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D 5.2.1: Literature review and comparative analysis of the existing methodologies for water balance

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Executive Summary

WASSERMed (Water Availability and Security in Southern EuRope and the Mediterranean) is a European Commission Seventh Framework (EU FP7) funded collaborative project, which draws on the expertise of engineers, scientists, industry and local stakeholders. The aim of WASSERMed is to analyse, in a multi-disciplinary way, the current and future climate-induced changes to hydrological budgets and extremes in southern Europe, north Africa and the Middle East under the frame of threats to all aspects of human, social, economic and environmental security. One of the WASSERMed objectives and Work Packages (WP5) is dedicated to developing holistic and integrated modelling and methodological approaches for the quantification of climate change impact, so as to understand in the best possible way the corresponding water-related security threats. Assessment will be made to the changes in mean flows, frequency and magnitude of extreme precipitation, surface runoff, the ground water balance as well as social and economic factors, which will be linked to suitable indicators, enabling the quantification of different types of security threats. Five specific case-studies are being considered, related to : 1) Syros Island (Greece); 2) Sardinia (Italy); 3) the Merguellil watershed (Tunisia); 4) the Jordan River basin and; 5) the Nile River System in Egypt.

WASSERMed will address water balance issues throughout the Mediterranean region, focussing on these five diverse case studies. Work Package 5.2 will contribute by (a) selecting the most suitable method(s) to apply to water balance simulations within each case study and (b) developing the models which will be used as Decision Support System (DSS) tools for evaluating water availability and related security threats for the five case studies under different climate change scenarios. It will also investigate various options for alleviating security threats, tailored to each case study under consideration. The case studies will be studied at local scale (cities, regions, hydrological basins), where demand for water is assessed and compared with potential supply. The main objective is to identify vulnerability and priorities for infrastructure investments.

This report presents a state-of-the-art literature review on water balance modelling, by introducing and comparing various methodologies, approaches and packages in literature. The main features are presented and compared with regard to the specific requirements of WASSERMed, while the most suitable methodologies to be applied are further analysed and presented. These include: (a) System Dynamics Modelling, (b) The Water Strategy Man (WSM) Decision Support System (DSS), and (c) other existing water balance methodologies and packages, such as WEAP (Water Evaluation and Planning System), which may also be applied alongside the first two.

System Dynamics Modelling (SDM) is a methodology for studying and managing complex feedback systems, typically used when formal analytical models do not exist. Visualisation of the system components is via specific graphical software. This also allows for complex differential/integration equations to be simply solved. The visual nature of the interface allows for a user-friendly, participatory process, and can be used effectively as a decision support tool for stakeholders and experts. SIMILE will be the software used to represent the dynamic systems for each case study in WP5. SIMILE has been chosen for three reasons: (a) it efficiently supports breaking the model into sub-models thus facilitating the development process of very complex systems (b) it can automatically produce model documentation in C, thus making the model re-usable for

further specialised applications, if necessary and; (c) it was successfully applied in similar participatory process within the EU FP6 project AquaStress.

In addition, the Decision Support System (DSS) developed for the WaterStrategyMan EU FP5 Project will also be used and modified to optimise water allocation of limited water supply in different water use sectors and quantify the resulting environmental and economic impact from potential water shortages, and will simulate and compare the impact of alternative measures for mitigating water scarcity. It will be used alongside SIMILE to provide robust answers to questions regarding water availability and security threats in the case studies.

SDM and the WSM DSS have been placed in the wider context by comparing them with other available water-balance and decision-support software tools and methodologies. In particular, WEAP (Water Evaluation and Planning System) is also presented in more detail, because of the expertise of a specific WASSERMED partner (PIK). It may also be considered for application within WASSERMED, alongside SDM and WSM DSS.

Ultimately, irrespective of the water balance methodology applied for each case study, the aim is for WASSERMed to deliver real and realistic options for evaluating and mitigating water-related security threats in the Mediterranean region through various technological, environmental, policy and societal options, and thus diffusing potential water shortage security issues as a result.

Contents

1. Introduction

1.1 Structure

The report is part of the EU FP7 project 'WASSERMed'. It forms Deliverable 5.2.1: 'Literature review and comparative analysis of the existing methodologies for water balance' within Work Package(WP) 5: 'Integrated modelling of water-related security threats'. It introduces the concept of water balance, as related to the project's aims and objectives, System Dynamics Modelling, Water Strategy Man, a Decision Support System (DSS) tool developed by a previous EU Framework Project, a development of which will be used here, and compares various pieces of software designed for the modelling of water systems.

The structure of the report is as follows: the rest of this Chapter gives a brief introduction to WASSERMed, its aims and objectives. Chapter 2 introduces the concept of water balance modelling, defining what water balance modelling is, why it is important and how it is relevant to WASSERMed. Chapter 3 presents a table comparing several water balance and decision-support tools from the literature. Chapter 4 introduces System Dynamics Modelling (SDM) and the specific piece of software to be used in WASSERMed: 'SIMILE'. Firstly an introduction to SDM is given, including its origins and the concepts behind it. The basic procedure behind any SDM is then outlined, followed by an explanation of conceptual models and then an example of the use of SDM, conceptual models and an introduction to the SIMILE software package. The use of SIMILE in a previous EU Framework Project is also outlined. Chapter 5 introduces another previous EU Framework Project 'WaterStrategyMan', outlining its aims and objectives. This project is considered specifically to introduce and briefly describe the Decision Support System that was developed as part of this project, and which will be used alongside SDM as a water resource management tool in this Project. Chapter 6 introduces WEAP – the Water Evaluation And Planning system. This is a software tool similar to SIMILE in that it is a water resources planning tool that incorporates issues such as allocation of limited water resources between agricultural, domestic and industrial demands, whilst balancing supply, demand, quality and ecological considerations amongst these different uses. An introduction to WEAP is given, followed by an outline of the approach used, and finally a brief section outlining some technical detail on which WEAP is based. WEAP is introduced as a tool which may be used within WASSERMed. Chapter 7 summarises and concludes the report.

