many levels of disaggregation to be handled, for example a population by age/size/etc.
- Object-based modelling. This allows any population of objects such as population or vegetation to be modelled.
- Spatial modelling. Spatial units such as grid cells or polygons are defined, and each unit is modelled separately. Each spatial unit can be given spatial statistics such are location and area, and the proximity to each other can also be specified.
- Modular modelling allows any SIMILE sub-model to be inserted into any other SIMILE model. The modeller then makes manual links between the inserted sub-model and the main model. Conversely, any sub-model can be extracted and run as a separate model in its own right.
- Fast simulation. Because models can be compiled in C++ if desired, runtime can be significantly sped up.
- Customisable output displays and input tools can be written by the user to suit the requirements of the specific model.
- Declarative representation of the model structure, with the model stored in separate statements in an open, unstructured text file. This allows any other group/developer to create additional SIMILE tools, promoting sharing of models and knowledge.

Because of SIMILE's visual nature, ease at which sub-models can be disaggregated into simpler sub-models, model self-documentation, the problems of conventional modelling practice especially making the models inclusive for non-specialists, have been overcome. What sets SIMILE apart from similar Systems Dynamics models is its ability to specify multiple instances of a single entity and to dynamically link many inter-related sub-models (Muetzelfeldt 2010). This makes spatial modelling far simpler when compared with other similar software packages. Full model details, including an example model are described in Muetzelfeldt and Massheder (2003) and in Muetzelfeldt (2010).

3.5 SDM applied for the 'AquaStress' project

A System Dynamics Model approach, similar to the one proposed here, has been successfully employed on a previous EU Framework Project: AQUASTRESS (EU FP6). AQUASTRESS: Mitigation of Water Stress through new Approaches to Integrating Management, Technical, Economic and Institutional Instruments (AQUASTRESS 2006) was an EC FP6 IP project (2005-2009), comprising 35 international partners and eight case studies, which differ considerably both in technical and spatial/societal terms. Some of the case studies involve agriculture/irrigation/water allocation issues, while others focus on urban/industrial water quantity/quality problems. The case study locations range from Northern Europe to Northern Africa. Most case studies involve re-cycling/re-use and/or re-allocation of water, whose water quality in turn varies over time and space.

In AQUASTRESS, the six-step model-development procedure outlined above was implemented (Ribarova et al, 2011). Firstly, various technical options were investigated for mitigating water stress. Each option was examined, assessed and considered for each case study test site. The options were then combined using conceptual modelling and SDM to represent to complex water systems being modelled. The Aquastress SDM models, built in SIMILE were applied to two case study areas: the Kremikovtzi plant in Bulgaria and the Merguellil Valley in Tunisia.

The Kremikovtzi case study modelled industrial water use, focussing on water re-use and management practices. The SDM looked particularly at reducing the industrial plants' fresh water needs, improving the rate of water re-use and studying the operating procedures during dry and very dry years. Following conceptual model development, SDM models were constructed in two pieces of software: SIMILE and VENSIM. The highly-complex water system for the industrial plant was conveniently split into multiple sub-models in SIMILE covering various different aspects of the plant (e.g. sub-models for domestic waste-water, the sludge pond and clean, fresh-water) (Figure 3; Vamvakeridou et al, 2007; Vamvakeridou and Savic, 2008).

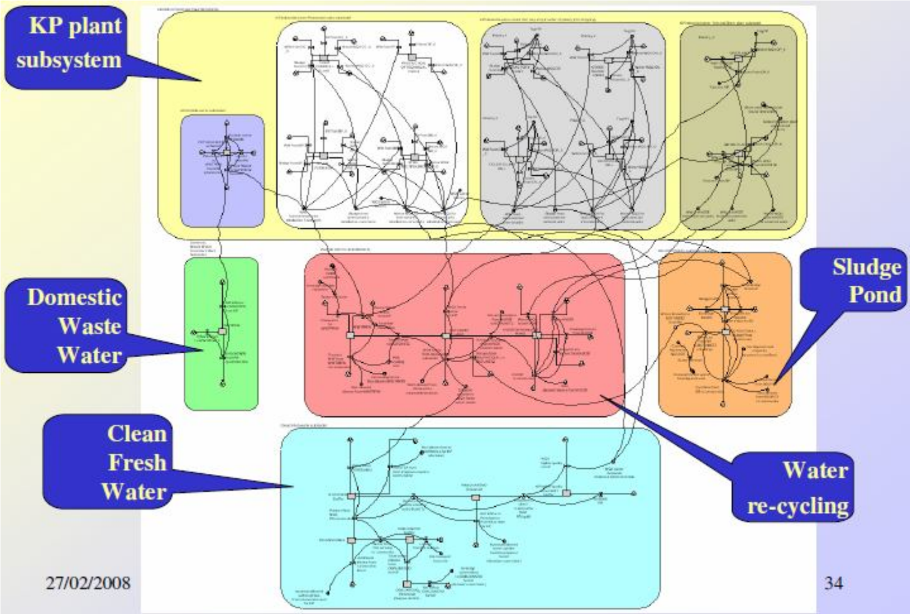


Figure 3: Final SDM model (in SIMILE) for the Kremikovtzi industrial plant.

The Merguellil case study was more hydrologically-focussed, and looked at improving agricultural water use and the recharge of water to aquifers. Following the SDM model building step-by-step procedure, a conceptual model was initially derived, followed by a first draft SDM model built using SIMILE. Over a period of iterations, the SDM mode was refined and complexity was added to better represent the system being studied. The final was divided into a number of smaller sub-models representing various parts of the water (Figure 4; AQUASTRESS, 2008).

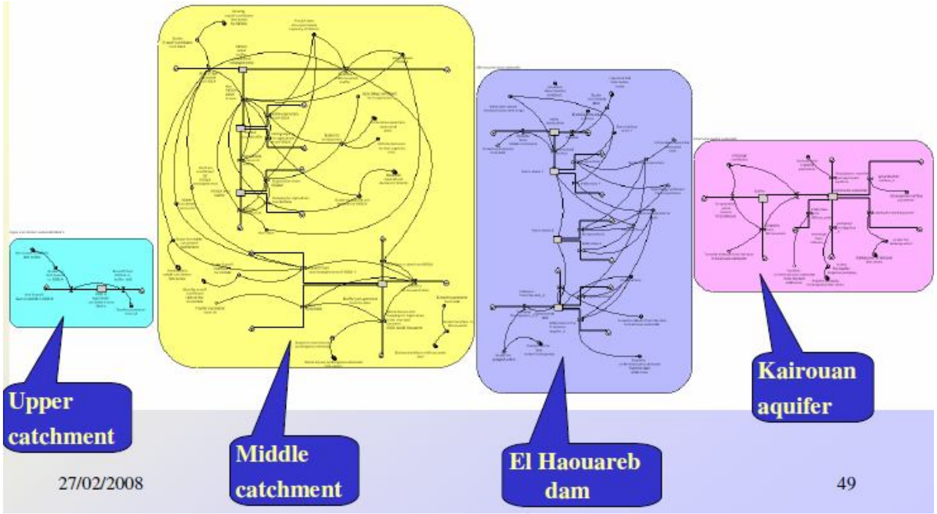


Figure 4: Intermediate SDM model (in SIMILE) for the Merguellil valley case study.

The above examples illustrate the flexibility of the SDM procedure: not only can it be used for industrial studies, but it is also a highly effective tool for studying natural systems and integrated natural-human systems. Further details of these two SDM case studies, their application within AQUASTRESS and the results are described in Vamvakeridou et al. (2007), AQUASTRESS (2008), Vamvakeridou and Savic (2008), Vamvakeridou et al. (2008), Ribarova et al. (2011) and Wintgens et al. (2009).

4. The WaterStrategyMan Decision Support System (WSM DSS)

4.1 Introduction

The WaterStrategyMan Decision Support System (WSM DSS) was one of the main final outputs of the WaterStrategyMan Project ("Developing Strategies for Regulating and Managing Water Resources and Demand in Water Deficient Regions"). The WaterStrategyMan project was funded by the EC through the 5th Framework Programme (Contract No: EVK1-CT-2001-00098), and was coordinated by the School of Chemical Engineering of the National Technical University of Athens, Greece.

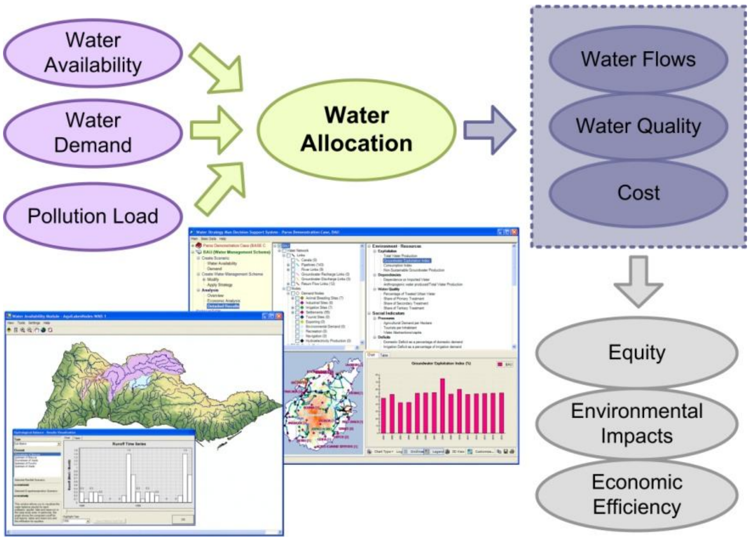


Figure 5: A schematic overview of the WSM DSS capabilities

The WSM DSS was developed with the objective to support the assessment of the state of water resource systems and to facilitate the simulation and evaluation of different scenarios and water management options in areas facing permanent or temporary water scarcity (Todini et al., 2006). It combines a hydrological model, a water demand and pollution load estimation model, and a simulation model for water allocation that minimizes water shortage under limited water availability (Manoli et al., 2001). It further includes models for economic water value and gross benefit assessments, and cost estimations. Costs can be allocated to corresponding use(r)s, on the basis of generalized graph algorithms. All the above components are integrated in a holistic environment, which allows the representation of water systems as networks of nodes, representing water supply sources, infrastructures and demands, and links, which stand for their physical or conceptual interconnections. Additional capabilities of the software package include modules to support the evaluation of water management options or plans by estimating and aggregating time series of indicators on the basis of statistical criteria. As it embeds both hydrological and economic aspects, the WSM DSS is considered a hydro-economic model, as it embeds economic analysis concepts in the assessment of water allocation schemes and the evaluation of water management options and scenarios (Manoli et al., forthcoming; Harou et al., 2007).

Within the framework of the WaterStrategyMan project, the WSM DSS was applied in river basins and regions across the Southern EU and Israel (Paros Island, Greece; Ribeiras do Algarve, Portugal; Tenerife, Spain; Tel Aviv wider area, Israel; Limassol region, Cyprus). After 2004, its implementation and validation continued in insular areas of Greece (Syros, Naxos, Samos, Ikaria), in Portugal (Ribeiras do Algarve and Guadiana) and in Cyprus, within the framework of the AquaStress Project.

4.2 The WSM DSS framework

The WSM DSS is a GIS-based package that emphasizes on the conceptual links between the different components and aspects of water resource systems. The overall approach and modules were conceptualized and formalized under the **"Drivers-Pressures-State-Impacts-Responses"** structure of indicators (DPSIR). Two pre-processors (modules) of the DSS are used to assess freshwater availability and demand, in order to estimate pressures exerted on the water system by external driving forces. These can include climate change and hydrological variations, demographic growth, agricultural development, changes in land use patterns, etc.

