



Water and energy sustainable management in irrigation systems network

Kaloyan N. Kenov, Helena M. Ramos

Civil Engineering Department and CEHIDRO, Instituto Superior Técnico, Technical University of Lisbon, Av. Rovisco Pais, 1049-001, Lisbon, Portugal.

Abstract

Water scarcity, water quality deterioration and the increasing demand for water and for renewable energy in water systems, require sound planning and management practices supported by computer modeling. Such management practices must ensure the sustainable use of water resources, including the achievement of a good status of water bodies as prescribed by the EU Water Framework Directive.

The purpose of this paper is to establish the applicability and limitations of two commercial software products to simulate the operation of a water system based on the Sorraia water project in Portugal. Particular attention was given to two products: (1) AQUATOOL, developed by the Universidad Politécnica de Valencia (UPV); and, (2) WEAP developed by the Stockholm Environment Institute (SEI).

The capabilities of the two models were analyzed focusing on the following aspects: (1) capability to reproduce the operation of a water system; (2) capacity to estimate the system's reliability to meet water demands; (3) easiness of the modeling process, including entry data requirements and presentation of results; (4) usefulness to support decisions of water authorities.

From the modeling activity process it is possible to conclude that: (1) AQUATOOL and WEAP are applicable in planning exercises, for which it is necessary to evaluate possible modifications in existing water systems and to analyze the effectiveness of resource exploitation policies, by taking into account objectives and infrastructure; and, (2) within certain modeling limitations, these software products can be used for water allocation predictions, multi-reservoir modeling, and reliability assessment of water systems.

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1. Introduction

Water is a finite natural resource, which needs sound and sustainable management practices to meet various demands, e.g. water consumption, irrigation, energy production, tourism, fisheries. Computer-supported assessment of water management practices and renewable energy production are important for the sustainable use of water. This is needed to ensure sufficient supply and quality of surface and ground waters as prescribed in the EU Water framework directive (WFD) (2000/60/CE) and in the Portuguese Water Act (Lei no. 58/2005).

Climate change has a direct impact on the availability, timing and variability of water supply. This puts an additional pressure on water systems and highlights the need for sound and sustainable management

practices. Adding to these direct impacts, there are the indirect impacts, those derived from changes in economic and social activities which may lead to new pressures on water systems, namely a water demand increase, a pollutant load increment or a significant change in the way we use our land and distribute our economic activities. Finally, water is needed and used to produce energy, which arguably does not increase emissions of CO₂ and other harmful gases.

The implementation of the EU WFD and of the Portuguese Water Act is an ongoing process and there is still a lack of modeling studies, especially in the selected study area of Sorraia in Portugal. The case area in this paper is turned into a hypothetical water system based on the Sorraia irrigation project built in the 1950s. The total irrigated area is 15,365 hectares. Water is stored in two reservoirs and conveyed downstream via an open-channel system.

The goal of this paper is to present an analysis of water systems management practices using simulation and optimization modeling tools, paying specific attention to the water-energy nexus. The software products analyzed in this paper are the AQUATOOL software product developed by the Universidade Politécnica de Valência and the WEAP product developed by the Stockholm Environment Institute (SEI). It was aimed to study whether these tools are capable to simulate and optimize water systems to meet water demands within water quantity and quality management practices, policies and targets adopted in Portugal. The rationale behind the use of the proposed tools lies in their flexibility for integration into the water management planning process, which aims to evaluate the present state and possible scenarios to water systems.

2. State-of-the-art

Modeling in the water sector is based on the simplified representation of water systems. This simplified description assist the model user to make estimates of the amount of water that needs to be supplied in order to meet present and future water demands scenarios, by taking into account social, economic, technical and environmental changes affecting the modeled system. Modeling of water systems is a powerful conceptual tool as it represents the interdependencies and interactions among the physical components, the water users and the water supply and demand management practices [1].

Generic simulation models are useful to obtain information and understanding on needed management steps that improve the water system management and planning processes. As the impacts of climate change are expected to intensify, models will become more needed and used as a way to predict scenarios regarding supply-demand water allocation interactions and will become invaluable in the assessment of the impacts on water operating rule modifications in order to set sustainable water management and supply measures. Appropriate intervention can reduce the impacts of climate change on water allocation and supply, resulting in mitigating economic, social, and environmental effects in water systems.

There are two prevailing water modeling practices: simulation and optimization. Simulation modeling of water resources is based on modeling representation of existing water allocation rules and on infrastructure operation. Simulation models answer “what if” questions and their input data define various water supply and water demand elements, as well as water supply systems’ configurations. The outputs can support the model user identify the water systems’ performance based on performance indicators. Five steps in simulation modeling can be generalized [*Ibid*]: (1) identification of needed information, (2) representation or modeling of the behavior of operating rules of the systems, (3) establishment of an environment in which input data and operating rules co-exist, (4) calibration and validation of the model, (5) model use.

Optimization modeling of water resources is based on the optimization of an allocation objective function of unknown decision variables, which need to satisfy certain imposed constraints. The joint use of simulation and optimization tools allows the assessment and improvement of water resources management practices. [2, 3] provide a description of approaches that have been proposed in the past.

The Decision Support System (DSS) is a computer system, which integrates analytical and information management tools, which interact with the user who needs to make decision about ill-defined water resources management problematic situations. More precisely, these systems are used to tackle the complex interrelations among the physical, socio-economic and environmental components of problematic situations. Generic simulation models are usually used as the core of such DSS. The DSS can assist at different levels of detail ranging from simple screening models for guiding data collection activities through the system’s Graphical User Interface (GUI) to complex assessment tools. However,

the existing DSS tend to focus exclusively on some model component or are restricted only on some aspect of the problematic situation.

Typically, a DSS consists of three subsystems: (1) a GUI, (2) model management, and (3), information management [4]. A DSS also has the following architecture: (1) data measurement: data gathering tasks, (2) data processing: data registration, retrieval and storage tasks, (3) analysis: formulation of decision alternatives, (4) decision support: gathering and merging of conclusions from knowledge-based and numerical techniques and the interaction of the users with the computer system through the GUI, (5) decision implementation: formulation of action steps to be implemented for the solution of a problematic situation.

Numerous generic models exist for multi-purpose water resources systems simulation and optimization [5]. For example, the SUPER model developed in the 1970s at the Dallas Southwestern Division office has been applied to reservoir systems in the Fort Worth, Tulsa and Little Rock Districts. HEC-ResSim is a reservoir simulation component of the US Corps Water Management System (CWMS). MODSIM was developed at Colorado State University and has been applied to studies of the Bureau of Reclamation and various other entities. OASIS (Operational Analysis and Simulation of Integrated Systems) is developed by Hydrologics, Inc. This is a general purpose water simulation model. Simulation is accomplished by solving a linear optimization model subject to a set of goals and constraints for every time step within a planning period. OASIS uses an object-oriented GUI to set up a model, similar to ModSim. A river basin is defined as a network of nodes and arcs using an object-oriented graphical user interface. Oasis uses Microsoft Access for static data storage, and HEC-DSS for time series data. The Operational Control Language (OCL) within the OASIS model allows the user to create rules that are used in the optimization and allows the exchange of data between OASIS and external modules while OASIS is running. OASIS does not handle groundwater or water quality, but external modules can be integrated into OASIS [6]. Aquarius is a temporal and spatial allocation model for managing water among competing uses. The model is driven by economic efficiency which requires the reallocation of all flows until the net marginal return of all water uses is equal. In the GUI, the components are represented by icons, which can be dragged and dropped from the menu creating instances of the objects on the screen. These can be positioned anywhere on the screen or removed. Once components are placed on the screen, they are linked by river reaches and conveyance structures. The model does not include groundwater or water quality. The model could be used to evaluate net benefits by subtracting costs from benefits in the individual benefit functions [7]. RiverWare was developed for application to the US Bureau of Reclamation and the Tennessee Valley Authority reservoir systems and is now also applied to other reservoir/river systems. RiverWare is a reservoir and river system that can be used as a operation and planning tool. The model can be tailored to a specific site by using a GUI for the selection of reservoirs, reach confluences and other objects. Data for each object can be either imported from files or provided by the user. RiverWare can model short-term (hourly to daily) operations and scheduling, mid-term (weekly) operations and planning, and long-term (monthly) policy and planning. Operating policies are created using a constraint editor or a rule-based editor depending on the solution method used. The user constructs an operating policy for a river network and supplies it to the model. RiverWare has the capability of modeling multipurpose reservoir uses consumptive use for water users, and simple groundwater and surface water return flows. Water quality parameters including temperature, total dissolved solids and dissolved oxygen can be modeled in reservoirs and reaches. Reservoirs can be modeled as simple, well-mixed or as a two layer model. Additionally, water quality routing methods are available with or without dispersion [8].

WaterWare is a DSS system based on linked simulation models that utilize data from an embedded GIS, monitoring data including real-time data acquisition, and an expert system. The system uses a multimedia user interface with Internet access, a hybrid GIS with hierarchical map layers, object databases, time series analysis, reporting functions, an embedded expert system for estimation, classification and impact assessment tasks, and a hypermedia help- and explain system. The system integrates the inputs and outputs for a rainfall-runoff model, an irrigation water demand estimation model, a water resources allocation model, a water quality model, and groundwater flows and pollution model [9]. CALSIM (California Water Resources Simulation Model) was developed by the California State Department of Water Resources. The model is used to simulate existing and potential water allocation and reservoir operating policies and constraints that balance water use among competing interests. Policies and priorities are implemented through the use of user-defined weights applied to the flows in the system. Simulation cycles at different temporal scales allow the successive implementation

of constraints. The model can simulate the operation of relatively complex environmental requirements and various state and federal regulations [10].

3. Methodology

3.1 Study area

The selected study area is based on the Sorraia hydro-agricultural complex, located along the valleys of Sorraia, Magos, Seda, Raia and Sôr rivers, near Lisbon, Portugal. The complex, presented in Figure 1, comprises the areas of Ponte de Sôr (531 ha) and Avis (1,027 ha), the Portalegre district in the area of Mora (1,600 ha), the Mora district (1,600 ha), the Evora district, and the Coruche (7,702 ha), Benavente (4,132 ha) and Salvaterra de Magos (1,359 ha) areas, which are part of the Santarém district. The Sorraia valley project was built between 1951 and 1959.