1.2 WASSERMed

WASSERMed (Water Availability and Security in Southern EuRope and the Mediterranean) is a European Commission Seventh Framework (EU FP7) funded interdisciplinary project, which draws on the expertise of engineers, scientists, industry and local stakeholders. The aim of WASSERMed is to analyse, in a multi-disciplinary way, the current and future climate-induced changes to hydrological budgets and extremes in southern Europe, north Africa and the Middle East under the frame of threats to national and human security. Assessment will be made to the changes in mean flows, frequency and magnitude of extreme precipitation, surface runoff, the ground water balance as well as social and economic factors.

Five specific case-studies are being considered: 1) Syros Island (Greece); 2) Sardinia (Italy); 3) the Merguellil watershed (Tunisia); 4) the Jordan River basin and; 5) the Nile River system in Egypt. Impacts on key strategic sectors such as agriculture and tourism will be analysed, as well as the macroeconomic implications of water availability in terms of regional income, consumption, investment, trade flows, industrial structure and competitiveness. WASSERMed is an interdisciplinary project, with three main contributions: 1) integration of climate change scenarios and holistic water system modelling; 2) interdisciplinary approach coupling macroeconomic implications and technical indicators, providing a better assessment of climate change effects to water resources, water uses and expected security risks; 3) proposal of specific adaptation measures for key sectors of the Mediterranean economy.

2. Introduction to Water Balance Modelling

2.1 What is water balance?

Water balance modelling can be thought of as defining and modelling a system in terms of the input, storage, re-use and output of water to, from and within a specific system and between systems. The water balance model in question may be for a natural scenario, examining the annual recharge to an aquifer or lake for example, or it may be a man-made system such as an industrial plant. The water balance model may also describe linkages between natural and anthropogenic systems (e.g. Vamvakeridou et al, 2007). Water balance modelling aims to determine whether a system is in a state of net balance (i.e. water in=water out), has too much water, or is water deficient. Water balance modelling can also consider what-if scenarios to determine the impact upon the current water balance if a component within the system changes (e.g. changes in rainfall, abstraction, etc.).

Inputs to a water balance model may include rainfall or snowmelt etc., while outputs may comprise evaporation and withdrawal for human consumption by any one of a number of sectors (domestic, agricultural, industrial). Storages may be the long-term (ancient) groundwater reservoirs or man-made reservoirs holding water behind dams. Re-use of water in the natural world can be represented in the traditional hydrological cycle as the uptake of water by plants, or surface runoff entering a lake, followed by evaporation back into the atmospheric circulation system to be re-distributed elsewhere on Earth. In an anthropogenic system, re-use may be thought of as treating and recycling waste water for use in other purposes (e.g. agricultural irrigation, or even re-use as drinking water).

The overall quantity of water on Earth has not changed over time, but its type and distribution have. At times in the geologic past, more fresh water has been locked in glaciers and snowpacks and the amount of saline (sea) water has been less. At other times, the reverse has been true, with very little fresh water and relatively more sea water when compared with the present day. At present, two major factors affect the availability of fresh water for human consumption: the overall human population on the planet and the impact that climate change is having on the amount and distribution of fresh water available to that population. All the time, more people are vying for an ever-smaller proportion of available fresh water, and in certain areas such as the Mediterranean basin, south-east Australia, and the southern United States, climate change, over-population and inefficient water (re-)use are having significant consequences on the availability of fresh water to the human population. Added to these demands are the demands of the natural world.

2.2 Relevance to WASSERMed

It is clear the balancing the quantity of water available with the demand pressures from multiple sources (human and natural) and with the effects of climate change is a key requirement in today's society. WASSERMed aims to model and simulate the water balance situation in the Mediterranean basin, focusing on five case studies that represent different challenges regarding water use and availability. For example one case study (Syros island) looks at the relationship between water availability, the local community and the large tourist sector, while the Jordan River case study looks at the demand of water from a dwindling supply between many nations. Demand for this water has, in some instances, led to human conflict and as the supply becomes less, the potential for further conflict becomes greater in an already unstable part of the world.

WASSERMed will focus on representing the water balances of each of these five case studies at the present day as a series of bespoke models, each created specifically for the individual case studies. Further to this, using the latest climate change data, climate change scenarios for the year 2050 will also be analysed, giving stakeholders and decision makers a better idea of the future water budget, water demands and stresses. WASSERMed will also consider solutions to the problem in an attempt to mitigate some of the effects of climate change and the (likely) future increase in demand in an already water-stressed region, leading potentially to security threats. These mitigation measures may be as simple as increasing waste-water recycling efforts, or irrigation efficiency, or may involve more technologically demanding and expensive options such as infrastructure upgrades and installation of desalination plants. WASSERMed promotes constant dialogue and interaction between academics, industry experts, stakeholders and local users, which will help elucidate these options, leading to better ideas of the potential risks to water supply and region security in the near-future, but also to effective, efficient ways to mitigate these climate-change induced effects, so as to lessen security threats in the future.

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

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 notable 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 System.	Modular data processing and modelling system, complete with validation and interpolation modules and a user-interface. Can be customised depending on the end-user	www.wldelft.nl/soft/fews/int/index.html
MedWater	EC funded FP5	Give a clear	MedWater is an MS Excel	www.medwater.de/results

Model	project 'MedWater'	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.	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.	.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	Model can be used in order to experiment and test to find out more about a real system.	www.powersim.com

		using Dynamic System Model (DSM) principles	Initially designed for business applications, but since extended. All variables are run in an integrated and dynamic way. Connects with Excel for input/output	
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 models of dynamic, complex systems	Can integrate managerial and technical elements to solve complex problems. Can construct models of business, scientific, environmental and social systems. Provides monte-	www.vensim.com

			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, Water Strategy Man and WEAP are of particular interest and they have been selected as the main water balance tools to be used for this project. All three are presented in detail in the sections that follow.