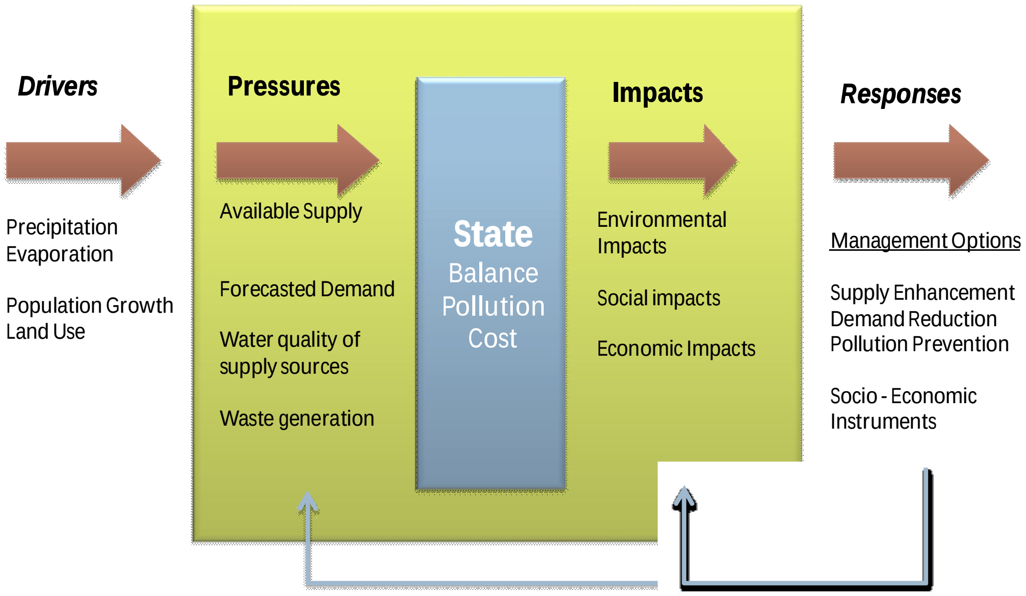


Figure 6: The analysis framework of the WSM DSS

The simulation of the state of the water resource system, under different scenarios on pressures is performed by two modules, for **water allocation** and **water quality estimation**, the former being the kernel of the DSS algorithms and computations. Finally, the assessment of impacts is based on the computation of different sets of indicators, which are further processed to assess the overall sustainability of the system, through the estimation of statistical criteria for reliability, resilience and vulnerability, for individual indicators. Through this approach, alternative scenarios, water management options and integrated plans can be compared and evaluated through multi-criteria analysis, based on user-defined weights.

The operational framework of the DSS is based on the concept of a water management scheme (WMS), defined as a set of scenarios for external drivers, and the application of one or more water management interventions. A WMS is defined in terms of a database containing information on the water infrastructure at a certain region and reference year (the baseline conditions), from which the simulation of scenarios and options begins. A base case is always present, serving as input for the creation of new WMSs. User interaction with the DSS falls under three functional groups, accessed via a hierarchical navigation tree: (1) base case editing, allowing for the editing and introduction of new data for a reference (baseline) year; (2) creation of WMSs, providing the capabilities for defining scenarios on water availability and demand, definition of water management options, and simulation and visualization of results; and (3) evaluation, which permits the comparison of different WMSs, using a predefined set of indicators.

The modelling of water systems

In the WSM DSS, water systems are modelled on the basis of geometric networks. A geometric network is described as a set of junctions (points) and edges (polylines) that are topologically connected to each other.

In the Object Model of the DSS, junction elements are conceptualized as water nodes while the connections between them are the water links. Network elements are drawn over the map of the area under consideration. Water nodes are classified into three categories, (1) supply nodes standing for alternative water supply sources and characterized by a monthly available supply; (2) demand nodes, modelling water uses and flow requirements; and (3) transshipment nodes standing for treatment plants and other junctions (Figure 7).

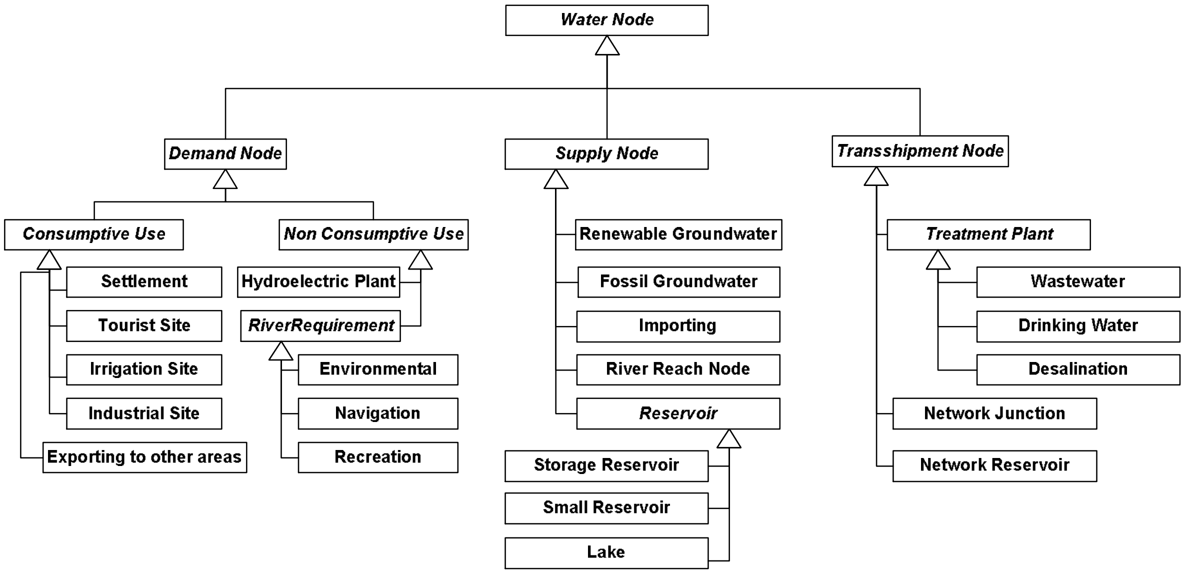


Figure 7. Overview of the categorization of different water nodes

Water link objects are classified in four categories according to connectivity rules among the different nodes and the particular modelling requirements of the DSS: (1) supply links (pipelines and canals), conveying water from supply to demand nodes; (2) conceptual groundwater interaction links (recharge and discharge), representing the natural interaction between surface and groundwater bodies; (3) return flow links, conveying return flows from consumptive demand nodes to receptor bodies (surface or groundwater) or wastewater treatment plants; and (4) river links, representing the natural course of a river water body.

The conceptualization of water management options

A characteristic of the DSS is that it predefines a number of 'abstract' water management options" (actions) and incorporates them as methods into the system. These methods modify accordingly the properties of the components of the water resource system, or introduce new ones, related to water infrastructure development. An 'abstract' action becomes 'application specific' by the user-definition of its magnitude, time horizon and geographic area of application. Incorporated actions are mainly focused on measures to deal with the frequent water shortages occurring in arid regions. Their aim is to either enhance supply, promoting the protection of vulnerable resources through structural interventions, or to regulate demand through conservation measures, technological adjustments for increasing the efficiency of water use, and pricing incentives. Instruments and measures not available in the DSS can also be modelled through changes to the conceptual representation of the water resource system or to the individual attributes of its components.

Table 2: Management options included in the WSM DSS

Policies	**Management options**
Supply Enhancement	o River diversions, dams reservoirs o Borehole and well drilling o Desalination o Inter-basin transfer o Water Reuse and artificial groundwater recharge o Conjunctive use
Demand Management	o Quotas, Regulated supply o Irrigation method improvements o Conservation measures in the home o Recycling in industry and domestic use o Improved infrastructure to reduce losses (networks, storage facilities)
Social-Developmental Policy	o Introduction of less water-intensive crops/change of cropping patterns o Change of regional development policy
Institutional Policies	o Water pricing, Cost recovery, Incentives o Environmental standards, recovery of environmental damage costs (penalties and fines)

4.3 Overview of modules and algorithms

Water Availability Module

The pre-processor for water availability estimations is used for computing the amount of water available at each water supply node, focusing particularly on freshwater supply sources (surface or groundwater). The assessment can be based on a lumped water balance at the watershed scale, based on the hydrological modeling approach known as the ARNO Rainfall-Runoff Model (Todini, 1996). Required input data concern rainfall, temperature and reference evapotranspiration for the entire simulation horizon. Scenarios for these variables can be generated in three alternative ways: (1) by repeating the average year, or a user-customized year, for the entire duration of the simulation; (2) by defining an annual or monthly increment over the entire horizon, thus determining a yearly or monthly trend; or (3) by building up a sequence of user-customized hydrological years.

As alternative, water availability scenarios can also be generated by assuming variations of freshwater availability compared to a normal (average) year for each water supply node, thus avoiding hydrological balance estimates.

A stochastic option is also available for generating forecasted discharge time series based on the statistical analysis of historical data. The produced time series maintain to the greatest extent the statistics of the historical data, such as mean value, standard deviation and skewness.

Water Demand Module

The water demand module produces forecasted monthly time series of demand for all uses, based on user-defined trends on the driving forces that are most likely to have an effect on water demanded for various purposes (domestic use, tourism, agriculture, hydroelectricity production, industry etc.).

In addition to this a priori estimation, a demand feedback loop is also incorporated in the WSM DSS, which can be used to simulate responses to demand management options, or the impact of socio-economic reactions to measures restricting the allocation of water supply to specific uses.

Water Allocation Module

Water allocation is the kernel of the WSM DSS, and is performed through a simulation model, which minimizes water shortage under limited water supplies. The implemented algorithm at each time step estimates the flow on the network (that is, a set of link flows) that minimizes the water shortage on all demand nodes under four types of constraints: supply, demand, flow conservation and capacity. The model, which is non-linear due to system losses, is solved by first constructing a reduction to a standard MaxFlow problem and then using the Ford-Fulkerson method, also known as the augmenting-path maximum flow algorithm.

For distributing the water available from the various supply sources to the connected uses under shortage conditions, two user-defined priority rules are applied. First, competing demand sites are treated according to specified priorities. Priorities can express social preference or constraints, economic preference (prioritization to activities with highest economic values), or a system of water rights. Where a particular use can be supplied by more than one resource, supply priorities are used to rank the choices for obtaining water. Supply priorities in this case express: (1) cost preference; (2) quality preference of uses (for example domestic or industrial use) for supply sources with high water quality; (3) need for environmental protection of resources and for ensuring strategic reserves to enhance resilience to extreme events (droughts).

Economic Analysis Module

One of the innovative elements of the WSM DSS is its capacity to perform an economic analysis for the estimation of financial, environmental and resource costs associated with water resource use and exploitation.

The assessment of costs assessments in the WSM DSS expand beyond financial costs for the operation of the current water system and capacity expansions, to include also external environmental and resource costs. On the basis of the water allocation performed by the core model, the DSS estimates financial, environmental and resource costs linked to water management interventions and allocation, and distributes these to water use(r)s. The estimation of financial costs is straightforward, depending on data entered for the amortization of capital investments, specific energy consumption and cost, and other infrastructure operation and maintenance costs, as well as demand management interventions. A distinction is made between measures that are implemented by the managing authorities or water service providers (e.g. infrastructure) and costs of demand management options that are directly borne by individual users.

External environmental costs are approximated using a generalized cost-based approach, and are calculated on the basis of: (a) user-defined unit costs that can be estimated according to the cost of measures required to mitigate or compensate environmental impacts, (b) impact coefficients to account for the sensitivity of each water body, and (c) threshold values to denote the level above which abstraction or discharge of pollution loads can result in significant environmental impacts.