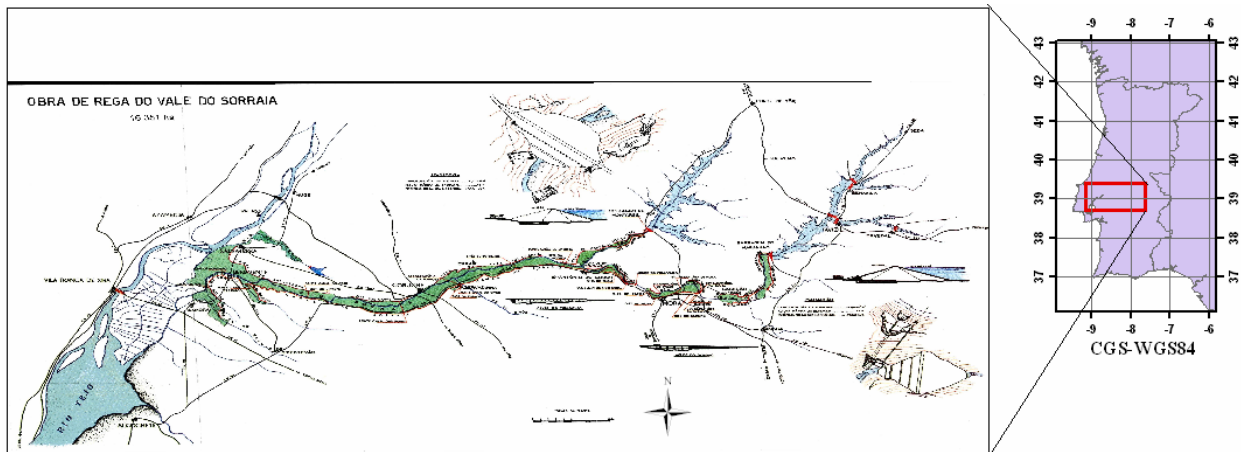


Figure 1. Geographic location of the Sorraia hydro-agricultural complex

The complex supplies water to a total area of 16,351 ha, of which, 15,365 ha belong to the Sorraia valley project. The Campos de Salvaterra de Magos water protection system (427 ha) and the Foros do Paúl de Coruche (24 ha) also belong to the Sorraia valley project.

The hypothetical water system is presented as a conceptual diagram in Figure 2. This hypothetical system has water inflows from the rivers Sôr, Seda, Almadale, Tera, Divor, Erra, Trejoito and ST0. Estevao. It consists of the Magos reservoir (capacity 3,000 x 1,000 m³), located on the Magos river, two upstream reservoirs, Montargil (capacity 142,700 x 1,000 m³), located on river Sôr, and Maranhão (capacity 180,900 x 1,000 m³), located on river Seda. This system also has two small diversion dams, Gameiro (capacity 1,300 x 1,000 m³) and Furadouro (capacity 400 x 1,000 m³), located on river Raia. The existing Sorraia project has ten elevation pump stations: Barroca, Moita, Mora, Paços, Engal, Formosa, Porto Seixo, Borrvalho, Bilrete, Montalvo, which were not included into the hypothetical water system due to software limitations. Two upstream reservoirs, Montargil and Maranhão, and a small diversion dam, Gameiro, have each a hydroelectric power station, although not included in the hypothetical system. Table 1 lists the elements considered for this study. In the real water system, water distribution is undertaken by an irrigation network with a total length of 395,026 m, 124,876 m of which constitute the primary irrigation network and 270,150 m constitute the secondary network. The irrigation network is an open concrete-lined canal network (main and secondary or distributors and channels) which delivers water to nine demand site areas: Cabeção, Camões, Mora, Furadouro, Venda, Sôr, Coruche, Benavente and Samora. The number of industrial and agricultural beneficiaries in these demand sites varies from year to year, and in 1996 this number was 1722, each with respective water demand needs. The demand sites are connected to the network via demand links presented as red dashed lines (Table 1).

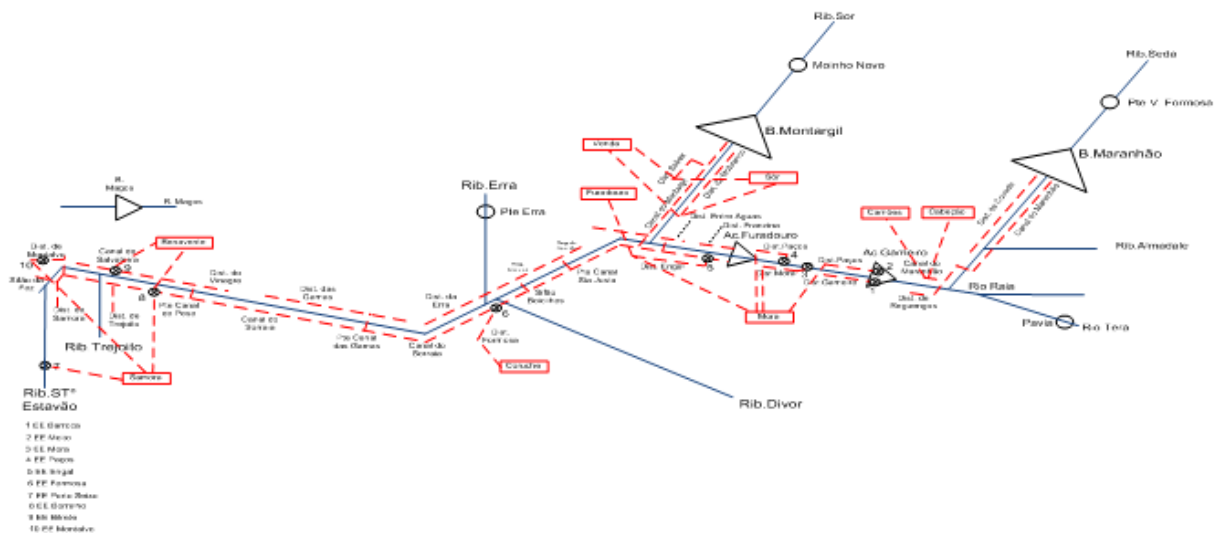


Figure 2. Conceptual scheme of the hypothetical water system

Table 1. Considered and not considered elements

Element type and name	Symbol	Color scheme	Considered
Reservoirs			
Magos			No
Montargil	Δ	Black	Yes
Maranhão	Δ	Black	Yes
Gameiro	Δ	Black	Yes
Furadouro	Δ	Black	Yes
Water inflows			
Seda	-	Blue	Yes
Almadale	-	Blue	Yes
Tera	-	Blue	Yes
Divor	-	Blue	Yes
Erra	-	Blue	Yes
Sor	-	Blue	Yes
STo Estevão	-	Blue	Yes
Trejoito	-	Blue	Yes
SNIRH hydrological monitoring stations			
Moinho Novo (on river Sôr)	O	Black	Yes
Pte. V. Formosa (on river Seda)	O	Black	Yes
Pavia (on river Tera)	O	Black	Yes
Pte Erra (on river Erra)	O	Black	Yes
Channel type 1			
Seda	-	Blue	Yes
Raia	-	Blue	Yes
C. do Maranhão	--	Red	Yes
Dist. da Reguengos	--	Red	Yes
Dist. da Cabecao	--	Red	Yes
Dist. Gameiro	--	Red	Yes
Dist. Gameiro	--	Red	Yes
Dist. Mora	--	Red	Yes
Dist. Pacos	--	Red	Yes
C. do Sorraia	--	Red	Yes
Dist. Engal	--	Red	Yes

Table 1. Continued

Dist. do Mobraço	--	Red	Yes
Dist. Sebes	--	Red	Yes
C. Montargil	--	Red	Yes
Dist. Formosa	--	Red	Yes
Pte. Canal do Peso	--	Red	Yes
C. Salvaterra	--	Red	Yes
Dist. de Montalvo	--	Red	Yes
STo. Estevo	-	Blue	Yes
Dist. Barroca			No
C. Barrosa-Foz			No
C.Peso-Salvaterra			No
Dist Colmiero-Vinagre			No
Demand site areas			
Cabeção	□	Red	Yes
Camões	□	Red	Yes
Mora	□	Red	Yes
Sôr	□	Red	Yes
Venda	□	Red	Yes
Furadouro	□	Red	Yes
Coruche	□	Red	Yes
Benavente	□	Red	Yes
Samora	□	Red	Yes
Elevation pump stations			
Barroca	⊗	Black	No
Moita	⊗	Black	No
Mora	⊗	Black	No
Paços	⊗	Black	No
Engal	⊗	Black	No
Formosa	⊗	Black	No
Porto Seixo	⊗	Black	No
Borrvalho	⊗	Black	No
Bilrete	⊗	Black	No
Montalvo	⊗	Black	No

3.2 Software selection

There are various private and public organizations, which develop commercial simulation products with interactive GUI. AQUATOOL and WEAP were selected based on the following criteria: (1) capability to conduct simulations; (2) to have a GUI; and, (3) vendor price. AQUATOOL is developed by the Universidad Politécnica de València (UPV) and WEAP is developed by the Stockholm Environment Institute's Boston Center (Tellus Institute).

These two software products are representative DSS / water allocation models and are used for the analysis of water management plans, policies and scenarios. AQUATOOL was used to model water quality issues (Manzanares River), for the evaluation of impacts of policy measures under different scenarios (Red River) and was extensively used by water authorities in Spain. WEAP was used to develop and evaluate adaptation strategies to alleviate climate changes and variability (Sacramento Basin), for the planning and evaluation of reservoirs (Sao Francisco River Basin, Volta River Basin, Limpopo River Basin).