4. Conceptual models, System Dynamics Modelling and SIMILE

4.1 Introduction to System Dynamics Modelling

System Dynamics Modelling (SDM) or System Thinking is a methodology for studying and managing complex feedback systems, typically used when formal analytical models do not exist, but system simulation can be developed by linking a number of feedback mechanisms. Visualisation of the system components is via specific software (i.e. the model interface). This also allows for complex differential/integration equations to be simply solved. The visual nature of the interface allows for a user-friendly, participatory process, 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. Starting from conceptual qualitative models, 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 can then be modified and improved to show the desired level of detail and complexity (Haraldsson and Sverdrup, 2004).

Forrester (1961) introduced system thinking and 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.

In order to build a model using standard SDM techniques, system components must be 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), although there are many others available depending on the specific use. These provide a graphical interface which adds to the participatory process described above, especially 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. 2010; Wintgens et al. 2009; Vamvakeridou et al. 2008). Results and full descriptions of the models developed for these previous projects are detailed in Dimova et al. (2007), Vamvakeridou et al. (2007), and Vamvakeridou and Savic (2008a).

Mathematically, most existing SDM visual environments are similar. SIMILE (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. There are two reasons for this: (a) it efficiently supports breaking the model into sub-models thus facilitating the development process of very complex systems and; (b) it can automatically produce model documentation (code) in C, thus making the model potentially re-usable for further specialised applications, if necessary. SDM as described here has been included as a software tool for i3S, the software tool workbench for AquaStress (Vamvakeridou-Lyroudia and Savic, 2008b). Two alternative SDM models are described in detail in Sections 5 and 6.

4.2 SDM application procedure

Within WASSERMed a continuous 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 fact 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). This process is strongly interactive, requiring mutual communication and understanding at all stages (Magnuszewski et al, 2005).

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

1. Initially all (case study specific) technically available water management options available for improving water use and mitigating water security threats will be defined and formally conceptualised in SDM terms.

2. Identify a problem or system within the case study. Problem identification 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.

3. 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 generic conceptual diagram that will be developed will be considered to be the “building block” for the subsequent water system simulation. The conceptual model is not linked to any specific software program and is merely a schematic representation of the system under consideration. Conceptual models will be built for each case study.

4. Build a computer simulation model (**SDM: Quantitative model**). Consequently case study specific initial quantitative models for each study area (including numerical data and parameters) will be developed in SDM visual environment (SIMILE graphics environment) by UNEXE, which will be revised and agreed upon during consecutive meetings.

5. Test the model. The SDM model will be continually updated and revised by technical meetings, exchange of information and discussions.

6. Use the model to produce and assess alternative policies. 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.

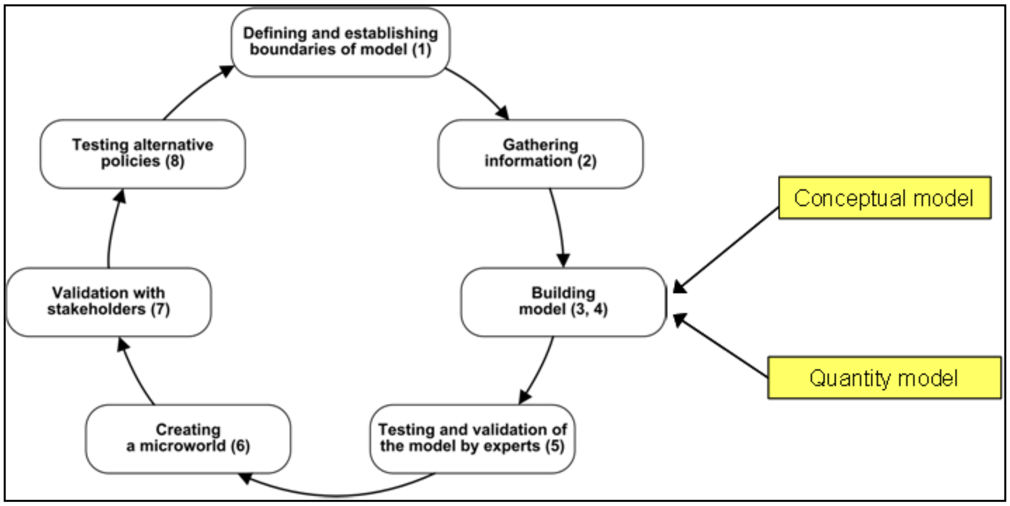

Figure 1: Schematic representation of SDM development.

4.3 Conceptual models

Conceptual models are diagrams of key variables and interactions, representing the dynamic nature of a system, including interconnections, feedback loops and delays (Sterman, 2000). Such graphical tools are generally far more transparent and easy to understand, especially for non-specialists. As such, conceptual models can be used in many (non-)scientific fields because they are participatory and transparent. Establishing a conceptual model is a demanding task because the processes involved are dynamic, interdependent, complex and non-linear. These processes may not be completely understood.

Each model must be designed to answer specific questions. Models should not start with data and quantitative modelling, but 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 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. This approach was pursued in the AQUASTRESS project (Ribarova et al. 2010, AQUASTRESS, 2006).

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 2).

In SDM environment, there exist two types of conceptual diagrams (Figure 3; 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.