Resource costs are estimated on the basis of the scarcity rent of the water resource, defined as the shadow value of water in situ (Fisher and Askari, 2001). They have been defined as the difference between the opportunity cost of water and the per unit costs of turning that natural resource into products (for example agricultural crops, industrial production etc.). The estimation of opportunity costs is based on the computation of the use value for each demand node. Values for irrigation are estimated according to the revenues from crop cultivation and the alternative value of land, whereas for animal breeding they are associated with net profit from livestock. Water values for industries are a function of the yearly production and the value of the product unit, while for the domestic sector these can be based on the urban demand curve or on the marginal cost of the most expensive supply source in use

The allocation of estimated financial, environmental and resource costs is performed on the basis of quantities abstracted or pollution discharged which determine: (a) the share of capital, and operation and maintenance costs that should be allocated to each use(r) and (b) the share of environmental and resource costs incurred from overexploitation, pollution discharges or inefficient allocation. Results can be further used to define water charges and mechanisms to recover different cost elements; a relevant iterative process can be found in Manoli and Assimacopoulos (forthcoming).

Evaluation and Multi-criteria analysis

On the basis of results from the above modules, the WSM DSS estimates time series of indicators, which characterize the various spatial entities of the water network. Furthermore, additional indicators for each WMS are computed by aggregating individual results, concerning freshwater exploitation, dependencies, water quality, pressures, deficits, cost/revenues and water quantity (Table 3).

Table 3: Indicators Implemented in the WSM DSS

Category	Indicator	Levels of computation
Resource Exploitation	Total Water Production	Overall (aggregated)
	Groundwater exploitation	Overall (aggregated)

Category	**Indicator**	**Levels of computation**
	index	
	Consumption index	Overall (aggregated)
	Non-sustainable production index	Overall (aggregated)
Dependencies	Dependence on imported water	Overall (aggregated)
	Anthropogenic water produced over total water production	Overall (aggregated)
Water Quality	Percentage of Treated urban water	Overall (aggregated)
	Share of Primary Treatment	Overall (aggregated)
	Share of Secondary Treatment	Overall (aggregated)
	Share of Tertiary Treatment	Overall (aggregated)
	Concentrations of quality variables	Pipelines, River Links, River Reach Nodes, Canal, GW Recharge/Discharge Link, Return Flow, Importing, Lake, Small Reservoir, Storage Reservoir, Fossil GW
	Concentrations of quality variables in inflows and return flows	Irrigation, Settlement, Exporting (only inflow), Waste Water Treatment Plant, Industry, Tourist, Environmental + Navigation + Recreational (only inflow), Drinking Plant, Hydroelectricity Production (only inflow)
Pressures	Agricultural demand per hectare	Overall (aggregated)
	Tourists per inhabitant	Overall (aggregated)
	Water abstractions per capita	Overall (aggregated)
Deficits	Specific Water use Deficit as a percentage of the specific water use demand	Overall (aggregated)
Cost/Revenues	Total Direct Cost	Overall (aggregated), Irrigation, Settlement, Industry, Tourist, Hydroelectricity Production
	Total Benefit from water use	Overall (aggregated), Irrigation, Settlement, Industry,

Category	**Indicator**	**Levels of computation**
		Tourist, Hydroelectricity Production
	Total Income	Overall (aggregated), Irrigation, Settlement, Industry, Tourist, Hydroelectricity Production
	Environmental Costs for abstractions and pollution	Overall and per sector, Irrigation, Settlement, Industry, Tourist
	Revenues	Overall (aggregated)
	Overall Rate of Cost Recovery	Overall (aggregated)
	Rate of cost recovery without Environmental costs	Irrigation, Settlement, Industry, Tourist
	Rate of cost recovery with Environmental costs	Irrigation, Settlement, Industry, Tourist
	Annualized Capital Costs	Pipelines, River Reach, Waste Water Treatment Plant, Network Reservoir, Canal, Importing, Lake, Small Reservoir, Storage Reservoir, Fossil GW, Renewable GW, Desalination, Drinking Plant
	Total Water Transfer Costs	Pipelines, Canal
	Running Cost	Pipelines, River Reach, Waste Water Treatment Plant, Network Reservoir, Canal, Importing, Lake, Small Reservoir, Storage Reservoir, Fossil GW, Renewable GW, Desalination, Drinking Plant
	Total Supply cost	River Reach, Importing, Lake, Small Reservoir, Storage Reservoir, Fossil GW, Renewable GW
	Total Treatment Costs	Waste Water Treatment Plant, Desalination, Drinking Plant
Irrigation	Cultivated Area	Irrigation
Livestock Number	Livestock Number	Animal Breeding
Industry	Industrial Production	Industry
Water Quantity	Inflow	Pipelines, Network Reservoir, Canal
	Outflow	Pipelines, Canal

Category	Indicator	Levels of computation
	Losses	Pipelines, Canal
	Flow	River Link, GW Recharge/Discharge Link, Return Flow
	Demand	Irrigation, Settlement, Exporting, Animal Breeding, Industry, Tourist, Environmental, Navigation, Recreational, Hydroelectricity Production
	Supply Delivered	Irrigation, Settlement, Exporting, Animal Breeding, Industry, Tourist, Environmental, Navigation, Recreational, Hydroelectricity Production
	Unmet Demand	Irrigation, Settlement, Exporting, Animal Breeding, Industry, Tourist, Environmental, Navigation, Recreational, Hydroelectricity Production
	Losses	Irrigation, Settlement, Animal Breeding, Industry, Tourist
	Return Flow Volume	Irrigation, Settlement, Animal Breeding, Industry, Tourist, Lake, Small Reservoir, Storage Reservoir, Renewable GW
	Abstraction	River Reach, Importing, Small Reservoir, Lake, Storage Reservoir, Fossil GW, Renewable GW
	Total Run-off	River Reach, Lake, Storage Reservoir
	Groundwater recharge	River Reach
	Groundwater discharge	River Reach
	Return flows	River Reach
	Volume of Water Treated	Waste Water Treatment Plant, Drinking Plant
	Available supply	Importing
	Storage	Lake, Small Reservoir, Storage Reservoir, Fossil GW, Renewable GW
	Evaporation Losses	Lake, Small Reservoir, Storage Reservoir
	Seepage Losses	Lake, Small Reservoir, Storage Reservoir
	Natural Recharge	Renewable GW

Category	**Indicator**	**Levels of computation**
	Discharge	Renewable GW
	Drinking Water Production	Desalination
Hydroelectricity	Electricity Production	Hydroelectricity Production
Population	Permanent Population	Settlement
	Seasonal Population	Settlement, Tourist
	Total Population	Settlement

The evaluation of alternative schemes is based on a multi-criteria approach that takes into account the entire or part of the simulation horizon. As a first step, time series of indicators are computed. Selected WMSs can be compared through multi-criteria analysis, based on the estimation of statistical criteria for reliability, resilience and vulnerability for selected indicators (Bogardi and Verhoef, 1995; ASCE, 1998). These criteria measure the behaviour of the monthly or yearly time series of each indicator with respect to the predefined range of satisfactory values that the indicator can assume. Through the assignment of weights for each indicator, a total score is calculated for each Water Management Scheme, allowing for their inter-comparison and the selection of the most suitable alternative.

4.4 The WSM DSS in relation to SDM and WEAP

The WSM DSS is particularly suited for water balance modeling under scarcity conditions. Given that one of the dominant climate-induced risks identified in most Case Study areas is increasing water stress, the DSS is considered applicable for the simulation and evaluation of potential adaptation options. Furthermore, and as one of the key questions when developing adaptation policies is the identification of “no-regret” and “win-win” options, the economic assessment performed within the context of the DSS can help to identify potential benefits and costs over a long time horizon and for different climate projections/socio-economic assumptions.

In relation to the other two modelling environments that are being applied for water balance modelling in WASSERMed, the WSM DSS offers the opportunity of applying a structured way of analyzing water resource systems. It can thus be used by persons and stakeholders with limited expertise in water system modelling (as relevant interactions and attributes are automatically calculated by the model and do not require the building of the corresponding conceptual links).

Furthermore, the built-in capabilities of the system (e.g. estimation of irrigation requirements based on precipitation and evapotranspiration data) and economic analysis modules offer an easy and integrative way of simulating and cross-comparing scenarios and alternative options using the same set of indicators.

Finally, the use of a GIS environment helps to easily identify major water uses, and water system elements in a given area and build the corresponding water resource system to explicitly represent the current system, if this is required for the scope of the analysis.

5. Details of models constructed for each of the Case Studies

This section details the models developed for each WASSERMed case study to-date. Because the modelling process is ongoing at the time of writing, and because of the participatory nature of this development, with many iterations of the model going between UNEXE and local case study partners, the models presented here may eventually change before they are finally approved. Presented here are the latest iterations of each case study model.

For some case studies, it is stated in the WASSERMed DoW to use other modelling software other than Simile to assess the water balance by way of comparison between the models or for case-study specific reasons. Where this is the case, both models will be presented for the case study.

5.1 Kairouan, Tunisia

The Kairouan case study is the most advanced in terms of model development, with the model being all but complete. The model and its application for Kairouan are the core for two recent publications (Susnik et al, 2011a and Susnik et al, 2011b). In this case study, part of the model developed for Aquastress is used in a slightly modified form. Essentially, the Upper and Middle catchment elements and the El Haouareb reservoir sub-models have been retained (see Vamvakeridou-Lyroudia et al., 2008). The Aquastress model is outlined briefly below, but full details can be found in Vamvakeridou-Lyroudia et al. (2008). The major modification here is the total redevelopment of the Kairouan aquifer sub-model. This new sub-model, including all the components, is outlined later in this section.

As a base to the Tunisia SDM model, some of the Aquastress Merguellil model was used. This was mainly to retain a model which has been shown to accurately reflect this particular part of the system, and to prevent duplication of effort. The portion of the Aquastress model that has been retained comprises of three main sub-models (Figure 8). The first models the very upper, and relatively simple, part of the Merguellil basin (Figure 8). Rainfall is distributed over the area and using a transform coefficient, some is converted to runoff and subsequently routed to the middle catchment sub-model. No water is stored within or abstracted from the upper catchment sub-model.

The next sub-model represents the complex middle catchment of the Merguellil system (Figure 8). It receives water as input from the upper catchment sub-model. It also receives rainfall input, some of which is converted to runoff and routed either as infiltration into aquifers or into one of the 35 small dams built in the middle catchment. The middle catchment sub-model incorporates another, self-contained, sub-model that represents the functioning of these small dams. The dams receive input from rainfall and output as evaporation, pumping or infiltration into the substrate. Relationships have been derived that link the dam surface area to the water volume and the evaporate rate. Thus at each model iteration, the surface area is updated according to rainfall input and then evaporative losses are calculated along with withdrawals for agricultural use and infiltration. Then, the surface area is assessed again and a final volume at the end of that iteration is given. This procedure then repeats in the next model iteration.

The rest of the middle catchment sub-model accounts for rainfall input and evaporative and infiltration losses. Some water is routed to aquifers that either feed into the El Haouareb dam or the Kairouan aquifer directly. Most surface water is evaporated. The water that is not stored in the small dams, lost to evaporation, or routed to groundwater, is fed into the final sub-model, that representing the El Haouareb dam (Figure 8).

The El Haouareb dam sub-model works in a similar way to the small dams sub-model contained within the middle catchment sub-model. The reservoir surface area is given for the start of each model iteration and linked to volume. This is then updated for rainfall input. Then, a given proportion of the updated volume is evaporated from the surface, the majority is lost through infiltration down a fissure and some of what is left is pumped for agriculture. The volume is then updated again after all the outputs have been accounted for. This sequence is repeated at every model iteration. Water can also be lost due to planned releases if the lake level exceeds a threshold, but this is rare because for most of the last decade the reservoir have been (nearly) empty.