3.2.1 AQUATOOL: Features

AQUATOOL ver, 4.40 is a generic decision-support system (DSS) [11]. The product was originally designed for the planning stage of decision-making associated with complex river basins. This software is implemented within the Microsoft Windows Environment and it was written in C++, Visual Basic and in FORTRAN. AQUATOOL has an AQUATOOLDMA GUI interface or working environment, for the

development and analysis of decision support systems for watershed planning and management. AQUATOOLDMA is used to control the following modules/models:

- SIMGES Model for basin simulation and management including conjunctive use;
- OPTIGES Module for optimizing basin management;
- GESCAL Module for the simulation of water quality in complete basins;
- SIMRISK Module;
- GRAFDMA Module for viewing:
 - Schemes
 - Shapefiles

For this simulation study, the AQUATOOL SIMGES Simulation Model of Water Resource was used. SIMGES is a general management simulation model for basins or complex water resources systems, which contains surface and underground elements for regulation and storage, intake, transport, consumption/use and artificial recharge.

The following elements are considered in SIMGES:

- Surface reservoirs;
- Intermediate inflows;
- Five types of channels;
- Consumptive demands;
- Return elements;
- Non-consumptive demands (hydroelectric power stations);
- Artificial recharge;
- Additional extraction facilities;
- 9 types of aquifers.

Results include monthly or annual evolution of the variables, and average simulation period variables and reliability.

Simulation is performed on a monthly scale and the model reproduces water flow through the system represented as a network of elements, at a level of detail specified by the user. Surface subsystem flows are calculated by continuity or balance. For underground subsystems or aquifers, flows can be simulated by single or multi-cellular models, as required by the user, or by distributed linear flow models. The system computes evaporation and infiltration losses from reservoirs and riverbeds and the interaction between surface and ground waters.

The simulation and management of the surface subsystem are run simultaneously by means of a conservative flow network optimization algorithm. The model user defines a scheme, which is a non-conservative flow network since it is not a closed system and there are storage nodes (corresponding to reservoirs). After first reading of the input data, the model modifies the scheme to a conservative network. This means that the model establishes "closing" nodes and then extends pattern elements into a sub-scheme of arcs and nodes to ensure the correct simulation of the hydraulic behavior and element management. This will give the model a complex and conservative "internal flow network". For each monthly period, the conservative flow network is solved by optimization with the corresponding inflows, reservoir evaporation, demands and operating rules, such as alarm indicators and sharing of water deficit. Water resources management is carried out by operating rules, which tend to maintain similar water levels in reservoirs, based on the initial reservoir zoning curves entered by the model user. Minimum ecological flows and different mode user's priorities can be defined as well. Iterations are performed and values are stored for annual accounting and statistics. Finally, after completing the simulation period, the relevant statistics are generated and water supply guarantees are calculated.

3.2.2 WEAP: Features

WEAP is a water balance software program, which was designed to assist water management decision makers in evaluating water policies and developing sustainable water resource management plans. WEAP operates following the basic principles of water balance accounting and links water supplies from rivers, reservoirs and aquifers with water demands, in an integrated system with scenarios constructed by the model user.

WEAP can simulate sectorial demand analyses, water conservation, water rights, allocation priorities, groundwater withdrawal and recharge, stream flow simulation, reservoir operations, hydropower generation, pollution tracking (fully mixed, limited decay), and project cost/benefit analyses.

Groundwater supplies can be included in the WEAP model by specifying a storage capacity, a maximum withdrawal rate and the rate of recharge. Minimum monthly in-stream flows can be specified. The following elements are considered in WEAP:

- Demand sites;
- Catchments;
- Reservoirs, local reservoirs, other water supply sources;
- Run-of-river hydropower;
- Flow requirements;
- Withdrawals;
- Diversions;
- Tributaries;
- Return flows;
- Stream-flow gauges;
- Groundwater;
- Transmission links;
- Run-off/Infiltration links;
- Return flow links;
- Waste water treatment plants.

WEAP calculates a water and pollution mass balance for every element in the system on a monthly time step. Water is dispatched to meet in-stream and consumptive requirements, subject to demand priorities, supply preferences, mass balance and other constraints.

WEAP operates on a monthly time step, from the first month of the Current Accounts year through the last month of the last scenario year. Each month is independent of the previous month, except for reservoirs and aquifers storage. Thus, all of the water entering the system in a month (e.g., headflow, groundwater recharge, or runoff into reaches) is either stored in an aquifer or reservoir, or leaves the system by the end of the month (e.g. outflow from end of river, demand site consumption, reservoir or river reach evaporation, transmission and return flow link losses). Because the time scale is relatively long (month), all flows are assumed to occur instantaneously. Thus, a demand site can withdraw water from the river, consume some, return the rest to a wastewater treatment plant that treats it and returns it to the river. This return flow is available for use in the same month to downstream demands.

Each month the calculations follow this order:

1. Annual demand and monthly supply requirements for each demand site and flow requirement.
2. Runoff and infiltration from catchments, assuming no irrigation inflow.
3. Inflows and outflows of water for every node and link in the system. This includes calculating withdrawals from supply sources to meet demand, and dispatching reservoirs. This step is solved by a linear program (LP), which attempts to optimize coverage of demand sites' and instream flows' requirements, subject to demand priorities, supply preferences, mass balance and other constraints.
4. Pollution generation by demand sites, flows and treatment of pollutants, and loadings on receiving bodies, concentrations in rivers.
5. Hydropower generation.
6. Capital and Operating Costs and Revenues.

A linear program (LP) is used to maximize satisfaction of water demand sites and instream flow requirements, subject to demand priorities, supply preferences, mass balance and other constraints.

Mass balance equations are used for monthly water accounting: total inflows equal total outflows, net of any change in storage (in reservoirs and aquifers). Every node and link in WEAP has a mass balance equation, and some have additional equations, which constrain their flows (e.g., inflow to a demand site cannot exceed its supply requirement, outflows from an aquifer cannot exceed its maximum withdrawal, link losses are a fraction of flow, etc.). Each mass balance equation becomes a constraint in the LP.

WEAP tries to maximize supply to demands sites, subject to all constraints and priorities. Demand sites are allocated water depending on demand priorities, supply preferences, and water availability. WEAP iterates for each priority and preference, so that demands with priority 1 are allocated water before those with priority 2. Thus, the LP is solved at least once for each priority for each time step. When solving for priority 1, WEAP will temporarily turn off (in the LP) allocations to demands with priority 2 and lower. Then, after priority 1 allocations have been made, priority 2 demands are turned on (but 3 and lower are still turned off).

Because the goal is to maximize the coverage rate (reliability) for all demand sites, the objective function maximizes CoverageFinal. In cases where there is not enough water to satisfy all demands with the same priority, WEAP tries to satisfy all demands to the same percentage of their demand.

3.3 Basic equations

3.3.1 AQUATOOL

For this paper, the following AQUATOOL elements were considered:

1. Surface reservoirs: including inter-basin flow. These are defined by their physical and management parameters (maximum volumes, target volumes and storage priority over other reservoirs).
2. Intermediate inflows: these are inflows that cannot or should not be considered as direct reservoir inflows.
3. Channels: it is possible to model five channel types, of which, channel type 1 was selected for use in this study. Channel type 1 is defined as river reaches, canals, etc., associated to their physical parameters (including maximum capacity) and possible minimum flows (normally ecological).
4. Consumptive demands: Consist of elements that use water, part of which is consumed and therefore lost to the system. This type includes irrigation zones and industrial and urban demands. They are defined by their demand curves, consumption parameters, intakes and connection to a return element. Individual consumptive demands can be supplied from different sources.

3.3.1.1 Priorities

A reservoir storage priority number is defined for each reservoir. In this way, the model will not use water from the intermediate zone of a reservoir until all the water has been used from the upper zones of all the remaining reservoirs. If two reservoirs are in the same zone, the model will first take water from the reservoir with the highest storage priority number. Priority numbers for each intake must also be defined with a relationship to the priority numbers of the rest of the demand zones.

3.3.1.2 Mass balance equations

Surface reservoirs correspond to points in the scheme at which there is water storage capacity and are basic management elements. Simulation is performed by mass balance, so that the end-of-month volume V_f , can be expressed as:

$$V_f = V_i + A_e + A_a - P_f - E - S_c - S_v \quad (1)$$

where V_i is the start-of-month volume, A_e is the reservoir hydrological inflow, A_a are inflows from upstream of the reservoir, P_f are seepage losses, E are losses due to evaporation, S_c are controlled releases, i.e. those that do not exceed reservoir drainage capacity, including intakes inside the reservoir, S_v are uncontrolled releases due to excess capacity that cannot be dealt with by controlled drainage. Seepage losses are calculated as a function of the instantaneous volume and other input parameters provided by the model user.

3.3.1.3 Management of the reservoir

The management of the basin reservoirs is done in such a way that they are all kept as far as possible within the same capacity zone, considered as the model user's definition of monthly target volume, V_{obj} , and monthly minimum volume, V_{min} , the zones being automatically defined as follows:

- Upper zone: between V_{max} and V_{obj}
- Intermediate zone: between V_{obj} and $V^* = \frac{1}{2}(V_{obj} + V_{min})$
- Lower zone: between V^* and V_{min}
- Reserve zone: between V_{min} and empty.

A storage priority number in reservoir, N_p , is also defined for each reservoir.

In this way, the model will not use water from the intermediate zone of a reservoir until all the water has been used from the upper zones of all the other reservoirs. If two reservoirs are in the same zone, the model will first take water from the reservoir with the highest storage priority number. When a reservoir is in the reserve zone, for the following months no water can be taken.

3.3.1.4 Target function

To solve the system management problem, the program constructs a conservative flow network, which it solves by optimization. When solving flow network optimization, the model uses the following target function for each month:

Minimize:

$$T_E + T_{R1} + T_{R2} + T_{R3} + T_{R4} + T_{R5} + T_{DC} + T_{DN} + T_{RA} + T_{BA} \quad (2)$$

where T_E is a term for reservoirs, T_{R1} is a term for type 1 river reaches, T_{R2} is a term for type 2 river reaches, T_{R3} is a term for type 3 river reaches, T_{R4} is a term for type 4 river reaches, T_{R5} is a term for type 5 river reaches, T_{DC} is a term for consumptive demands, T_{DN} is a term for non-consumptive demands, T_{RA} is a term referring to artificial recharges. T_{BA} is a term referring to additional extraction

The terms T_{R2} , T_{R3} , T_{R4} , T_{R5} , T_{DN} , T_{RA} and T_{BA} were not considered in this study. For this reason, only the contributions of the terms T_E , T_{R1} and T_{DC} to the objective function will be described in the following sections. The terms are subject to mass conservation constraints (continuity) and to the physical transport limits imposed by channels and the capacities of reservoirs and other elements.