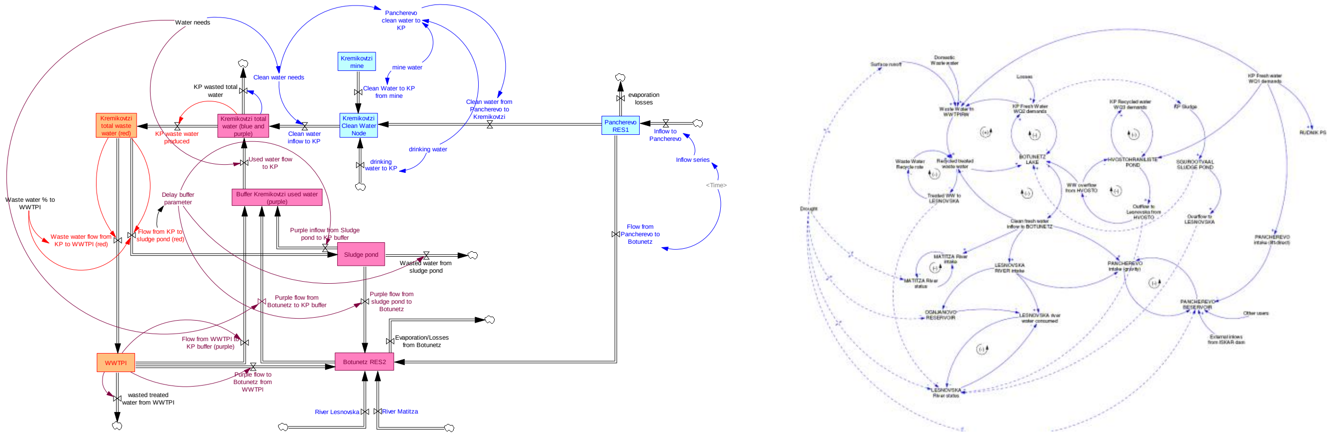

Figure 2: Example of a flow diagram (left) and casual loop diagram (right) conceptual model (from AQUASTRESS, 2008).

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.

It should pointed out that the main advantage of SDM, as compared to any other water balance modelling tool, is the flexibility of accepting any kind of variables/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. Thus it is possible to develop and adapt water balance models that will automatically give as output to the decision maker suitable indicators related to water security issues, that will be readily viewable and comparable among different scenarios/models. 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.

4.4 Quantitative models and SIMILE

As noted above, SIMILE (www.simulistics.com) will be the 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). 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, yet 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, i.e., not business applications, as with most of the other SDM tools. Accordingly it has been applied to many research projects related to the environment/ecology (Wintgens et al, 2009, Vamvakeridou et al, 2009, Magnuszewski et al 2005, Haraldsson and Sverdrup 2004, Mazzoleni, et al 2004).

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

- 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.

Within SIMILE, models are split into two components (Muetzelfeldt and Massheder, 2003): System Dynamics tools and sub-model tools. The System Dynamics tools include the stocks, flow and convertors, while the sub-model suite of tools allows sub-models to be disaggregated (e.g. a population sub-model could be divided according to age, size, etc.), or to define conditional rules which must be met before a certain aspect of a disaggregated sub-model is considered.

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. 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).

4.5 SDM and SIMILE in 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) is 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. 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 SDM models, built in SIMILE, in AQUASTRESS were applied to two case study areas: one at the Kremikovtzi plant in Bulgaria and the other in 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, 2008a).

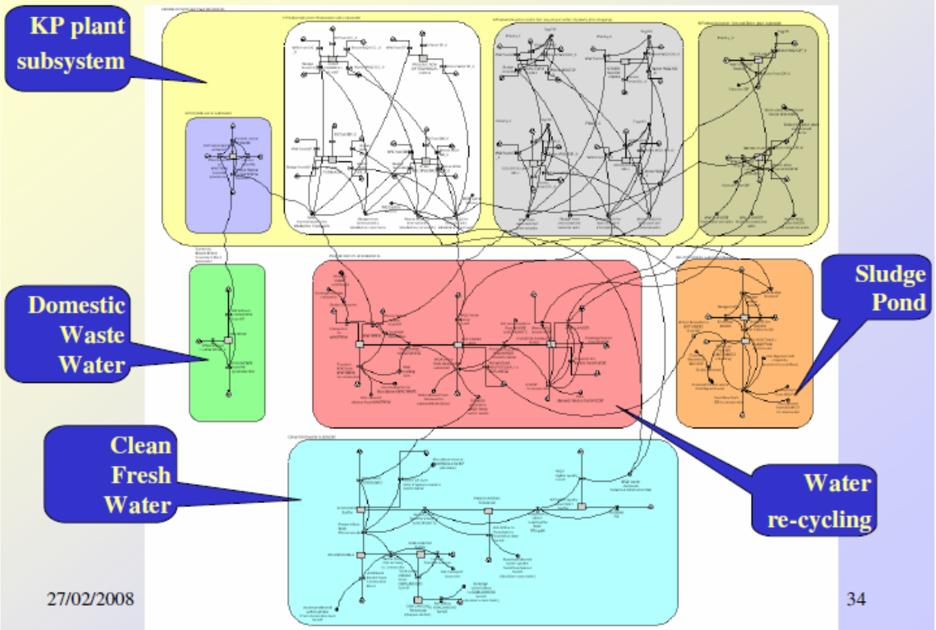

Figure 3: Final SDM model (in SIMILE) for the Kremikovtzi industrial plant.

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. As with the Kremikovtzi case study, the final was also divided into a number of smaller sub-models representing various parts of the water system (e.g. the upper and middle catchment and the El Haouareb Dam) (Figure 4; AQUASTRESS, 2008).