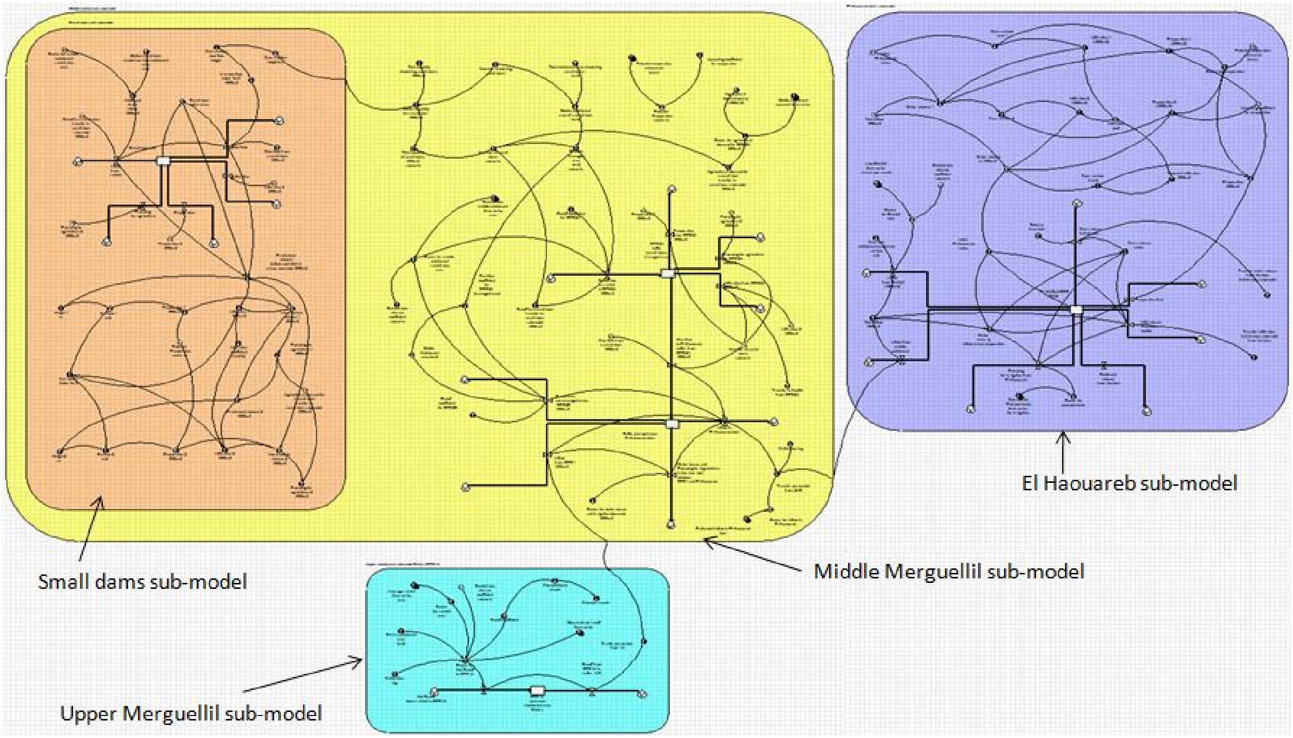


Figure 8: Section of the current model for the Merguellil valley, based on the previous model from the Aquastress project. Each sub-model explained in the text is labelled on the figure. Note that the small dams sub-model is a sub-model that in contained within the middle Merguellil sub-model. This is a feature which is heavily exploited in Simile for WASSERMed.

Outputs from the Aquastress model that serve as inputs to the newly developed Kairouan aquifer model are:

- infiltration beneath El Haouareb dam down the fissure and into Kairouan aquifer;
- planned water releases, a proportion of which recharges Kairouan aquifer;

infiltration recharge from the small dams in the middle catchment.

The Aquastress model did incorporate a very rudimentary sub-model to account for the Kairouan aquifer. However, as this was not the focus of that study, it was lacking in detail and realism. For WASSERMed, the old Kairouan sub-model has been completely redeveloped, and now incorporates the full range of processes required for this project. The new Kairouan aquifer sub-model (Figure 9) consists of two input sub-models, six output/abstraction sub-models and a separate sub-model for the selection of rainfall data. These inputs and outputs all feed into the main water balance component of the model (Figure 9). The new aquifer model was developed closely with the local partner, INAT.

The rainfall selection sub-model simply holds the data for both the baseline and future monthly rainfall totals. By changing just one value, either the baseline or the future rainfall can be selected for use as input to the rest of the Kairouan aquifer model.

There are two input sub-models. These comprise of a surface water input sub-model and of an infiltration input sub-model (Figure 9). The surface water input takes the rainfall time-series and any water released from the El Haouareb dam as inputs. For the water releases, an evaporation coefficient is applied to act as a loss, with the remaining water infiltrating. For the rainfall, firstly the rain is distributed over the entire catchment, which is unrealistic in this catchment. As such, a reduction factor is used to better represent actual rainfall input. Of this volume, a certain proportion is lost to evaporation, with the rest contributing to recharge. The infiltration input sub-model takes into account direct recharge from adjacent aquifers upstream of Kairouan and of the water that infiltrates down the fissure in El Haouareb dam. The surface water and infiltration sub-model inputs are summed, with this value representing the total input (recharge) to the main Kairouan aquifer water balance component.

There are six output/abstraction sub-models in the Kairouan aquifer sub-model: a model accounting for natural losses; a model accounting for anthropogenic transfers of water directly out of the aquifer; and models accounting for agricultural, domestic, industrial and tourist water use (Figure 9). All these models, except the natural out-transfer model, have been designed with the same structure, allowing easier interpretation and use by non-experts. The natural out-transfer model takes the volume of water naturally lost from Kairouan aquifer to other downstream aquifers and to a nearby Sebkha region. The sum of these accounts for the natural out-transfer.

All the other abstraction sub-models have the same structure (Figure 9), though they use different input data. They all have, as the basic input, the baseline (present-day) monthly water abstraction data. In order to allow for the testing of the future scenarios, a scaling coefficient is used which multiplies the baseline data according to future projections estimated by the local partner. This coefficient is different for each sector (domestic, industry and agriculture). By changing just one value in the sub-model for each sector, the modeller can choose to use as input either the present day data, the future data (i.e. present day scaled by the coefficient), or a policy option which is just another scaling coefficient which can be changed by the modeller to whatever value is desired in order to explore the impact of different policy measures.

The sum of all the abstractions represents water withdrawn from Kairouan aquifer. There is also an abstraction to take account of unofficial 'private' water use for agriculture. Because there are no data on this sector (it is unregulated), it is simply assumed to be some proportion of the public, regulated, volume. Finally, the model incorporates a feedback loop which accounts for the reuse of treated waste water. A proportion of the abstracted water for each sector is assumed to be treated and re-used. The sum from each sector contributes the total treated waste water re-use volume. This goes back into the main aquifer storage unit as a recharge that can be used again in the next model iteration. The new Kairouan sub-model is shown in Figure 9.

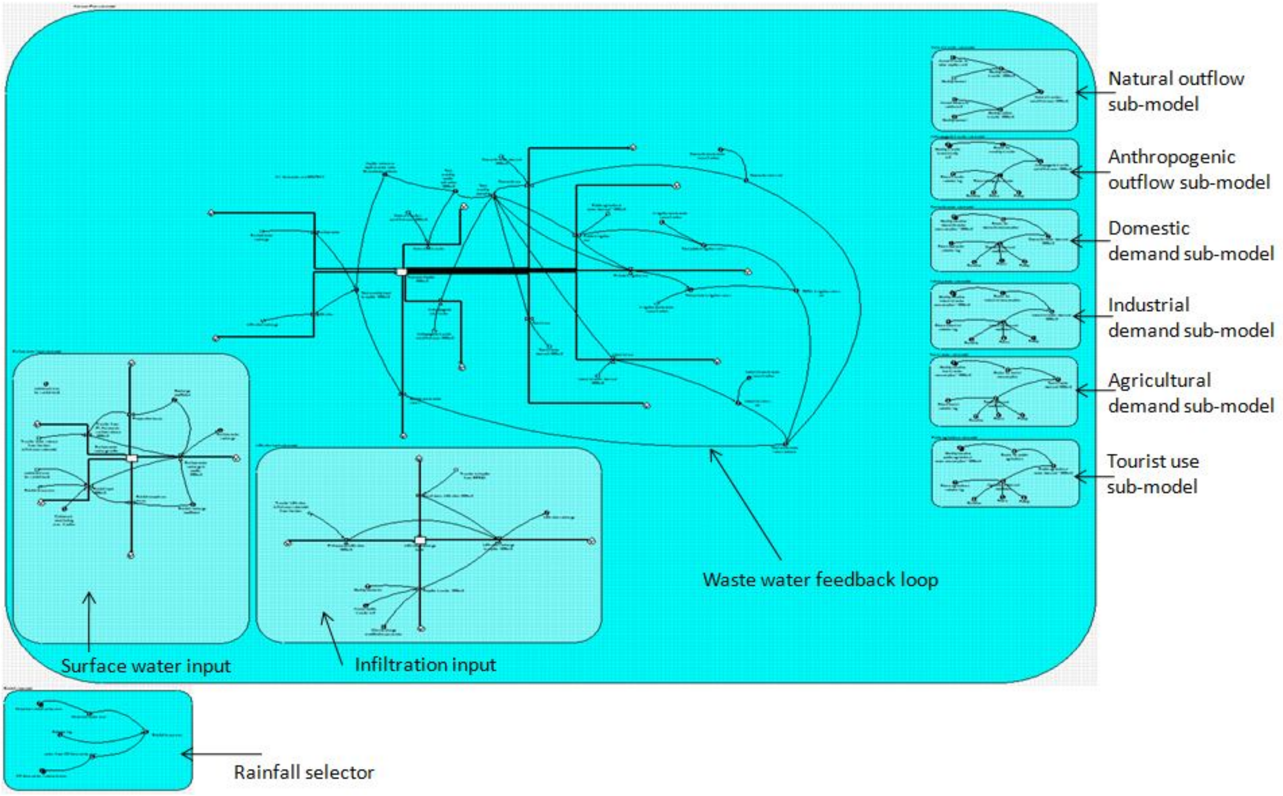
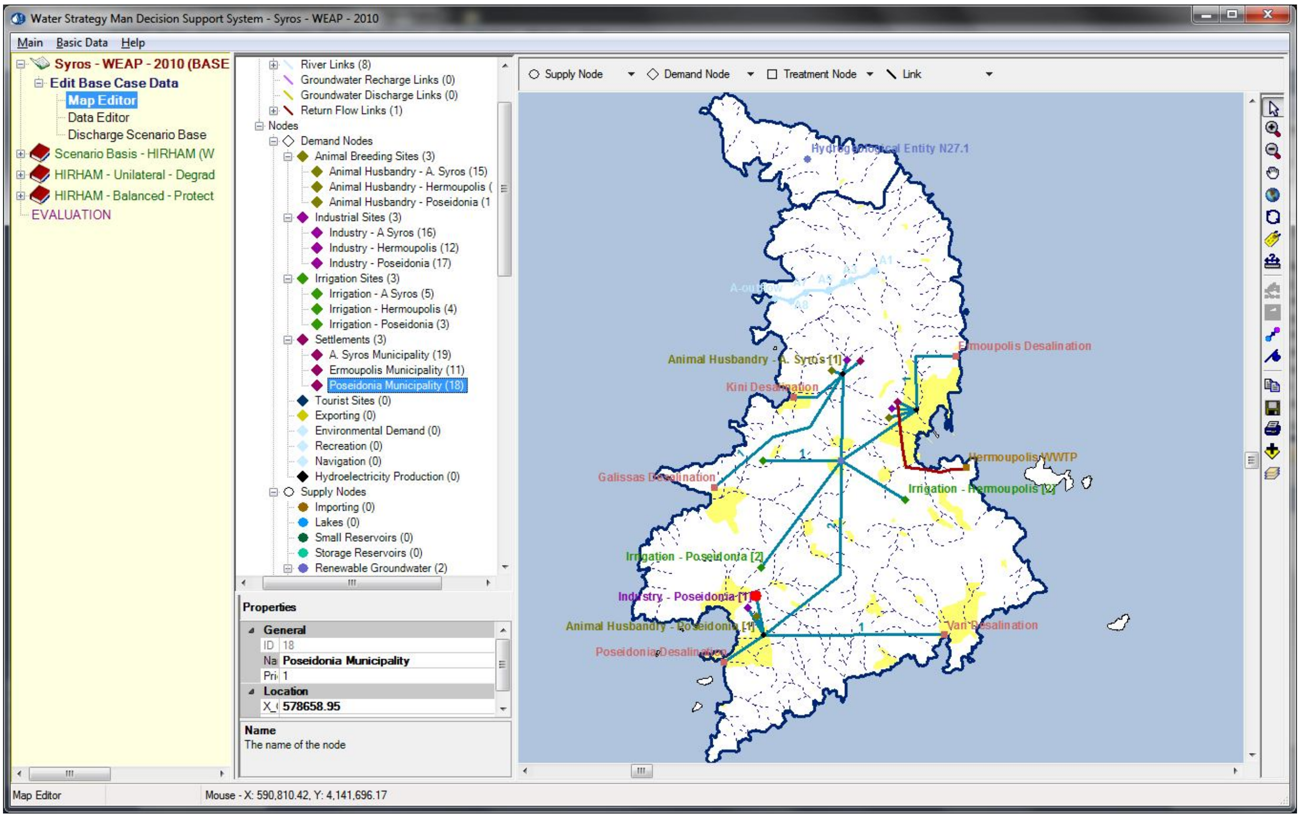