Reservoir elements

Given the configuration of the internal network created for a reservoir element, its contribution to the target function is:

$$T_E = \sum_{i=1}^{nemb} \left(\left(\sum_{j=1}^4 V_{ij} CE_{ij} \right) + P_i CV \right) \quad (3)$$

where $nemb$ is the number of reservoirs, V_i is the month-end volume in each zone j , $j=1,2,3$ and 4 of reservoir i . Zone 1 is the reserve, 2 is the lower zone, 3 the intermediate and 4 the upper zone, P_i is (uncontrolled) releases from reservoir i , CE_{ij} is the fictitious cost associated with the volume stored in zone j , and is given by:

$$CE_{ij} = k_j + NP_i \quad (4)$$

where k_j are pre-established values (by default, they are: $k_1=-1700$; $k_2=-1100$; $k_3=-1000$; $k_4=-700$) and NP_i is the priority number assigned to the reservoir, and CV is the fictitious cost associated with overflow (default $CV=2000$).

Type 1 channels

Given the configuration for a type 1 river reach in the internal network, we have:

$$T_{R1} = \sum_{i=1}^{ntr1} (D_i CD_i + Q_i CQ_i) \quad (5)$$

where $ntr1$ is the number of type 1 river reaches, Q_i is the flow in river reach i . If a minimum flow has been defined in the river reach, the value of Q_i will be the maximum between actual flow and the defined minimum flow. A fictitious cost in a river reach is therefore not added to the cost associated with the minimum flow deficit. D_i is the deficit with respect to the declared minimum flow. CD_i is the fictitious cost associated with minimum flow deficit given by:

$$CD_i = KD - NP_i \quad (6)$$

where KD is a constant value (default $KD = 2000$) and NP_i is the priority number assigned to minimum flow in river reach i .

Consumptive demands

Given the configuration of the internal network generated by consumptive demand elements, the strict formula is:

$$T_{DC} = \sum_{i=1}^{ndc} \left(D_i CK + \sum_{t=1}^{ntoi} (S_{it} (CT_{it} + 1) - DS_{it} CT_{it}) \right) \quad (7)$$

$$CT_{it} = -CTC + (NP_{it} - 1)CDC \quad (8)$$

where ndc is the number of consumptive demands, D_i is the deficit of total demand of zone i for the month under study, CK is a constant fictitious cost associated with the deficits of the demand zones ($CK=750$ by default), $ntoi$ is the number of intakes of demand I , S_{it} is gross supply to intake t of demand I , DS_{it} is the deficit of minimum gross supply calculated by the model, CTC and CDC are constants ($CTC=750$, $CDC=5$, by default), NP_{it} is the priority number of intake t of demand i .

3.3.1.5 Explanation of the system management as a consequence of the target function

Since the target function is a minimization-type function, and since the contributions to it are the costs corresponding to the variables explained by (Eqs.3-4), the optimization algorithm used in AQUATOOL tries to increase the value of the variables with the lowest cost.

Reservoirs

From Eqs. 3-4 it can be concluded that a unit of water stored in reservoir zone j involves an increase in the target function given by Eq. 4, which, since k_j are negative by default, in fact mean a decrease in the target function. As NP_i increases, the value of the target function also increases, so that the algorithm will tend store water in the j zone of a reservoir with lower NP_i than in one with higher NP_i . However, since $|k_{j+1}| \ll |k_j|$, the algorithm will tend to store in the j zone of reservoir i before the $j+1$ zone of reservoir k , even if $NP_i < NP_k$. The result will therefore be to keep both reservoirs at the same level and to take water first from the one with the highest NP_i .

With the default values k_j ($k_1=-1700$, $k_2=-1100$, $k_3=-1000$, $k_4=-700$) we see that water can be taken from any zone to satisfy demands, except from the reserve zone, which will remain untouched, since it is at level 1700 while demands were at level 1500.

The cost associated with uncontrolled releases is simply to avoid the algorithm sending water through this part of the network before the reservoir is full. If there were several reaches with ecological flow situated in series downstream, then we could have the situation of extracting water from the reservoir by spillage, which would not correspond to the physical reality of the system. Any such situations must be detected by the user.

Channel type 1

From Eqs. 5 and 6 it can be concluded that a unit of water that does not pass through a minimum flow channel until the minimum is reached implies an increase in the target function of:

$$F = CD_i = KD - NP_i \quad (9)$$

a deficit unit in the minimum flow in a channel with priority 1 implies an increase in the target function of 1999 units, with priority 2 of 1998, and so on.

Consumptive demands

From an analysis of Eqs. 7 and 8 it can be concluded that a unit of water that is not supplied to demand i through intake t involves an increase in the target function whose value is:

$$F = CK + CTC - NP_{it}CDC + CDC - 1 \quad (10)$$

which, given the default values of CK , CTC and CDC of 750, 750 and 5, respectively, imply that:

$$F = 1504 - 5NP_{ii} \quad (11)$$

which means that a deficit unit in a zone with priority $NP_{ii}=1$ increases the target function by 1499 cost units, and a unit with priority of 2 increases it by 1494 and so on. It can thus be seen that the model will first try to satisfy the demands with the lowest priority number.

3.3.2 WEAP

For this study, the following elements have been considered in WEAP:

- Reservoir nodes, which represent reservoir sites on a river. A river reservoir node can release water directly to demand sites or for use downstream, and can be used to simulate hydropower generation.
- Rivers and diversions: both rivers and diversions in WEAP are made up of river nodes are river nodes connected by river reaches. Other rivers may flow in (tributaries) or out (diversions) of a river.
 - Diversion nodes, which divert water from a river or other diversion into a canal or pipeline called a diversion. This diversion is itself, like a river, composed of a series of reservoir, run-of-river hydropower, flow requirement, withdrawal, diversion, tributary and return flow nodes.
 - Tributary nodes define points where one river joins another. The inflow from a tributary node is the outflow from the tributary river.
- Transmission links deliver water from surface water (reservoir nodes, and withdrawal nodes), groundwater and other supplies to satisfy final demand at demand sites. In addition, transmission links can deliver wastewater outflows from demand sites and wastewater treatment plants to other demand sites for reuse. WEAP uses two user-defined systems to determine the water allocation along each transmission link in each month, as described in Priorities for Water Allocation.
- Demand sites are a set of water users that share a physical distribution system, that are all within a defined region, or that share an important withdrawal supply point. The user can lump demands together into aggregate demand sites (e.g., counties) or to separate key water uses into individual demand sites. The level of aggregation is generally determined by the level of detail of the available water use data. Demand data may not be available for individual sites, but may only be available for a larger unit such as a city or county. In addition to data, the definition of demand sites may also depend on the level of detail desired for the analysis. Each demand site needs a transmission link from its source, and where applicable, a return link either directly to a river, wastewater treatment plant or other location. The demand site cannot be placed directly on the river. The user-defined priority system determines the order of allocations to demand sites.

3.3.2.1 Priorities

Two user-defined priority systems are used to determine allocations from supplies to demand sites and catchments (for irrigation), for in-stream flow requirements, and for filling reservoirs.

Competing demand sites and catchments, the filling of reservoirs, and flow requirements are allocated water according to their demand priorities. The demand priority is attached to the demand site, catchment, reservoir (priority for filling), or flow requirement. Priorities can range from 1 to 99, with 1 being the highest priority and 99 the lowest. Reservoir priorities default to 99, meaning that they will fill only if water remains after satisfying all other demands. Many demand sites can share the same priority. If a demand site or catchment is connected to more than one supply source, the user may rank its choices for supply with supply preferences. The supply preferences are attached to transmission links. Using the demand priorities and supply preferences, WEAP determines the allocation order to follow when allocating the water. The allocation order represents the actual calculation order used by WEAP for allocating water.

3.3.2.2 Mass balance equations

Mass balance equations are the foundation of WEAP's monthly water accounting: total inflows equal total outflows, net of any change in storage (in reservoirs and aquifers). Every node and link in WEAP has a mass balance equation, and some have additional equations which constrain their flows (e.g., inflow to a demand site cannot exceed its supply requirement, outflows from an aquifer cannot exceed its maximum withdrawal, link losses are a fraction of flow, etc.).

A reservoir's (Res) storage in the first month (m) of the simulation is specified as data.

$$\text{BeginMonthStorage}_{Res,m} = \text{InitialStorage}_{Res} \quad \text{for } m=1 \quad (12)$$

Thereafter, it begins each month with the storage from the end of the previous month.

$$\text{BeginMonthStorage}_{Res,m} = \text{EndMonthStorage}_{Res,m-1} \quad \text{for } m>1 \quad (13)$$

This beginning storage level is adjusted for evaporation. Since the evaporation rate is specified as a change in elevation, the storage level must be converted from a volume to an elevation. This is done using the volume-elevation curve.

$$\text{BeginMonthElevation}_{Res} = \text{VolumeToElevation}(\text{BeginMonthStorage}_{Res}) \quad (14)$$

The elevation is reduced by the evaporation rate.

$$\text{AdjustedBeginMonthElevation}_{Res} = \text{BeginMonthElevation}_{Res} - \text{EvaporationRate}_{Res} \quad (15)$$

Then the adjusted elevation is converted back to a volume.

$$\text{AdjustedBeginMonthStorage}_{Res} = \text{ElevationToVolume}(\text{AdjustedBeginMonthElevation}_{Res}) \quad (16)$$

A reservoir's operating rules determine how much water is available in a given month for release, to satisfy demand and instream flow requirements, and for flood control. These rules operate on the available resource for the month. This "storage level for operation" is the adjusted amount at the beginning of the month, plus inflow from upstream and return flows from demand sites (DS) and treatment plants (TP).