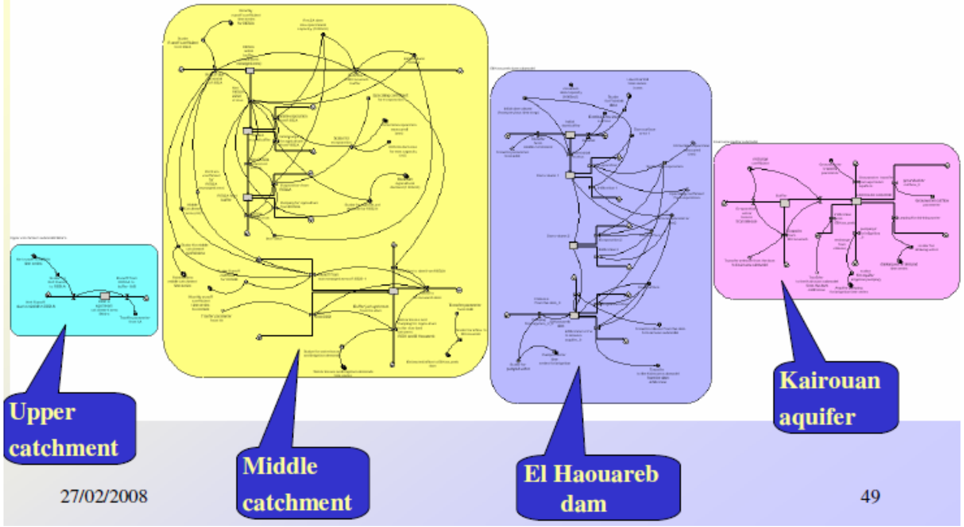

Figure 4: Final SDM model (in SIMILE) for the Merguellil valley case study.

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 (2008a), Vamvakeridou et al. (2008), Ribarova et al. (2010) and Wintgens et al. (2009).

5. WaterStrategyMan (EU FP5 Project) and the Decision Support System

WaterStrategyMan (WSM) was a project under the EU Fifth Framework Program (FP5) which contributed to the key action of 'Sustainable management and quality of water'. The goal of the WSM project was to develop strategies for regulating and managing water resources and demand in water deficient region (http://environ.chemeng.ntua.gr/wsm/Default.aspx?t=1). A methodology, tools, guidelines and protocols of implementation were developed that enabled decision makers to select and implement relevant water schemes for full water cost recovery. The project also aimed to develop an 'integrated water resources management' taking into take account of economic, social, technological, institutional and environmental implications to meet EU requirements for the preservation and enhancement of the quality of the environment and the availability of natural resources and sustainable development.

The project aimed to take into account generalised and more specific issues by looking at regional and local case studies respectively, data and ideas. One of the central ideas to the project was recognising that the existing framework of water management infrastructures, natural environment, water supply and consumption, institutional and socioeconomic conditions is the main factor in determining appropriate strategies that may improve water resources management. The interactions between the environmental and socio-economic systems were seen as the main components in deciding the decisive issues that the project would analyse (Figure 5).

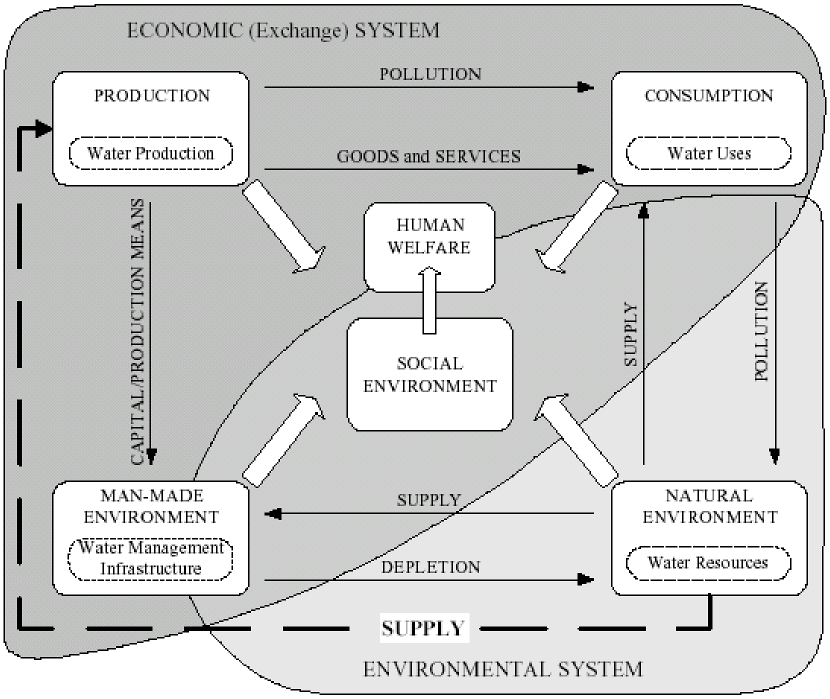

Figure 5: The WSM water resources management framework (from http://environ.chemeng.ntua.gr/wsm/Default.aspx?t=1)

5.1 The Decision Support System (DSS)

A main feature of WSM was the development of the DSS, a GIS-based decision support tool. The DSS was developed around existing methods and models for the quantitative analysis of water resource systems. Various models were reviewed based on their data requirements and complexity. Emphasis was also placed on the ability to forecast future water demands, taking into account various spatial and temporal scales as well as data availability. Models were reviewed that represented water availability, resource management, water demand and those that attempt to model the links and interrelationships between these various components. A suite of models suitable for implementation into the DSS was recommended.

The developed DSS (see http://environ.chemeng.ntua.gr/wsm/Default.aspx?t=1) uses the concept of 'water management scheme' (WMS), defined as a set of scenarios for variables that cannot be directly influenced by the decision maker and the application of one or more water management interventions. The concept of the DSS is to simulate water management strategies under different climatic and socio-economic scenarios. These can then be compared and the decision maker can formulate a response to mitigating water stress according to economic and/or environmental objectives and constraints.