Figure 9: The newly developed Kairouan aquifer sub-model used in WASSERMed. This sub-model is directly linked to the sub-models shown in Figure 8.

5.2 Syros Island, Greece

The Syros Island water balance modelling is being carried out by NTUA using the WaterStrategyMan Decision Support System (WSM DSS). No SDM water balance model is being constructed for this case study. For comparison purposes, the conceptual representation of the Syros water resource system is based on previous work, undertaken by local authorities within the framework of a study by the Ministry of Development, aimed at developing water resources management plans (WMPs) in all Greek hydrological departments. Figure 10 presents the current schematization of the water resource system, in the WSM DSS.



ID 18
Name Poseidonia Municipality
Pri 1
X 578658.95

Name
The name of the node

Figure 10: The current water balance model for Syros in the WSM DSS depicting also the boundaries of hydrogeological entities (dark blue) and main agglomerations (yellow)

In more detail:

- The main sources of water supply in the island comprise groundwater and desalination. For groundwater, two hydrogeological units are defined, one corresponding to the small basin in the northern part and the other corresponding to the rest of the island. Monthly recharge for each hydrogeological unit is calculated externally, using input data on precipitation, evapotransipration and infiltration coefficients. A minimum volume for discharge towards the sea, equal to 33% of the aquifer storage capacity is also entered.
- Water uses are aggregated at the level of former municipalities (Poseidonia, Hermoupolis and Ano Syros). A distinction is made according to the type of use (domestic, urban, crop irrigation and livestock breeding). Water requirements are calculated at this level as follows:

    - For urban water demand according to the levels of permanent population, seasonal population (summer housing), overnight stays, per capita consumption for all categories, and losses in water distribution networks.
    - For crop irrigation, according to cropping patterns (a distinction is made between arable crops, vegetables, olive trees, vineyards and orchards), effective precipitation, evapotranspiration, areas equipped for irrigation and irrigation efficiency.
    - For livestock breeding according to the number of animals per type and demand per head;
    - For industry (secondary sector activities), no detailed estimation is made, as demands are minor and are not expected to further increase.
- Desalination capacity (maximum possible water production) is also aggregated at the level of municipalities.
- Wastewater treatment capacity for urban agglomerations is also aggregated at the municipal level.
- Economic information on water production costs and income from agricultural activities were derived through previous studies, and consultations with the Municipal Enterprise for Water Supply and Sewerage of Hermoupolis (urban water supply cost), and farmers (groundwater supply costs).

According to the current water supply and demand priorities and operating rules of the system, the following are applied:

- Domestic, industrial and livestock breeding demands have a higher priority than crop irrigation. Their primary source of water supply is desalination, followed by groundwater from the large hydrogeological unit;
- Crop irrigation has a lower priority and is supplied only by groundwater. Furthermore, additional restrictions are applied: according to current borehole capacity, only 65% of water demand can be met. An additional constraint of 80% in the water supply/water demand ratio is defined for the individual irrigation needs of the municipalities of Poseidonia and Ano Syros, to account for the current practice of deficit irrigation.

The current model was further used to perform a preliminary evaluation of future scenarios, incorporating climate projections based on the HIRHAM Regional Climate Model forced by the ECHAM5 and HadCM3 GCMs for the A1B IPCC scenario and socio-economic developments, describing a best and worst case scenario. Figure 11 presents preliminary results, focusing on irrigation demand coverage and groundwater abstraction.

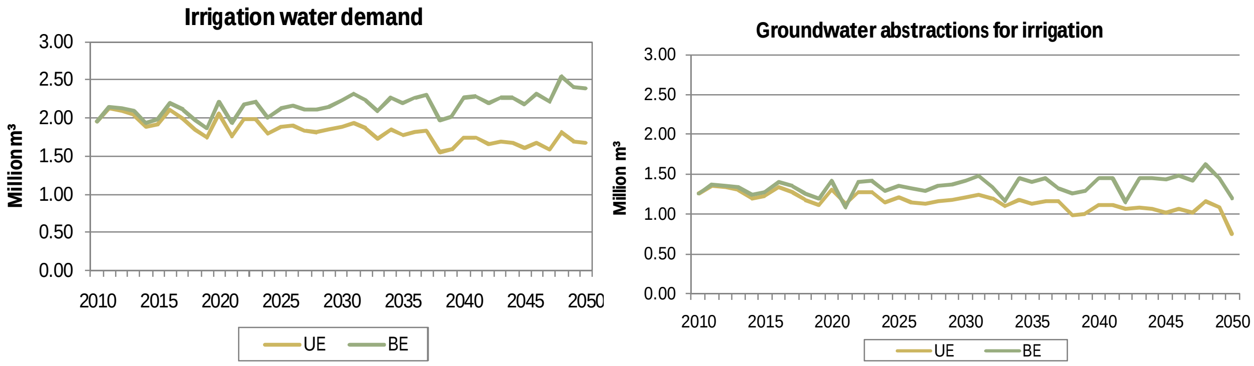


Figure 11: Preliminary results on irrigation water demand and groundwater abstractions for irrigation based on: (a) regional climate dataset from the HIRHAM climate model, and (b) two scenarios of socio-economic development, the Unilateral Economic Development scenario (UE) and the Balanced Economic Development Scenario (BE)

This, baseline representation of the water system, was extensively discussed with local stakeholders during the Syros workshop (17-18 June 2011), and the following corrections have been decided:

- The division into 2 hydrogeological entities does not offer an adequate representation of the current system. The main hydrogeological units of the island are 4, not interconnected and mainly used for irrigation water supply. Domestic water supply is met through groundwater in the villages of the rural hinterland.

- The current aggregation of desalination capacity does not allow the correct calculation of local deficits. According to the overall water balance results, the current capacity can very well meet local water demands even during the summer peak period; however, as desalination plants are not interconnected, this is often not the case (for example in areas of Poseidonia, the current desalination capacity is often marginal in meeting summer water needs). To that end, a more detailed representation of: (a) urban water uses, and (b) desalination units, is required.

- There is need to introduce rainfall harvesting within the model, as a 20% of irrigation water requirements is currently met through local cisterns and rainfall collected from the roof of greenhouses.

In addition to the above, further enhancements to the current water balance model will involve the use of more detailed data on cropping patterns and the introduction of tourism water demand projections, based on correlations with the Tourism Climate Index.

5.3 Rosetta, Egypt

Unlike the Tunisia SDM, the Rosetta model has been developed specifically for this project, and does not have any previous iterations. The SDM model has, as with all the case studies, been developed in cooperation with the local partner, ECRI. The latest version of the model at the time of writing is shown in Figure 12.

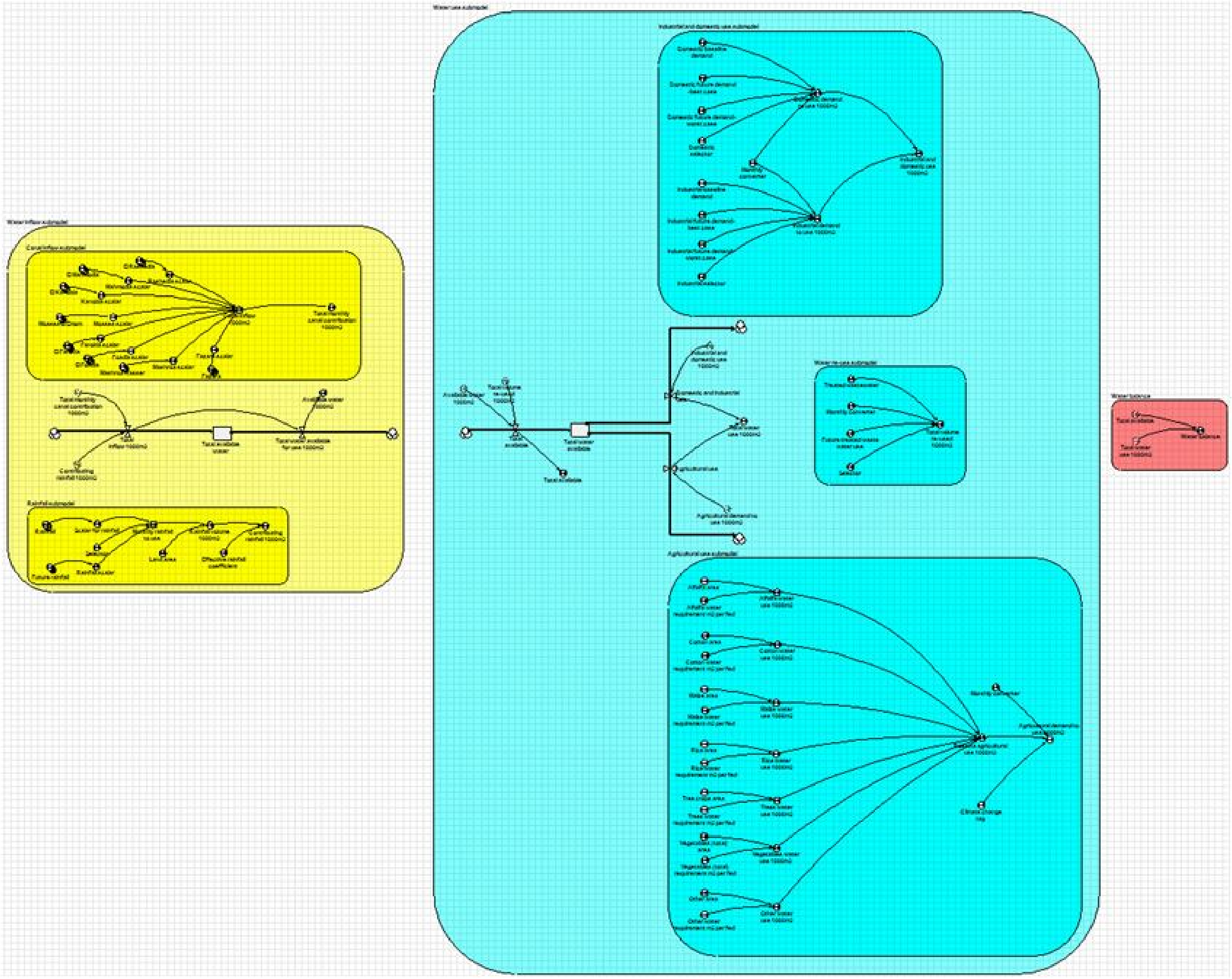


Figure 12: The latest version of the Rosetta SD water balance model.