$$\text{StorageForOperation}_{Res} = \text{AdjustedBeginMonthStorage}_{Res} + \text{UpstreamInflow}_{Res} + \sum_{DS} \text{DS ReturnFlow}_{DS,Res} + \sum_{TP} \text{TP ReturnFlow}_{TP,Res} \quad (17)$$

3.3.2.3 Management of the reservoir

The amount available to be released from the reservoir is the full amount in the conservation and flood control zones and a fraction of the amount in the buffer zone. Each of these zones is given in terms of volume (i.e. not elevation) as:

- Flood control Zone
- Conservation Zone
- Buffer Zone
- Inactive Zone

The water in the inactive zone is not available for release.

$$\text{StorageAvailableForRelease}_{Res} = \text{FloodControlAndConservationZoneStorage}_{Res} + \text{BufferCoefficient}_{Res} \times \text{BufferZoneStorage}_{Res} \quad (18)$$

All of the water in the flood control and conservation zones is available for release, and equals the amount above Top Of Buffer:

$$\text{FloodControlAndConservationZoneStorage}_{Res} = \text{StorageForOperation}_{Res} - \text{TopOfBuffer}_{Res} \quad (19)$$

or zero if the level is below Top Of Buffer.

$$\text{FloodControlAndConservationZoneStorage}_{Res} = 0 \quad (20)$$

Buffer zone storage equals the total volume of the buffer zone if the level is above Top Of Buffer,

$$BufferZoneStorage_{Res} = TopOfBufferZone_{Res} - TopOfInactiveZone_{Res} \quad (21)$$

or the amount above Top Of Inactive if the level is below Top of Buffer,

$$BufferZoneStorage_{Res} = StorageForOperation_{Res} - TopOfInactiveZone_{Res} \quad (22)$$

or zero if the level is below Top Of Inactive.

$$BufferZoneStorage_{Res} = 0 \quad (23)$$

WEAP will release only as much of the storage available for release as is needed to satisfy demand and instream flow requirements, in the context of releases from other reservoirs and withdrawals from rivers and other sources. (As much as possible, the releases from multiple reservoirs are adjusted so that each will have the same fraction of their conservation zone filled. For example, the conservation zone in a downstream reservoir will not be drained while an upstream reservoir remains full. Instead, each reservoir's conservation zone would be drained halfway).

The storage at the end of the month is the storage for operation minus the outflow.

$$EndMonthStorage_{Res} = StorageForOperation_{Res} - Outflow_{Res} \quad (24)$$

The change in storage is the difference between the storage at the beginning and the end of the month. This is an increase if the ending storage is larger than the beginning, a decrease if the reverse is true.

$$IncreaseInStorage_{Res} = EndMonthStorage_{Res} - BeginMonthStorage_{Res} \quad (25)$$

3.3.2.4 Target function

Reservoirs

Reservoirs with storage levels below the top of conservation pool are treated like demand sites so that WEAP will not drain them unless to meet downstream demands, and to try to fill them up when there is surplus surface water. Where multiple reservoirs with the same demand priority exist, WEAP will try to fill them up to same level (as a % of the top of conservation pool), just as it will try to satisfy demand sites to the same percentage of their demand.

Demand site

WEAP strives to maximize supply to demands sites, subject to all constraints and priorities. Demand sites are allocated water depending on demand priorities and supply preferences. WEAP iterates for each priority and preference, so that demands with priority 1 are allocated water before those with priority 2. Thus, the LP is solved at least once for each priority for each time step. When solving for priority 1, WEAP will temporarily turn off (in the LP) allocations to demands with priority 2 and lower. Then, after priority 1 allocations have been made, priority 2 demands are turned on (but 3 and lower are still turned off).

A new LP variable is created for each demand site, which will equal its "coverage"- percent of demand satisfied.

$$\sum Inflow_{DS} = SupplyRequirement_{DS} \times Coverage_{DS} \quad (26)$$

Because the goal is to maximize the coverage rate for all demand sites, the objective function maximizes the final Coverage.

Because WEAP tries to satisfy all demand sites with the same priority equally (in terms of percentage of demand), additional constraints are added to the LP. Each coverage variable is set equal to a new variable

that represents the final coverage. In this way, all the coverages being solved for must be equal. In other words, in cases where there is not enough water to satisfy all demands with the same priority, WEAP tries to satisfy all demands to the same percentage of their demand. (The coverage constraints ensure this).

3.4 Comparison

Both AQUATOOL and WEAP are software products based on optimization methods for the studied period and the results are used for performing simulations. In AQUATOOL, the simulation and management of the network are simultaneously executed, and the conservative flow network optimization problem is solved for each month in the simulation period. In WEAP, a standard linear program is used to solve the water allocation problem at each time step. Its objective is to maximize satisfaction of demand based on supply preferences and demand priorities. These two software products are capable of simulating operating rules. In AQUATOOL, operating rules are fixed and in WEAP they are defined as a combination of system states and hydrologic conditions. Both AQUATOOL and WEAP include the concepts of priorities and preferences. AQUATOOL and WEAP can also be used for water quality modeling, where WEAP can be linked to the US EPA QUAL2E modeling framework in order to provide highly detailed and comprehensive modeling of water quality conditions in the system. WEAP can also be linked with the MODFLOW model, which is a 3-D finite difference groundwater model, to study how changes in groundwater levels affect the overall system. AQUATOOL has an extensive list of models to represent groundwater realistically.

Based on analysis in the sections 3.3.1 and 3.3.2, the following can be concluded:

- In WEAP the user can aggregate and disaggregate the demands. The level of aggregation generally is determined by the level of detail of water use data available. In AQUATOOL demands cannot be disaggregated;
- In WEAP the Activity level is a measure of social or economic activity. When used in WEAP's Demand analysis, activity levels are multiplied by water use rates to yield overall levels of annual water demand. In AQUATOOL the user inputs twelve monthly water demand figures;
- In WEAP the user can simulate catchments (including rainfall runoff and infiltration, evapotranspiration, crop requirements and yield). In AQUATOOL it is not possible to simulate catchments;
- AQUATOOL has a diverse number of channels that can be modeled. In WEAP it is possible to define only one type. The analog in AQUATOOL is the channel type 1;
- AQUATOOL has a diverse number of aquifers that can be modeled however it is possible to link WEAP with external models such as MODFLOW – 2000;
- In WEAP the target function maximizes the coverage rate for all demand sites. In AQUATOOL, the optimization algorithm tries to increase the value of the variables with the lowest cost. In contrast, WEAP is not associating costs to the variables, as it uses priorities and coverage rates;

3.5 Implementation

3.5.1 AQUATOOL

3.5.1.1 Initiating the sorraia model as a new project

On start-up, the AQUATOOLDMA working window is empty except for the different options of the upper Windows menu. To embark on a new project, the [New] → [New] option is used. Before starting on the project, a work directory and a file name for the project data base must be selected. This is done in the window for creating new files. After selecting a work directory and database file, the basic data for the simulation project is entered.

“**Name of model**” and “**Name of scenario**” are two headings that will be used in later processes to describe the working scenario. In this study, “**Name of model**” was set as Sorraia and “**Name of scenario**” as Escenario001, which is given by default and can be changed by the user. “**Scenario subfolder**” is the file folder where all files specific for this project and scenario are written. “**Year**” and “**Number of years**” are the initial year and the duration of the simulation, where 1952 was selected as the initial year for this study, based on availability of data from the Portuguese Sistema Nacional de Informação de Recursos Hídricos (SNIRH), and the duration of the simulation period was set to 57 years. “**Topology's file**” is the name of the file in which AQUATOOL will write the data for the scheme graph, which is given by default and can be changed by the user. Finally, the “**Hydrological inflows file**” will

contain the simulation model of intermediate inflow data contained in a file with an .apo extension. By default, the name is set to simges.apo, and can be modified by the user. The inflow data must be prepared outside AQUATOOL and included in the .apo file

3.5.1.2 Adding elements to the Sorraia model

When the data window has been accepted, the screen will show a drawing board on which to draw a scheme of the simulation model. A toolbar will also appear from which to select elements for inclusion in the model (Figure 3).

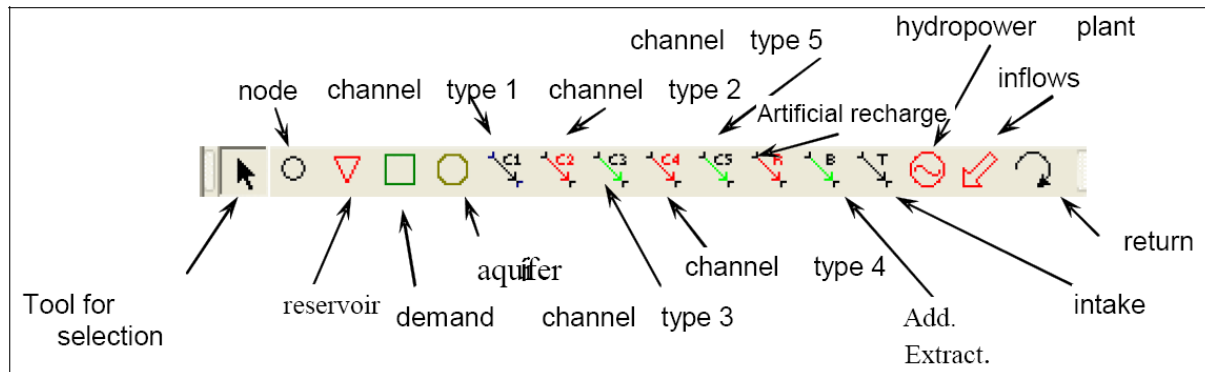


Figure 3. Toolbar for drawing plan of scheme

To enter a new element in the scheme, the corresponding icon is selected from the toolbar and placed in the desired position by clicking on the mouse. Linear elements must start and finish in appropriate locations. After drawing an element, a dialogue window is opened to edit the relevant data. After accepting this window, the data are filed. If cancelled, the element is eliminated from the scheme. To edit the element's data sheet, double click on the element itself.