The DSS assesses the state of a water system in terms of sources, usage, cycles and environmental quality in a simulation environment that responds to various modifications. It can evaluate the effects of actions and measures taken during the simulation on the basis of different scenarios and policies that may be implemented. The main capabilities of the DSS are:

- Estimating water availability
- Estimating water demand
- Determining any necessary interventions
- Determining optimal water allocation
- Ranking of scenarios based on indicators
- Cost estimation, both financial and environmental

Of particular importance to the DSS are social system responses, comprising of four types of measures:

1. Supply measures, aiming at improving availability during drought
2. Measures aimed at decreasing demand
3. Measures to mitigate impacts
4. Methods for producing management strategies

The DSS can model conditions in a given area and can be used to estimate current and future demand, to determine what interventions are necessary as well as their cost. It can provide indicators of performance under various availability and demand scenarios, and can rank the scenarios based upon the indicators. The user can assess the performance of the water system in the entire region as well as at individual points of interest.

The DSS models water allocation and the economic implications in two separate models/modules. The water allocation module minimises water shortage when supply is limited. User-defined priority rules are used to aid this process. First, competing demand sites are prioritised according to social preference/constraints, water rights, etc. If demands can be supplied by more than one source, then supply priorities are used to rank choices for obtaining water. Supply priorities include the cost and quality of water and the protection of resources. The main aim is to either enhance supply, promoting protection of vulnerable resources, or to regulate demand through conservation measures, technological improvement or pricing incentives. The economic analysis and scheme evaluation module serves two purposes. The first is to assess each management option in terms of reliability, resilience and vulnerability. The second is to undertake economic analysis of the water management schemes. Financial, environmental and resource costs are all considered.

It is envisaged that the WSM DSS will be used in WASSERMed because the WSM DSS can (i) optimise water allocation of limited water supply in different water use sectors and quantify the resulting environmental and economic impact from potential water shortages, and (ii) simulate and compare the impact of alternative measures for mitigating water scarcity. It will be used alongside SDM to provide robust answers to questions regarding water availability and security in the case studies, or as an alternative to SDM modelling, if applicable.

More detail regarding the WaterStrategyMan project, including the DSS and free to download technical documentation can be found at http://environ.chemeng.ntua.gr/wsm/Default.aspx?t=1.

6. WEAP

6.1 Introduction

WEAP (Water Evaluation and Planning system) is a commercial user-friendly software tool that takes an integrated approach to water resources planning (Sieber and Purkey 2007). According to its user guide, it aims to incorporate issues such as allocation of limited water resources between agricultural, domestic and industrial demands, whilst balancing supply, demand, quality and ecological considerations amongst these different uses. WEAP has six main highlights: 1) it incorporates an integrated approach, which allows for a unique approach for conducting integrated water resources planning assessments; 2) it promotes a stakeholder process whereby a transparent structure facilitates engagement between a diverse range of parties; 3) it includes assessment of the systems water balance through a database which holds supply and demand information which drives a mass-balance model on a link-node architecture; 4) it is simulation-based, calculating water supply, demand, infiltration, runoff, crop requirements, flow and storage, pollution generation, treatment and water quality under a range of scenarios; 5) it can include policy scenarios to evaluate a full range of water development and management options, and can take account of multiple and competing uses of water systems and; 6) it has user-friendly interface with flexible model outputs as maps, charts and tables (Figure 6).

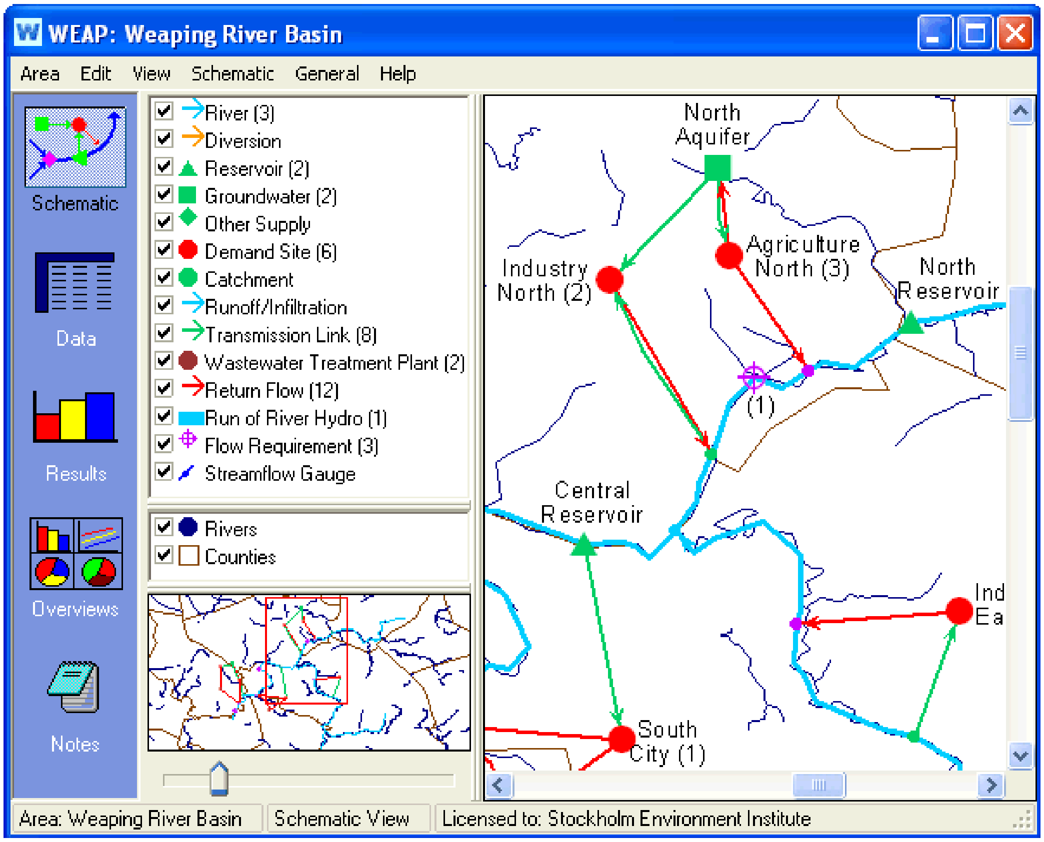

Figure 6: Screenshot showing the map-based schematic overview within WEAP (from the WEAP website: www.weap21.org)