The model has three distinct sub-models: a water inflow/supply model (left in Figure 12), a water use sub-model (large box in centre of Figure 12) and a sub-model that performs the final water balance calculation (right in Figure 12). Each of the sub-models will be discussed in turn.

The water input/supply sub-model (Figure 13) deals with water supplying the study area from rainfall and from canals which receive water from the Nile. This sub-model contains two embedded sub-models, one for the rainfall supply and the other for the canal water supply. For the rainfall, either the baseline or the future rainfall data can be selected, depending on the scenario that is being modelled. The rainfall depth is then scaled up by the total land area, then a reduction factor is applied in order to account for evaporation and the fact that rainfall does not fall evenly over the study area. The final value is the volume of effective (i.e. useful) rainfall delivered to the study area. For the canal water supply, the study area is fed by eight canals which take water directly from the Nile. Data are available for each canal. Therefore the monthly supply from each canal is simply summed to give a total monthly water supply from the canals. The canal supply is represented by the top embedded sub-model in Figure 13. The rainfall and canal supply totals are added together to give the total water supply available in the study area.

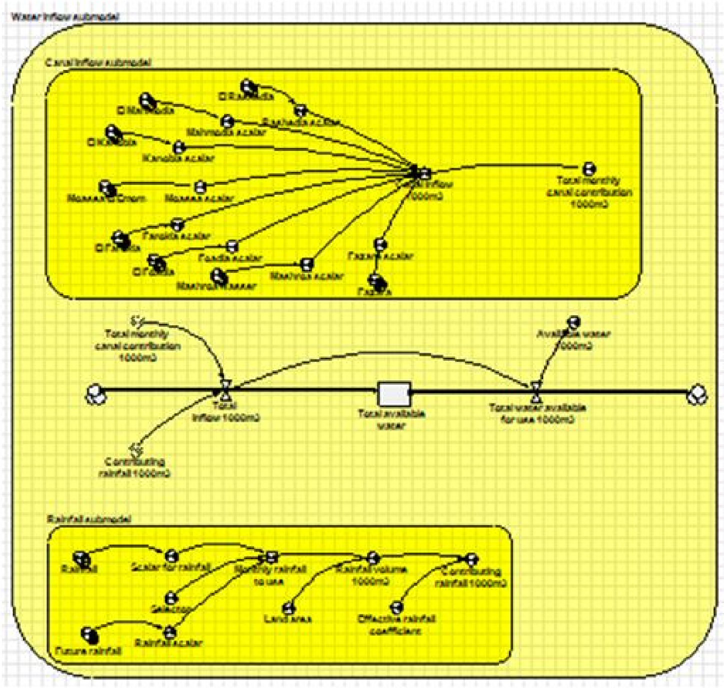


Figure 13: The water input/supply sub-model in the Rosetta SDM.

Figure 14 shows the sub-model for the water use in the Rosetta study area. For the Rosetta case study, industrial and domestic water demand are taken into account (top embedded sub-model in Figure 14), as is agricultural water demand (bottom embedded sub-model), by far the biggest water user in the study area. Also taken into account is waste water recycling and re-use (middle embedded sub-model). For domestic and industrial use, the modeller can choose to use as input either the baseline datasets or one of two future (2050) datasets. One of these represents the 'best' case, while the other represents the 'worst' future case in terms of climate and socio-economic development. See Deliverable 5.1.2 for more details. The use from each sector is summed to give a total 'domestic + industrial' use.

For the agricultural water demand, seven different crop categories are accounted for separately: alfalfa, cotton, maize, rice, trees, vegetables and 'other' (Figure 14). For each crop classification, the water demand per unit area is given along with the area planted by that crop in the study area. Thus a total annual water demand per-crop is calculated. The crop-specific demands are then summed to give total agricultural water demand. The potential future impact of climate change can be investigated by changing just one parameter value that downscales planted area according to government projections. Alternatively, each crop could be adjusted individually to give a more detailed analysis.

The 'domestic + industrial' and agricultural water demand volumes are summed to give the total water demand in the study area.

For the waste-water re-use, the total annual treated waste water volume is used (data supplied by ECRI). In addition, the modeller can also choose to use the estimate for the future treated waste water volume. Treated waste water is modelled as an input, and so is added to the rainfall and canal input calculated in the supply sub-model (Figure 13).

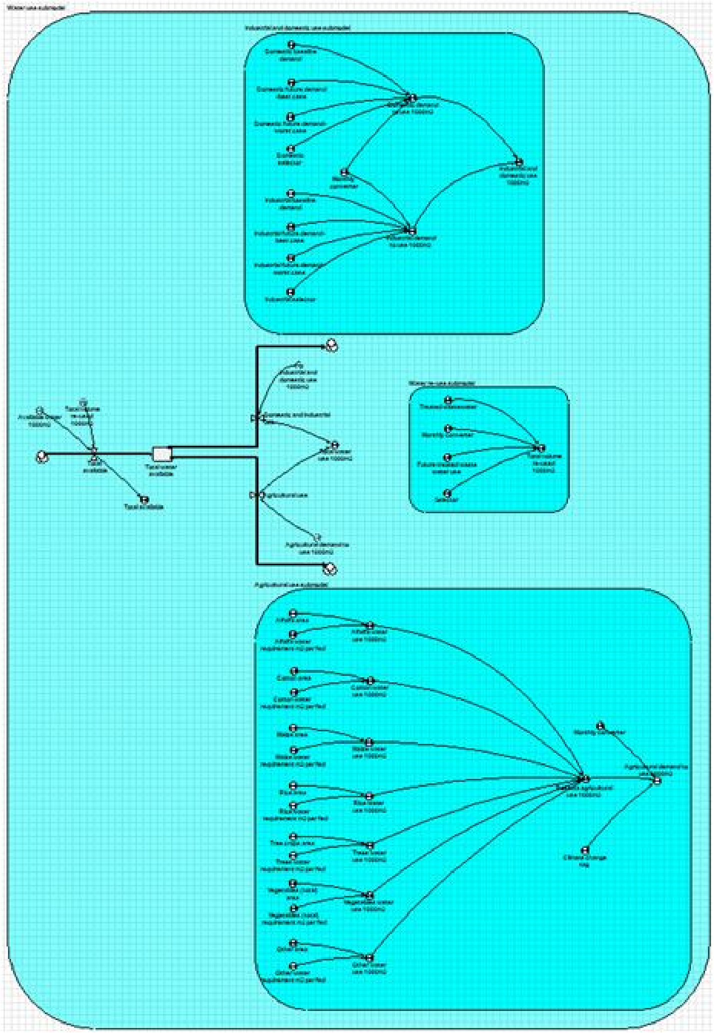


Figure 14: The water use sub-model for the Rosetta case study.

Finally, there is a sub-model that calculates the water balance (right hand side in Figure 12). This simply calculates how much water remains once all the different supplies and demands have been taken into account. Results can be output as either a table or as a graph.

An additional baseline representation of the Rosetta water system has been developed in the WSM DSS (Figure 15).

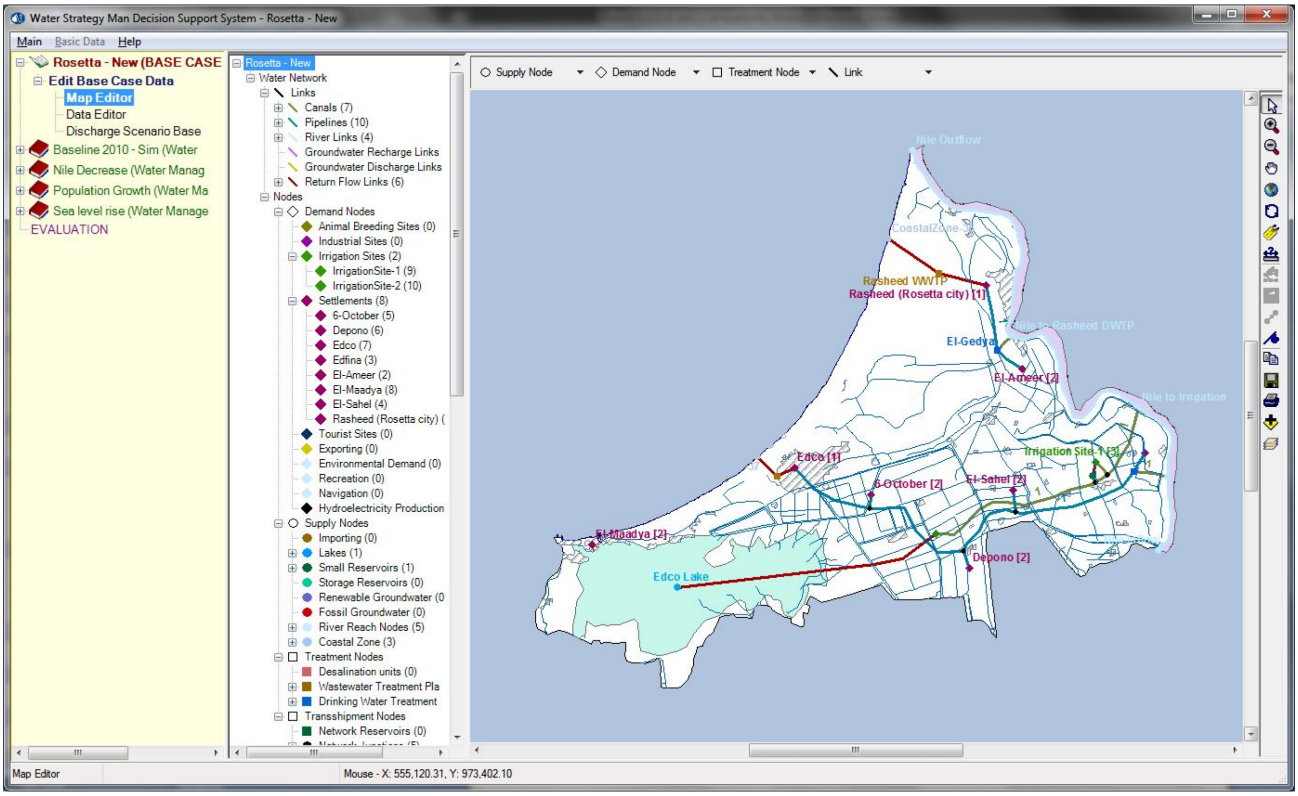


Figure 15: The baseline representation of the Rosetta water system, using the WSM DSS

The model distinguishes between different water uses (urban vs. irrigation) and different water supply sources in irrigation water supply (freshwater vs. drainage water). It has been developed using data provided by ECRI and includes:

- All major urban water uses in the area, which are modelled as 8 settlements/urban agglomerations. Of those:
    - El Rashid (Rosetta) and Edco cities have the highest priority in terms of water supply;
    - The remaining 6 settlements (6-October, Depono, Edfina, El Ameer, El Maadya, El Sahel) have a lowest priority (equal to 2).

  All settlements receive freshwater from the Nile, treated in the local drinking water treatment plants. According to the data provided by ECRI, wastewater from Rosetta and Edco cities is treated in the corresponding wastewater treatment plants and discharged to the sea and the Edco lake respectively, whereas wastewater from the remaining agglomerations is probably discharged to irrigation/drainage canals.