Using a template for the Sorraia model

For developing the Sorraia model, a template was used to locate elements accurately in relation to their geographical location. For this purpose, AQUATOOLDMA offers the use of an image file for display underneath the model elements.

The image is initially drawn with the pixels of the original image. A menu also appears to configure image dimensions (Figure 4). Configuring the scheme and data editing cannot be continued until the Accept menu button is pressed. The data contained in this window are as follows:

“**Posición X**” and “**Posición Y**” are the coordinates of the upper left hand corner of the screen as indicated in the figure. “**Longitud X**” indicates the length of the horizontal side of the image in image measurement units (the coordinates in the image can be seen in the status bar). “**Prop. Y/X**” is the ratio between image height and width. “**Ocultar**” option, if activated, the image disappears. “**Ver**” button is used to see a preliminary view of the scheme of the model. The “**Aceptar**” button closes the configuration window and continues with the configuration of the scheme.

Node elements

A node does not require data but only an identifying name. Names must not be repeated, as this may cause confusion later in distinguishing between elements with the same name. The user can choose own method of numbering nodes. The only exception to this is that a node must be defined to accept all system outflows and which will be assigned the number 0. This is done by selecting the node and then the menu option: [Edit] → [Final node] → [Assign final node]. The assigned final node can be de-assigned by the option: [De-assign final node].

Reservoirs elements

For the Sorraia model, two reservoirs were modeled: Montargil and Maranhão, as well as, two diversion dams: Gameiro and Furadouro Reservoir Montargil is given as an example, showing the type of needed data, which contains a series of data classified according to type, as follows.

“**Infiltration losses**“, “**Coefficient A**“, “**Coefficient B**” and “**Coefficient C**” are coefficients for the monthly infiltration loss formula. For this study, the default coefficients were used. The aquifer that receives the infiltrated water is selected in “**Aquifer**”, and in “**Basic stress**” for infiltration recharge. In “**Aquifer**” the “**(to be determined)**” option can be chosen provisionally, if the aquifer still has not been included in the scheme. However, if this field is not modified before the model execution, the program will show a design error. As no aquifers were considered in this study, the option “**none**” was used, which means that the infiltrated water is lost to the system. “**Initial volume**” indicates the stored water volume at the start of simulation. Arbitrary initial volume, according to reservoir capacity volume, was entered for the two reservoirs, (100 for Montargil and 130 for Maranhão). The “**Spillover node**” option indicates a node through which excess water volume, defined for each month, is sent when the reservoir level exceeds V_{max} , and the excess cannot pass through controllable outlets (bottom drains, etc.). For this study, the reservoir itself was selected as the spillover node and in this case the discharge outlets will be through the reservoir’s outlet channel selected on the grounds of costs and priorities. The capacity of these outlets is included in “**Release maximum flow (hm^3/mes)**” and the default monthly value was used. The “**Priority number**” option allows basin reservoirs to be managed in such a way as to keep all of them as far as possible within the same capacity zone. This is done by characterizing reservoir levels, establishing different (capacity) zones and assigning reservoir priority numbers. Capacity zones are defined on the basis of target volume (V_{obj}), minimum volume (V_{min}) and maximum volume ($V_{máx}$) for each month. For this study the same priority number 1 was assigned to the four reservoirs/dams. Management of the reservoir). The “**Hydrological inflows column**” is a drop-down menu that shows the names of the columns of the inflows data sheet. For this study this option was not used since the water inflows to the reservoirs was provided from an .apo files.

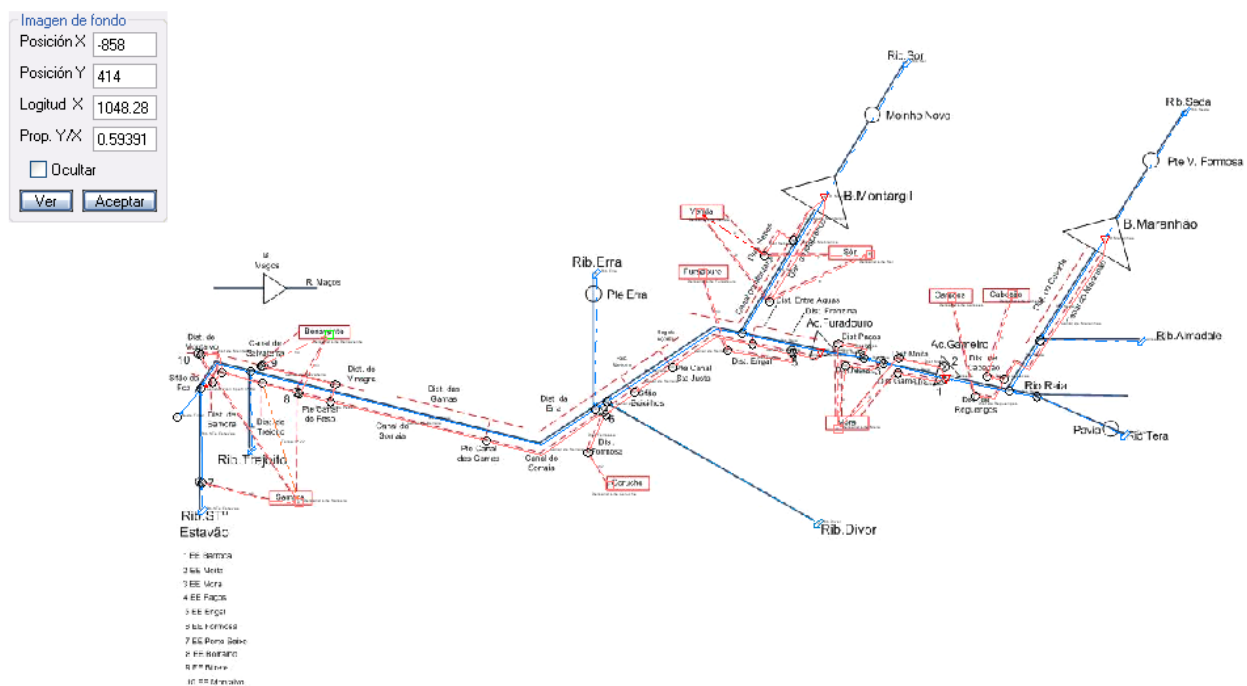


Figure 4. Configuration of background image

Volumes tab:

In this tab, the reservoir maximum, target and minimum volumes are entered for each month (Figure 5). The “**Maximum volume**” \geq “**Target volume**” \geq “**Minimum volume**” ≥ 0 ratio must be complied with.

Elevations tab:

In this tab (Figure 6), the elevation-surface-volume curve data is entered. The values in the fields of elevations, surface and volume must always be increasing. For this study, cota, area and volume data was used for Montargil and Maranhão and no data was entered for the diversion dams.