It has been designed as a planning tool to assist experts and decision-makers. The flexible and user-friendly system means that it also allows for easy communication of ideas between experts and non-experts. WEAP uses a water balance as its operating principle, and can be applied to municipal or agricultural systems, to a single watershed, or to a complex basin. It can also simulate the natural and engineered aspects of a system. A financial module allows for simple cost-benefit analyses to be carried out. The data structure and level of detail are easy to customise to the required level.

It includes setting up of the time frame for study, the spatial extent, system components and configuration of the problem. A snapshot of actual water demand, pollution loads etc., can be defined. Alternative sets of future assumptions based on policies, cost, technological development and other factors can also be defined. Different scenarios are constructed using alternative assumptions and policies. Finally, the scenarios are evaluated with regard to water availability, costs, benefits, environmental targets and so on (Sieber and Purkey, 2007).

It has been used on many diverse projects all over the world. Some examples include water supply augmentation in Texas, regional solutions to developing water supplies in the American north-west, adapting water management to the loss of glaciers in the Andes, water demand scenarios for a water-stressed basin in South Africa, investigating strategies for water use in the Aral Sea and establishing methodologies for water allocation in Bang Pakong River Basin. It should be pointed out that the main reason WEAP is included in detail in this report is that a WASSERMed partner (PIK) has specific expertise in its use, and it may be used alongside SDM and WSM for some of the project case studies.

6.2 The WEAP Approach

WEAP is guided by a number of methodological considerations (Sieber and Purkey, 2007): 1) an integrated planning framework. This aids integration of the problem over several dimensions such as supply and demand, water quantity and quality, developmental and environmental constraints, etc.; 2) scenario analyses to understand different development choices. Based on data, a reference scenario can be defined. Policy scenarios with varying assumptions about future development can then be formulated. Scenarios can be used to address many 'what-if' questions. Scenarios can be viewed simultaneously for ease of comparison; 3) demand-management capability. Water requirement may be derived from a detailed set of final uses in any economic sector. For example agricultural use can be defined in terms of many different component parts, allowing better definition of the system. Priorities for water allocation can be defined by the user; 4) environmental assessment capability. The needs of aquatic ecosystems can be taken into account, and pollution can be tracked though the system being studied, and; 5) ease of use. The graphical interface allows for intuitive, easy data handling and scenario tracking. The system can be easily modified as required. The user can add their own equations as required.

In addition to the above, WEAP also incorporates urban water management as a tool. A range of spatial and temporal scales can be studied. Groundwater and sewage retention systems can be modelled, as can infiltration basins and retention ponds. Pollution can easily be tracked through a system (Sieber and Purkey, 2007).

6.3 Technical detail

WEAP is essentially comprised of two modules: a physical hydrology module and an allocation module (Yates et al., 2005). The physical hydrology module has been developed to take account of two hydrological facts: firstly that precipitation located in sub-catchments in upstream portions of watersheds contribute to groundwater baseflows that serve a gaining stream year round, with a short time-lag. Secondly, sub-catchments located in downstream areas of a watershed tend to contribute to alluvial aquifers that are directly linked to the river system to which they can contribute flow and from which they can receive seepage, depending on the local hydrological conditions. These groundwater systems also provide water storage which may be drawn upon.

The physical hydrology module is made up of several components (Yates et al., 2005): surface water hydrology, groundwater-surface water interaction, irrigated agriculture and surface water quality. The surface water hydrology module uses empirical functions that describe evapotranspiration, surface runoff, interflow and deep percolation. The impact of snow and snowmelt on runoff is also accounted for. The groundwater-surface water component dynamically links surface and groundwater such that each can contribute to the other depending on hydrological conditions. The aquifer is modelled as a stylised wedge, the seepage to and from which is essentially controlled by the area in contact with the ‘wet’ portion of the river and the hydraulic conductivity of the local sedimentary material. The groundwater table is also assumed to be in equilibrium with the river level. In the irrigated agriculture component, when calculated soil moisture drops below some threshold, an irrigation demand is triggered. This demand is crop- and climate-dependant. The water quality component models dissolved oxygen and biological oxygen demand using exponential decay functions. Water temperature is also modelled.

The allocation module is also made up of various components (Yates et al., 2005): water demands, in-stream flow requirements and surface reservoirs. Demographic and water-use information is used to examine how water demand evolves over time. The demands are programmed into WEAP then applied deterministically using Linear Programming (LP) methods. Demand priority for each node can be specified by the user. The analysis is typically broken down into sectors such as industry and agriculture, but these can then be broken down further, depending on the level of detail required. Demand can also be projected into the future. The in-stream flow requirement component ensures that at any given time-step in the model, minimum flow requirements in channels (which can be set by regulatory constraints, or which can be assumed future scenarios specified by the user) are always adhered to, regardless of demand from other sources, although they can also be given a priority by the user to place minimum flow below agricultural demand for example. Finally, the surface reservoir component can be configured to store water from a number of sources. The operating criteria can be set which specify how much water must be stored, how much can be released, its role in flood mitigation etc.