- Water use for crop irrigation is divided in two demand nodes, according to the water supply source, with priorities lower than urban water supply. The first node corresponds to freshwater use, directly from the Nile canal system. The second node receives also drainage (return flows from irrigation with freshwater) as the primary water supply source, and deficits are complemented with freshwater supply from the Nile. Drainage ends up in Edco lake, which acts as a receptor body.
- The Nile section of the Rosetta area is modelled through a set of river reach nodes, of which the first receives as run-off the share of Nile water that enters the area.

Input data entered in the model concern the cropping pattern, crop coefficients and growing seasons, precipitation, evapotranspiration, population and per capita consumption, share of return flow from irrigation (used as drainage), and capacity of drinking water and wastewater treatment plants.

In addition to the baseline representation of the system, the following scenarios have been built for further development and validation:

- A scenario for the decrease of Nile inflows to the area. As the water system of Egypt is highly centralized, the inflow to the upper river reach of the Nile segment pertaining to Rosetta will depend on future, national, water allocation policies, which will be influenced by: (a) population growth and land reclamation schemes upstream, (b) potential changes in the Nile quota allocated to Egypt, as a result of transboundary agreements between riparian countries, and (c) climate change affecting run-off and inflows to the High Aswan Dam.
- A scenario on population growth. Due to the increasing salinity of soils, further agricultural development seems unlikely. Nevertheless, there are plans for urban expansion along the Mediterranean coast (marked in orange in Figure 16), in an area that is unsuitable for cultivation.

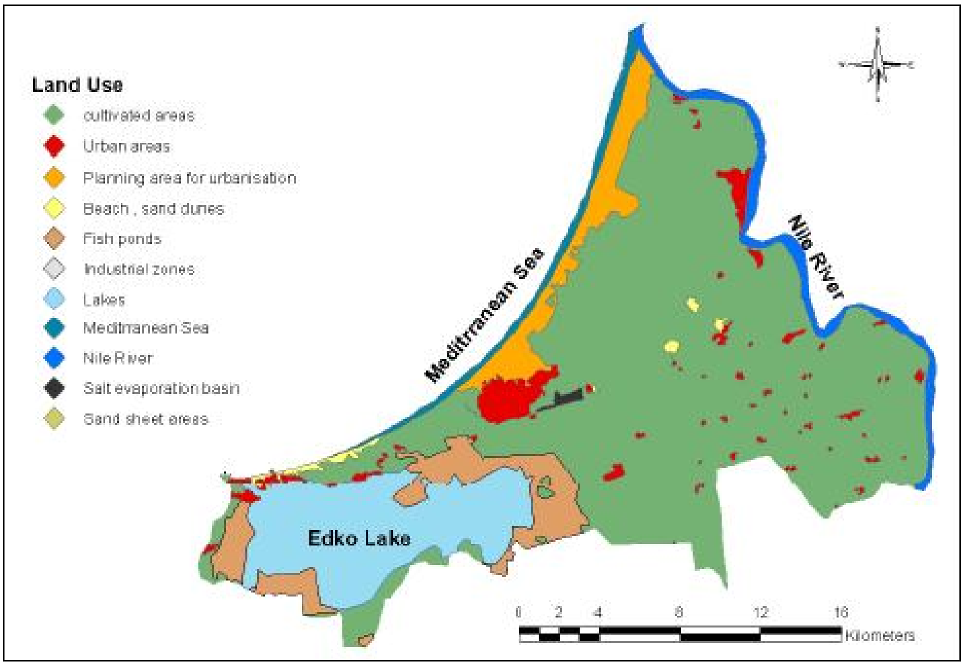


Figure 16: Current and future land use plans in Rosetta

- A scenario on land loss, due to sea level rise, particularly affecting the maximum cultivable area.

The current model is under validation by ECRI, and the main issues relevant to its finalization concern: (a) the inflow from the Nile in the Rosetta area, as current values have been based on the pertinent literature; (b) the validation of wastewater outflows, and (c) the validation of irrigation demands covered by drainage waters.

5.4 Jordan Basin, Jordan

The latest developments of the Jordan Basin case study SDM are shown in Figure 17 and Figure 18. At present there are two versions of this model because the final model structure has not been agreed by all parties. The two models have exactly the same inputs and outputs, but the way the system is represented is different between the two. The different inputs and outputs will be discussed, but first the difference between the model structures will be described.

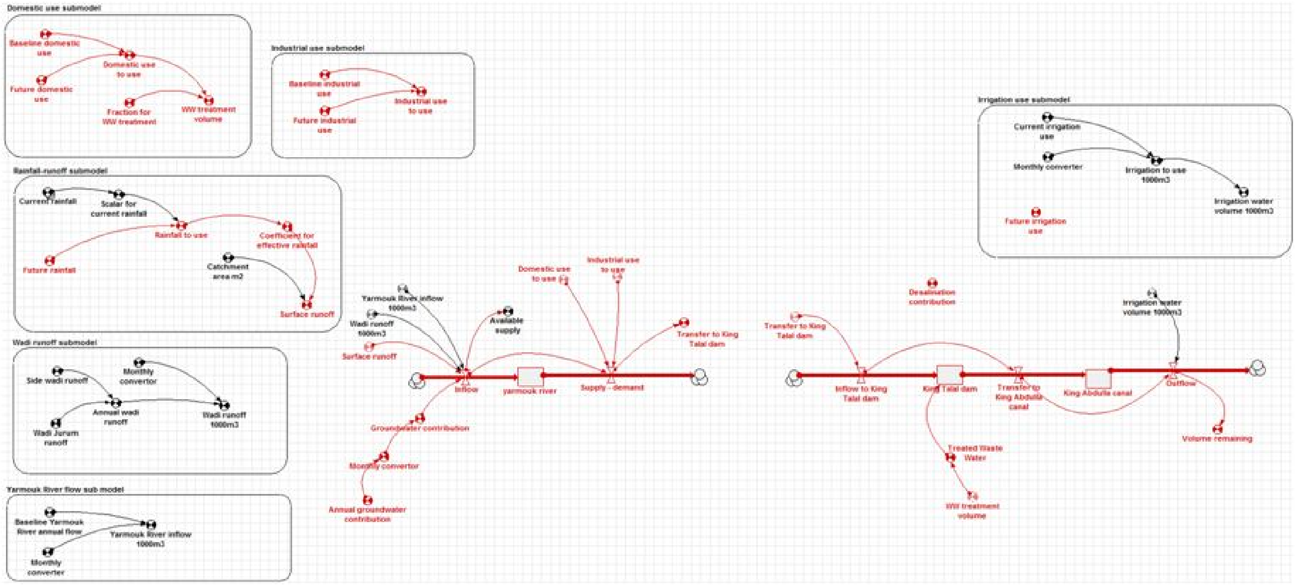


Figure 17: Showing one possible version of the Jordan case study SDM model.

The first possible model structure (Figure 17) comprises of two main parts that are analysed in series. The left hand side of the figure deals with the Yarmouk River system and includes all the water inputs to the Yarmouk River as well as domestic and industrial abstractions. Once the supply and demand have been accounted for, the remainder is transferred to the King Talal dam part of the model, shown on the right hand side of Figure 17. This part of the model deals with treated waste water input and agricultural abstraction, and the amount of water available in the King Abdullah Canal (KAC).

The second possible model structure (Figure 18) has the same inputs and outputs, but structures the system slightly differently. Because the Yarmouk River and the King Talal dam both act as inputs to the King Abdullah Canal, they are treated in parallel in this version of the model with the supply from both contributing to the available water in the KAC, from which water for irrigation is abstracted (Figure 18). Which this change in structure will not affect results, it may ultimately be a more realistic schematic representation of the water system, and thus easier to understand for non-experts.

As stated above, the input to and abstractions from the model are the same, and these will now be described. With respect to water balance inputs, rainfall-runoff is the first water source. Rainfall data is distributed over the land surface with a proportion being lost to evaporation, as is the case with the Tunisia and Rosetta case studies. The remainder is used as input/supply to the Yarmouk River sub-model.

The next source is that deriving directly from Yarmouk River runoff. This sub-model accounts for the annual available water in the Yarmouk River. The annual total is converted to a monthly value and used as input. Another water source is that from side wadis. Wadis are ephemeral streams, only flowing after intense or prolonged rainfall. Some of these have been exploited so as to capture their runoff, making it available for water supply. The wadi supply data are split into Wadi Jurum, for which specific data are available, and 'other wadis' which is the sum of the other wadi sources. Treated waste water, mainly from the city of Amman, can also be viewed as a water source, and is therefore taken in account as a supply. In the Jordan SDM, treated waste water feeds into the King Talal dam store, and not into the Yarmouk River. Finally, the last water source is the King Talal dam itself, which is a dam formed across the Zarqa River. Water is taken from here and transferred into the KAC, from which it is abstracted for a number of uses, but mainly agriculture. Industrial and domestic demand is abstracted from the Yarmouk River.

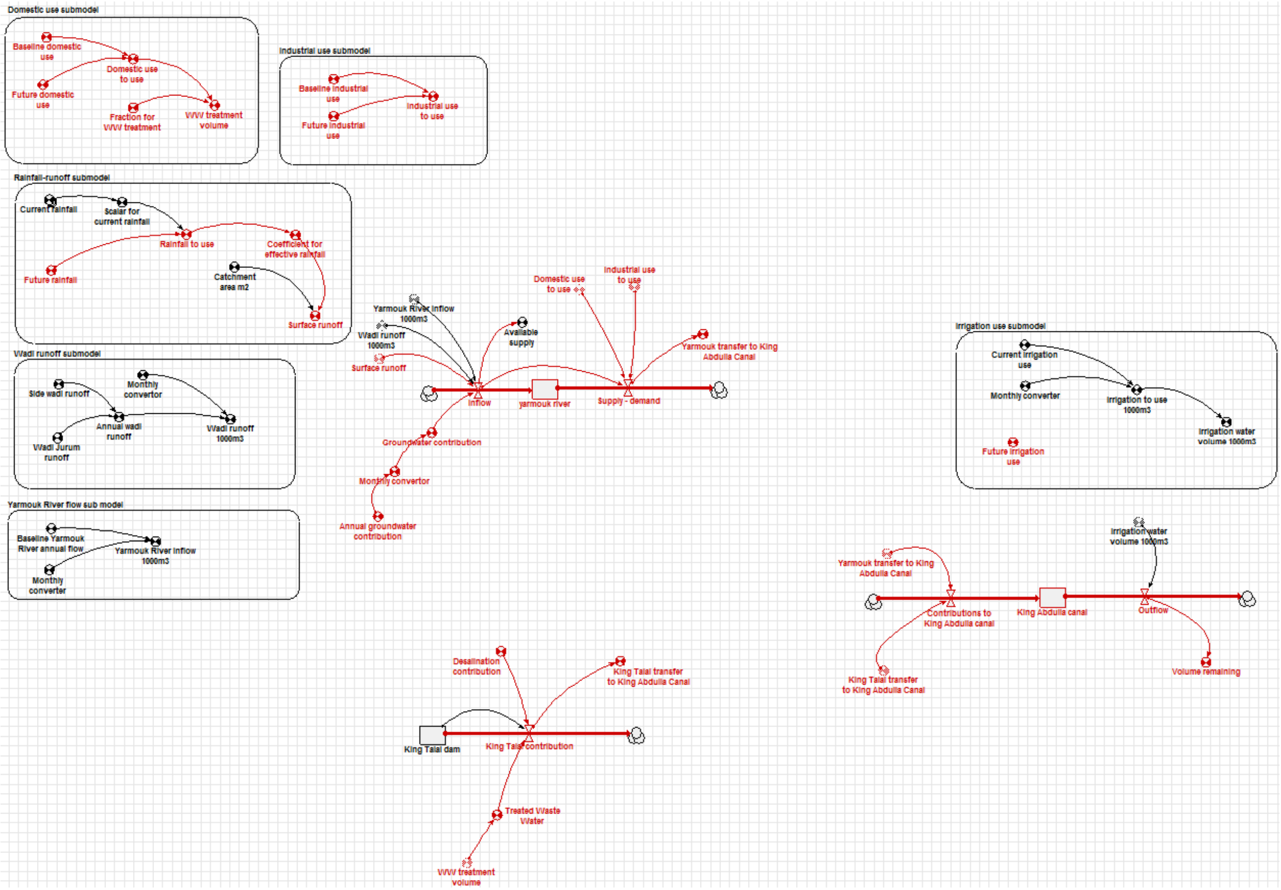


Figure 18: Showing the second potential version of the Jordan case study SDM.