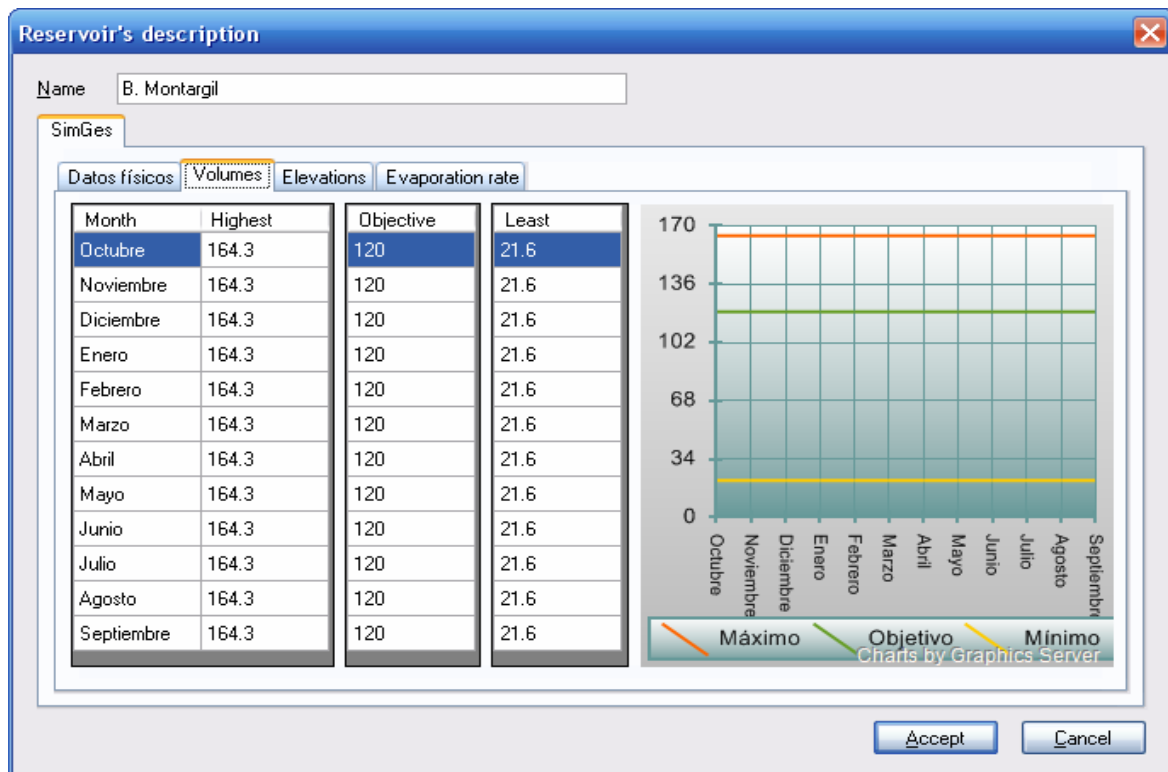


Figure 5. Montargil volume entry sheet

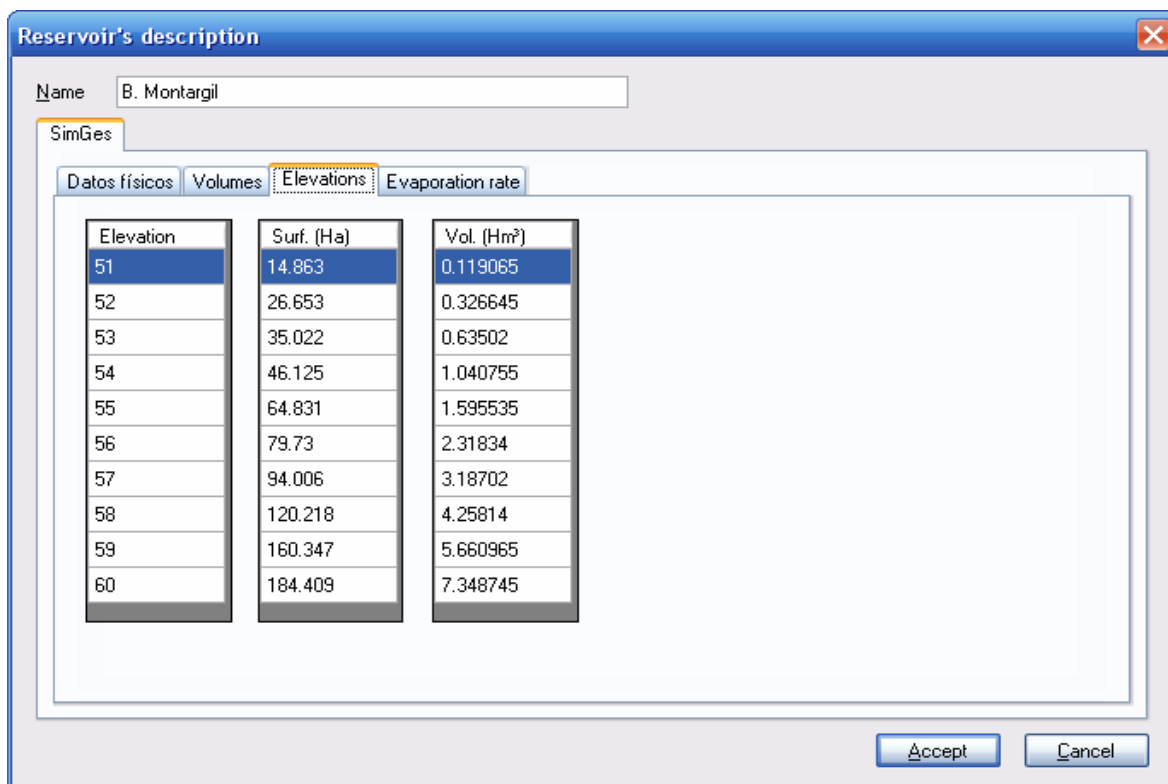


Figure 6. Montargil elevations entry sheet

Evaporation tab:

In Figure 7, monthly evaporation rate data for 12 months is entered. For this, evaporation rate data from SNIRH was used for Montargil and Maranhão and no evaporation data was entered for the diversion dams.

Reservoir's description

Name: B. Montargil

SimGes

Datos físicos | Volumes | Elevations | **Evaporation rate**

Month	mm/month
Octubre	77.997
Noviembre	43.774
Diciembre	33.252
Enero	32.22
Febrero	39.732
Marzo	68.542
Abril	85.365
Mayo	117.471
Junio	140.323
Julio	181.552
Agosto	179.587
Septiembre	127.335

Evaporation column: [Ver tasa evaporación]

Accept Cancel

Figure 7. Montargil evaporation entry sheet

Water inflow elements

Intermediate inflows are understood to be the water entering the system at irregular intervals at a node or reservoir. The node or reservoir at which the water enters must therefore be in existence before including the inflow. The observed monthly inflows in the rivers Tera, Sor, Seda, Erra, Trejoito, Divor, Almadale, and Sto Estevao were used for the period October 1952 – October 2009 (Table 2).

Table 2. Average monthly water demand (in million m³)

Rivers	Oct	Nov	Dec	Jan	Feb	Mar
Tera	2.375	8.504	17.250	21.586	21.624	17.254
Sor	4.538	15.692	29.255	35.290	36.545	31.746
Seda	7.022	33.120	67.071	73.369	76.592	60.736
Erra	0.805	3.019	6.612	6.867	7.388	5.802
Trejoito	0.397	1.421	2.882	3.606	3.613	2.883
Divor	2.305	8.253	16.742	20.949	20.987	16.745
Almadale	0.826	2.956	5.997	7.505	7.518	5.999
Sto Estevao	0.397	1.421	2.882	3.606	3.613	2.883
Rivers	Apr	May	Jun	Jul	Aug	Sep
Tera	7.177	1.438	0.693	0.093	0.004	0.038
Sor	16.334	5.072	2.060	0.946	0.345	0.566
Seda	27.325	8.112	3.668	1.378	0.037	0.454
Erra	2.531	0.762	0.345	0.090	0.021	0.097
Trejoito	1.199	0.240	0.116	0.015	0.001	0.006
Divor	6.965	1.396	0.672	0.090	0.004	0.037
Almadale	2.495	0.500	0.241	0.032	0.002	0.013
Sto Estevao	1.199	0.240	0.116	0.015	0.001	0.006

The water inflow data for this study was entered in the model from an external .apo data file. To create this .apo file, the user can use an AQUATOOL excel tool "GestorAportaciones". To indicate that the

data are to be entered from a file, the user goes to the menu [Modelos] → [Project options] to access the screen on. In [Options] “SimGes modeling” must be selected; in [Datos aportaciones Simges] “File” must be selected and “simges.apo” entered as the name of the file.

Demand site elements

Nine demand sites were identified and simulated in this study (Table 3). During the months of November, December, January and February, there is no water demand.

Table 3. Average monthly inflows (in million m³)

Demand sites	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Cabecao	0.27	0	0	0	0	0.27	0.27	0.27	0.27	0.27	0.27	0.27
Camoos	1.45	0	0	0	0	1.45	1.45	1.45	1.45	1.45	1.45	1.45
Mora	0.58	0	0	0	0	0.58	0.58	0.58	0.58	0.58	0.58	0.58
Furadouro	0.49	0	0	0	0	0.49	0.49	0.49	0.49	0.49	0.49	0.49
Venda	2.3	0	0	0	0	2.3	2.3	2.3	2.3	2.3	2.3	2.3
Sor	0.43	0	0	0	0	0.43	0.43	0.43	0.43	0.43	0.43	0.43
Coruche	3.24	0	0	0	0	3.24	3.24	3.24	3.24	3.24	3.24	3.24
Benavente	3.3	0	0	0	0	3.3	3.3	3.3	3.3	3.3	3.3	3.3
Samora	1.62	0	0	0	0	1.62	1.62	1.62	1.62	1.62	1.62	1.62

It is necessary to define the following data for each demand site. The data sheet for demand site Cabecao is given as an example (Figure 8):

The screenshot shows a software window titled "Demand's description" for "Demand site Cabecao". It features a "Total demand (hm³/month)" table with the following data:

Month	Hm ³
Octubre	0.27
Noviembre	0
Diciembre	0
Enero	0
Febrero	0
Marzo	0.27
Abril	0.27
Mayo	0.27
Junio	0.27
Julio	0.27
Agosto	0.27
Septiembre	0.27

Other configuration options include:

- Infiltration:** Recharged aquifer (Ninguno), Recharging basic stress (dropdown).
- Extractions:** Withdrawn aquifer (Ninguno), Pumping control parameter (dropdown), Extraction maximum flow (0), Control parameter threshold value (0).
- Monthly Reliability:** Monthly failure (% M.D.) = 1.
- Annual Reliability:** Monthly failure (% M.D.) = 15, Annual failure (% A.D.) = 30.
- UTAH DWR criteria:** Annual failure (% A.D.) = 50, 2 years failure (% A.D.) = 75, 10 years failure (% A.D.) = 100.
- IPH 2008 criteria, municipal demands:** Maximum monthly failure (% M.D.) = 8, Maximum 10 years failure (% A.D.) = 10.

Figure 8. Demand site data sheet

"**Total demand**" requires 12 gross monthly water volume values. The "**None**" option for "**Recharged aquifer**" was chosen as no aquifers were included in this study. Using the "**None**" option implies that the infiltrated water is lost to the system. This also implies that "**Basic recharge stress**" was not used. Similarly, the "**None**" option was selected for "**Extraction aquifer**". This implies that the options "**Pumping basic stress**", "**Pumping control parameter**", "**Extraction maximum flow (hm³/month)**" and "**Control parameter threshold value**" were not used. The "**Guarantees**" group permits definition of criteria for identifying failures for each of the guarantee criteria calculated by AQUATOOL. This group was left with its default values.

Demand intakes

Demand intakes are elements that supply water to demand sites. A demand site may be supplied by more than one intake. To include an intake in the scheme, a node or reservoir must have been previously defined within the scheme as the node or reservoir from which the intake is supplied and also a demand site which it serves. It is necessary to define the following data for each demand intake. The data sheet for demand site Cabecao is given as an example (Figure 9).

Intake description

Name: 1

SimGies

Monthly maximum flow

Month	Hm ³
Octubre	1000
Noviembre	0
Diciembre	0
Enero	0
Febrero	0
Marzo	1000
Abril	1000
Mayo	1000
Junio	1000
Julio	1000
Agosto	1000
Septiembre	1000

Priority number: 1

Operating rule: New...

On annual flow On monthly flow

Annual assigned volume: 2.16

Return coefficient (between 0-1): 0

Consumption coefficient: 1

Return element: (Ninguno)

Intake elevation: 0

Accept Cancel

Figure 9. Demand intake data sheet

"**Monthly maximum flow**" is the maximum volume that can be supplied in a month. These values were left as default values, except for the months from November till February where the values were set to 0. "**Return coefficient**" is a value (between 0 and 1) which determines the percentage of water that is returned to the surface system. This value was set to 0 and no "**Return element**" was defined. "**Consumption coefficient**" is a value (between 0 and 1) which defines net consumption (or the part of the supply delivered at the intake which is lost to the system). This value was set to 1. "**Annual assigned volume**" is the maximum value of the permitted annual supply. "**Priority number**" is used to establish the relative priority among the system intakes. For this study, all intakes were assigned with the same priority number. The options "**Intake elevation**" and "**Alarm indicator**" were not used for this study.