Water is allocated to the various demands by prioritising those demands (Yates et al., 2005). Those with the top priority get water allocated first, then those with the next priority and so on until either each demand has been satisfied, or there is no more water left to distribute. This scheme means that in some cases, a demand may not get its full water requirement depending on availability. So a top priority demand node may not get all its water is the supply to that demand is limited. Full technical details, including the equations used in each of the components described above, are described by Yates et al. (2005).

7. Summary and Conclusions

This report has introduced the WASSERMed project, System Dynamics Modelling and conceptual modelling, SIMILE (the software environment to be used within this Work Package), the Decision Support System that was developed as part of the WaterStrategyMan project and that will also be used within this Work Package, and WEAP, another water balance simulation tool that may also be used alongside the first two. It has also provided a comparative overview table of various water-balance and decision-support software packages.

Water balance modelling for WASSERMed is essentially defining and simulating a system in terms of the input, output and storage of water within that system, whether it be natural, anthropogenic, or some combination of the two. Water balance modelling looks at defining these interactions to assess whether a system has too much water or whether it is under water stress. Future predictions of the water balance situation based on climate change and policy scenarios can also be simulated. WASSERMed aims to represent the water balance situation in the Mediterranean basin, focusing on five case studies that represent different challenges regarding water use and availability. WASSERMed will focus on representing the water balances of these case studies at the present day as a series of bespoke models. Further to this, using the latest climate change data, scenarios in the year 2050 will also be analysed. WASSERMed also aims to consider solutions to the problem of water stress and shortage in the Mediterranean region. WASSERMed will promote dialogue between academics, industry experts, stakeholders and local users, which will help elucidate these options, leading to better ideas of the potential risks to water supply and region security in the near-future, but also to effective, efficient ways to mitigate these climate-change induced effects.

System Dynamics Modelling (SDM) is a methodology for studying and managing complex feedback systems, typically used when formal analytical models do not exist, but system simulation can be developed by linking a number of feedback mechanisms. Visualisation of the system components is via specific software. This also allows for complex differential/integration equations to be simply solved. The visual nature of the interface allows for a user-friendly, participatory process, and as such can be used effectively as a decision support tool for stakeholders and experts. The SDM process is iterative, allowing a simple system to be developed in the first instance followed by adding ever more levels of complexity to the model as required. SDM models usually begin with a conceptual model, which is not linked to any mathematical software, but is intended as a simple way to visualise a system, how it works, and the links between its various components. Conceptual models of large and complex systems can be easily divided in various sub-models representing various components of the larger system. These sub-models are then linked together to form the main system. This process, like SDM creation, is also iterative and complexity can be built up as required. In WASSERMed, the SIMILE software package will be used for the formal development of the systems models for each case study. Two examples are presented from the AQUASTRESS project in which SDM modelling and SIMILE were both successfully employed. The main advantage of SDM, as compared to any other water balance modelling tool, is the flexibility of accepting any kind of variables/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. Thus it is possible to develop and adapt water balance models that will automatically give as output to the decision maker suitable indicators related to water security issues, that will be readily viewable and comparable among different scenarios/models. 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.

A previous EU Framework Project 'WaterStrategyMan' was introduced in order to review the Decision Support System (DSS) that was developed during this project. It is comparable to SIMILE and was used effectively during the project. SIMILE is preferred here for some tasks however because (a) it efficiently supports breaking the model into sub-models thus facilitating the development process of very complex systems and; (b) it can automatically produce model documentation (code) in C, thus making the model potentially re-usable for further specialised applications, if necessary. The DSS will also be used in WASSERMed because the WSM DSS can (i) optimise water allocation of limited water supply in different water use sectors and quantify the resulting environmental and economic impact from potential water shortages, and (ii) simulate and compare the impact of alternative measures for mitigating water scarcity.

Also to place SIMILE in context, the Water Evaluation And Planning (WEAP) system was also analysed, and it may be used within this Work Package. It too is a water balance and resource software package, similar to SIMILE. It also aims at being an interactive, participatory software tool to aid planners in making water supply/demand decisions while also taking into ecological and economic considerations. Various management options can also be analysed. WEAP has been designed as a planning tool, also aiming to include non-experts in the development process. WEAP essentially comprises of two modules: a physical hydrology module aimed at routing water through the system under study and a water allocation module which determines how much water is available for distribution then distributes it according to user-specified supply priorities. This may make WEAP less accessible than SIMILE as it is less 'generic', while SIMILE can be applied to many different dynamic systems, natural and anthropogenic, not just those concerned with water supply and demand.

In conclusion, WASSERMed aims to analyse water availability and security in southern Europe and the Mediterranean, and will focus on five specific case studies, each suffering different types of water scarcity and water related security threats, with each facing different challenges in the near-future. These water scarcity issues and challenges will be addressed within this Work Package by developing SDM or WSM models for all five case studies, using SIMILE and the WSM DSS as the SDM and decision-support modelling software. WEAP may also be applied alongside the first two by a WASSERMed partner (PIK) with specific expertise. SIMILE has been selected for its iterative approach, ease of linking to conceptual models, inclusive nature among scientists, industrial experts, decision-makers and the public, non-generic basis allowing great flexibility which is essential here as all five case studies are very different and ability to break down very complex systems into many easy-to-manage sub-models. SIMILE will be used in conjunction with the WSM DSS as described above. The WSM DSS has been chosen because it can (i) optimise water allocation of limited water supply in different water use sectors and quantify the resulting environmental and economic impact from potential water shortages, and (ii) simulate and compare the impact of alternative measures for mitigating water scarcity, while WEAP has been included because it may be suitable for some of the case studies, while PIK, a partner in the project, has significant expertise in using it.

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