With regard to abstractions from the system, domestic and industrial demand are considered in separate sub-models. However, their joint demand is abstracted from the Yarmouk River system, rather than from the KAC as defined by the local case study partner, NCARE. Therefore, the Yarmouk inflow to the KAC takes into account the abstractions for domestic and industrial use, and is reduced accordingly. This prevents the double-counting of this abstraction. The final abstraction is from the agricultural sector. Irrigation water is taken from the KAC, and thus its volume is reduced accordingly. The final model output defines how much water is left in the KAC once the total abstracted volume is deducted from the inputs from the Yarmouk and King Talal systems and from waste-water reuse. Because of the extreme water scarcity in this region, it is expected for this number to be negative, implying over-abstraction and depletion of the resource.

5.5 Sardinia, Italy

At the time of writing, the Sardinian case study is poorly developed, and no initial SDM model yet exists. The initial idea discussed with the local partner (CMCC) and the stakeholders in January 2011and at the SDM training seminar (February 2011) is that the model will simulate the whole island, broken down roughly in seven sub-systems corresponding to the principal hydrological catchments of the island, with interconnections representing water transfers between submodels. However, no further progress has been made so far, and there is no adequate conceptual or quantitative information arriving from the local partner for the SDM to be built . However, it is hoped that this situation will improve over the coming months.

6. Conclusions

This report has outlined the two main models that will be used in developing the water-balance models for the five WASSERMed case studies. These are System Dynamics Modelling (SDM) and the use of the Water Strategy Man Decision Support System (WSM DSS). The history and concept of the SDM process was introduced, and it is highlighted that by design, SDM development is an iterative process that usually involves not only the modeller but also a third-party, in this case the local WASSERMed case study partners and stakeholders. Models start off by describing qualitatively how the system operates. From this, a simple quantitative model is developed which is then expanded and complexity introduced until it is deemed fit for purpose. Following from this, the model outputs are usually tested against real data to ensure that it is performing well, and that it is representing the system realistically. Because of the flexibility of SIMILE to take almost any values as input, the outputs can be tailored to suit the needs of the end-user without the need to use other software for analysis. In addition, scenario testing, sensitivity tests and uncertainty analysis can all be readily carried out in a well constructed model. The WSM DSS will also be used to characterise the water balance of some of the case studies. Here, water demand and supply are analysed by the model, however supply sources and demand-users can be prioritised such that environmental regulations are adhered to or so that critical infrastructure (e.g. hospitals) never lose their water supply in times of water shortages. WSM DSS can also analyse potential policy options and mitigation measures and, where possible, can analyse the economic benefits of one measure over another. SDM is to be used for the following case studies: Tunisia; Egypt; Jordan; Sardinia, while WSM DSS will be used for: Egypt; Syros.

Following from the introduction of the models to be used, the current status at the time of writing, is described for each case study. The most up-to-date model structure is presented and described for each of the case studies. At present Tunisia and Syros are the most advanced case studies in terms of water balance modelling, however significant progress has also been made with respect to the Egypt and Jordan case studies. At the time of writing, the Sardinian case study was poorly developed, but it is hoped that significant work will progress on this case study in the coming months.

Once water-balance modelling is completed using the techniques presented in this report, it is hoped that the local case study partners and stakeholders will have a better idea as to the current situation in their respective study areas. It is also hoped that local stakeholders and policy makers will be better informed as to the potential future direction of water availability in response to climate and socio-economic changes, and thus will be better equipped to develop meaningful and effective water shortage mitigation strategies. These objectives can be tested using the models developed here such that the best option in terms of economic and political feasibility and water-saving potential can be chosen.

7. References

ASCE and Working Group of UNESCO/IHP IV, Task Committee on Sustainability Criteria, Water Resources Planning and Management Division, ASCE and Working Group of UNESCO/IHP IV Project M-4.3 (1998). Sustainability Criteria for Water Resource Systems. ASCE Publications, Virginia.

Atanasova, N, Todorovski, L, Dzeroski, S. and Kompare, B. (2006). Constructing a library of domain knowledge for automated modelling of aquatic ecosystems. *Ecological Modelling*, 194: 14-36.

AQUASTRESS, 2008, System Dynamics Modelling: The Merguellil Valley water system, *Aquastress Report* 2008/04, 98pp.

Barlas,Y. (2002). 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

Bogardi J.J., Verhoef A. (1995), *Reliability Analysis of Reservoir Operation, New Uncertainty Concepts in Hydrology and Water Resources,* Cambridge University Press.

Chung, G., Lansey, K., Blowers, P., Brooks, P., Ela W., Stewart, S. and Wilson, P., (2008). A general water supply planning model: Evaluation of decentralized treatment, *Environmental Modelling & Software*, 23, 893-905.

Fisher F. M. and Askari H. (2001), Optimal Water Management in the Middle East and Other Regions, *Finance and Development*, 38, 3.

Ford, A. (1999). *Modeling the Environment: An Introduction to System Dynamics Modeling of Environmental Systems*. Washington DC, U.S.A: Island Press.

Forrester, J. (1961). *Industrial Dynamics*. Waltham, MA, U.S.A.: Pegasus Communications.

Haraldsson, H.V. and Sverdrup, H.U. (2004). Finding simplicity in Complexity in Biogeochemical modelling. In Wainwright J. and Mulligan M. (eds.), *Environmental Modelling: Finding Simplicity in Complexity*: 211-223. West Sussex, England, UK: John Wiley & Sons Ltd.

Harou J.J., Pulido-Velazquez M., Rosenberg D.E., Medellin-Azuara J., Lund J.R., Howitt R.E. (2009), 'Hydro-economic models: Concepts, design, applications and future prospects', *Journal of Hydrology*, 275, 627-643.

Khan, S., Yufeng, L., and Ahmad A. (2009). Analysing complex behaviour of hydrological systems through a system dynamics approach. *Environmental Modelling and Software,* 24: 1363-1372.

Kojiri, T., Hori, T., Nakatsuka, J. and Chong T-S. (2008). World continental modelling for water resources using system dynamics. *Physics and Chemistry of the Earth*, 33: 304-311.

Manoli E., Arampatzis G. Assimacopoulos D. forthcoming, Allocation of Water Resources and Cost under scarcity: A case study, in "*Economics in Water Management Models. Applications to the EU Water Framework Directive*", Springer Publications.

Manoli, E., Arampatzis, G., Pissias, E., Xenos, D., and Assimacopoulos, D. (2001). Water demand and supply analysis using a spatial decision support system, *Global NEST: The International Journal*, 3, 3, 199-209.

Mazzoleni, S., Rego, F., Giannino, F. & Legg, C. (2004). Eco-system Modelling: Vegetation and disturbance. In Wainwright J. & Mulligan M. (eds.), *Environmental Modelling: Finding Simplicity in Complexity*: 171-186. West Sussex, England, UK: John Wiley & Sons Ltd.

Muetzelfeldt, R. & Massheder, J. (2003). The Simile visual modelling environment, *Europ. J. Agronomy*, 18: 345-358.

Meutzelfeldt, R. 2010. 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). 27pp.

Mulligan, M. & Wainwright, J. (2004). Modelling and Model Building. In Wainwright J. & Mulligan M. (eds.), *Environmental Modelling: Finding Simplicity in Complexity*: 7-73. West Sussex, England, UK: John Wiley & Sons Ltd.

Ribarova, I., Assimacopoulos, D., Jeffrey, P., Daniell, K., Inman, D., Vamvakeridou-Lyroudia, L.S., Melin, T., Kalinkov, P., Ferrand, N. and Tarnacki, K. (2011). Research-supported participatory planning for water stress mitigation, *Journal of Environmental Planning & Management*, 54(2), 283 – 300.

Simonovic, S. (2002). World water dynamics: global modelling of water resources. *Journal of Environmental Modelling*, 66: 249-267.

Simonovic, S. (2003). 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

Sterman, J.D. (2000). *Business Dynamics, Systems Thinking and Modeling for a Complex World*. New York, USA: Irwin/ McGraw-Hill.

Sušnik J., Vamvakeridou-Lyroudia L. S., Savić D. A. and Kapelan Z., (2011a). System Dynamics Modelling applied for the integrated simulation of complex water systems, *Proceedings of the 8th IWA Symposium on Systems Analysis and Integrated Assessment*, San Sebastian, Spain, 20-22 June 2011, pp. 535-542.

Sušnik J., Vamvakeridou-Lyroudia L. S., Savić D. A. and Kapelan Z., (2011b). Evaluating water-related security threats for complex water systems using system dynamics modelling, *Proceedings of Computing and Control in the Water Industry 2011*: Urban water management - Challenges and opportunities, Exeter, UK, 5-7 September, 2011 (Accepted for presentation).

Todini, E. (1996), 'The Arno rainfall-runoff model'. *Journal of Hydrology* 175, 339–382.

Todini E., Schumann A. and Assimacopoulos D. (2006), The WaterStrategyMan Decision Support System. In: *Water Management in Arid and Semi-arid Regions: Interdisciplinary Perspectives*. Edward-Elgar Publishing Ltd.

Vamvakeridou-Lyroudia, L. S., Savic, D.A., (2008). *System Dynamics Modelling: The Kremikovtzi Water System*, Report No.2008/01, Centre for Water Systems, Univ.of Exeter, UK, accessible at www.ex.ac.uk/cws, 132p

Vamvakeridou-Lyroudia, L.S., Savic, D.A., Tarnacki K., Wintgens T., Dimova, G. and Ribarova I. (2007). Conceptual/System Dynamics Modelling Applied for the Simulation of Complex Water Systems, in *Water Management Challenges in Global Change*, Proc. Int. Conf. CCWI 2007 and SUWM 2007, Ulanicki, B., Vairavamoorthy, K., Butler, D., Bounds, P.L.M., Memon, F.A. (Eds), Leicester UK, 3-5 Sept. 2007, Taylor & Francis Group, London UK, pp. 159-167.

Vamvakeridou-Lyroudia L.S., Leduc C., and Savic D. (2008). System dynamics modelling: *The Merguellil valley Water system*, Report No.2008/04, Centre for Water Systems, Univ. of Exeter, UK, accessible at www.ex.ac.uk/cws, 96p

WASSERMed, (2010). *Literature review and comparative analysis of the existing methodologies for water balance*, WASSERMed report: Deliverable D 5.2.1, pp 33 (uploaded June 2010)

Wintgens, T., Dimova, G., Ribarova, I., Druzynska, E., Caruk, M., Vamvakeridou-Lyroudia, L.S, Tarnacki, K., Melin T. and Savic D. (2009).“Industrial water management as a water stress mitigation option, Chapter 8 in *The Use of Economic Valuation in Environmental Policy* (Koundouri P. Ed.), Routledge, Oxon UK, ISBN 978-0-415-45323-3, pp. 125-195