Type 1 channel elements

When all nodes have been defined, the next step is to define their interconnections. Channels always go from an "initial node" to a "final node", so that before defining a channel these nodes (or reservoirs) must be previously defined. For this study, nineteen type 1 channels, which represents canals and rivers, were identified and modeled in AQUATOOL. The data sheet for Canal do Sorraia is given as an

example. Monthly minimum and maximum flows can be defined for Type 1 channels as well as operating rules for controlling flow (Figure 10).

Description of the channel (type 1)

Name: Canal do Sorraia

SimGes

Flows (hm³/month)

Month	Least	Month	Highest
Octubre	0	Octubre	10000
Noviembre	0	Noviembre	10000
Diciembre	0	Diciembre	10000
Enero	0	Enero	10000
Febrero	0	Febrero	10000
Marzo	0	Marzo	10000
Abril	0	Abril	10000
Mayo	0	Mayo	10000
Junio	0	Junio	10000
Julio	0	Julio	10000
Agosto	0	Agosto	10000
Septiembre	0	Septiembre	10000

Reach cost

No Cost

Unit cost or by pass

Choose cost

Flow cost: 0

Maximum Annual Volume

Unlimited

Limited

Operating rule

New...

On annual maximum

On monthly maximum

On annual and monthly maximum

On monthly minimum

Minimum flow priority number: 1

Threshold for monthly failure (%): 1

Accept Cancel

Figure 10. Type 1 channel data sheet

“**Least flow**” and “**Highest flow**” for in which $0 \leq Q_{min} \leq Q_{max}$ must be satisfied. The default values were used. “**Maximum Annual Volume**” allows an upper limit to be set to the annual volume flowing through the channel. When this volume is reached, the channel will not transfer any more water until the following year. For this study, the “**Unlimited**” option was selected. “**Cost of reach**” is associated with optimization of the scheme and permits the cost of sending a unit of water through the channel to be selected. “**No cost**” was selected. The “**Threshold for monthly failure (%)**” and “**Minimum flow priority number**” options were used with their default values. No “**Alarm indicators**” were assigned.

3.5.2 WEAP

3.5.2.1 Initiating the Sorraia model as a new project

To setup the Sorraia project in WEAP, this study needs to be characterized by defining physical elements comprising the water demand-supply system and their spatial relationships (Figure 2 and Table 1) and the study time period, which is October 1952 – October 2009. A central feature of WEAP is its GUI used to lay out and visualize the physical features, used for constructing the Sorraia water supply and demand system. This spatial layout represents the Schematic in the form of “Area”. An “Area” in WEAP is defined as a self-contained set of data and assumptions. The data is separated into Current Accounts (October 1952 – September 1953) and scenario (October 1953 – September 2009). In the context of this study, scenario is used as a frame to hold a data set and scenario does not bring the commonly understood connotation of analyzing future developments.

Establishing a New, Blank Area

When WEAP is opened for the first time, a project area called “Weeping River Basin” appears. For this study, first it was necessary to select the “**Create Area**” menu option to make a new, blank area (Figure 11).

WEAP prompts for the selection of the geographic area for this project from the world map that appears. It was necessary to draw a green rectangular in the particular geographic section representing geographically the Sorraia valley in Portugal (Figure 12).

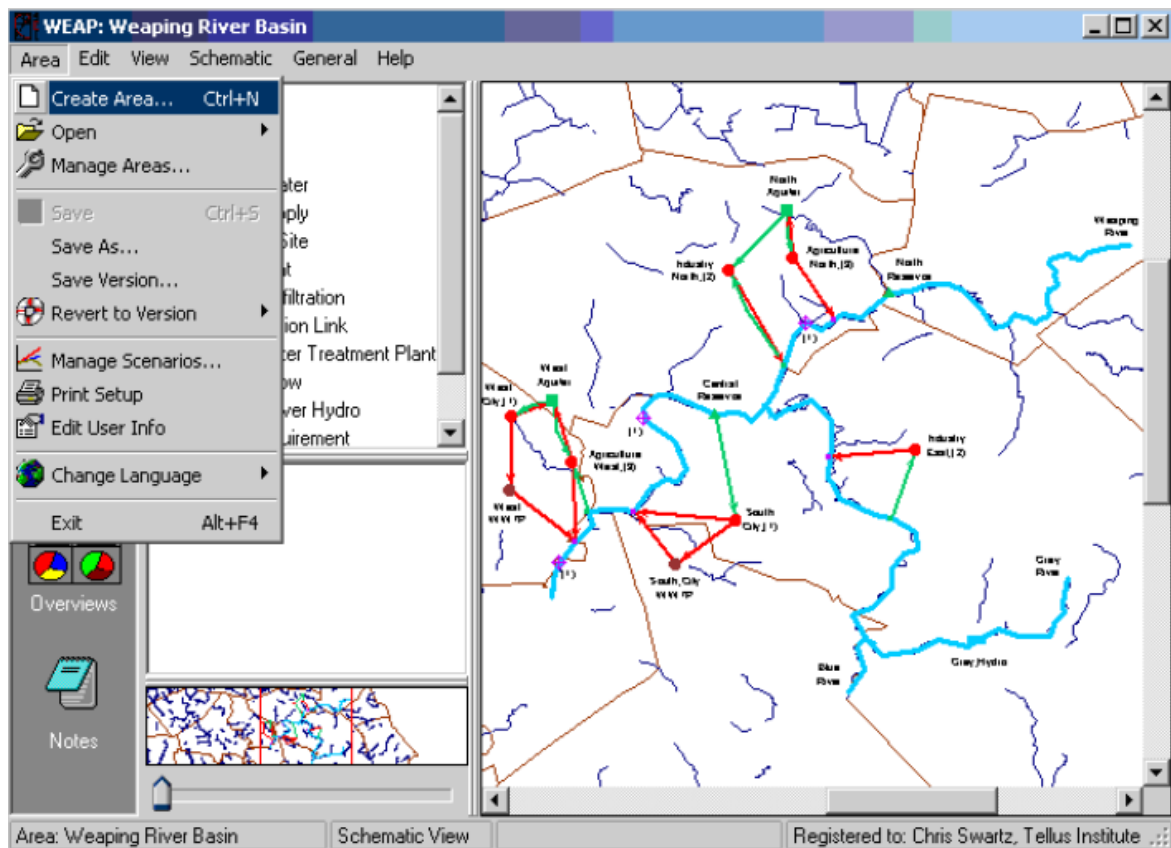


Figure 11. Create new area

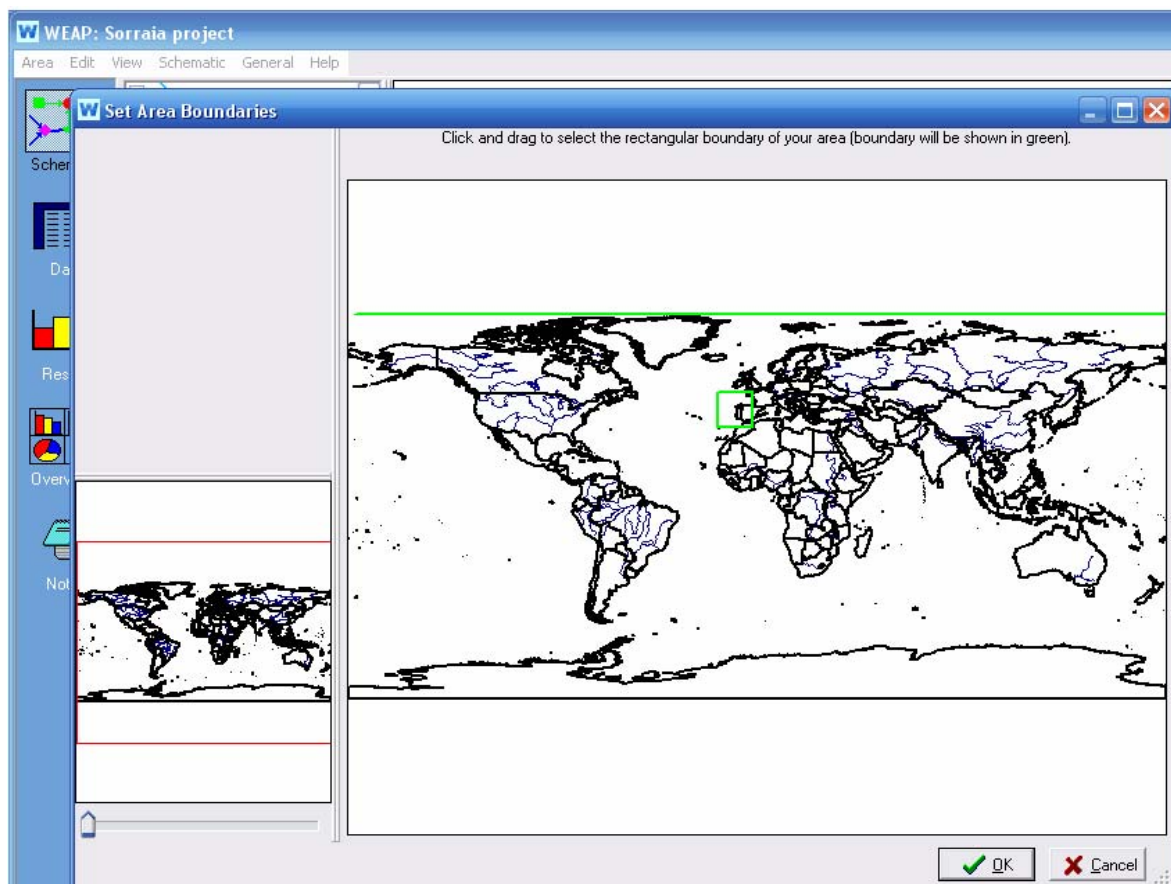


Figure 12. Area boundary selection

Adding of a GIS layer to the Area

For this study a GIS-based Raster map was added to the Sorraia project area by [Schematic] → [Add a Vector Layer]. A window appears in which to select the name of this raster file and where WEAP can find it on the computer.

Setting General Parameters

To set the General Parameters, it is necessary to click on the “**General**” menu to set “**Years and Time Steps**” (Figure 13).

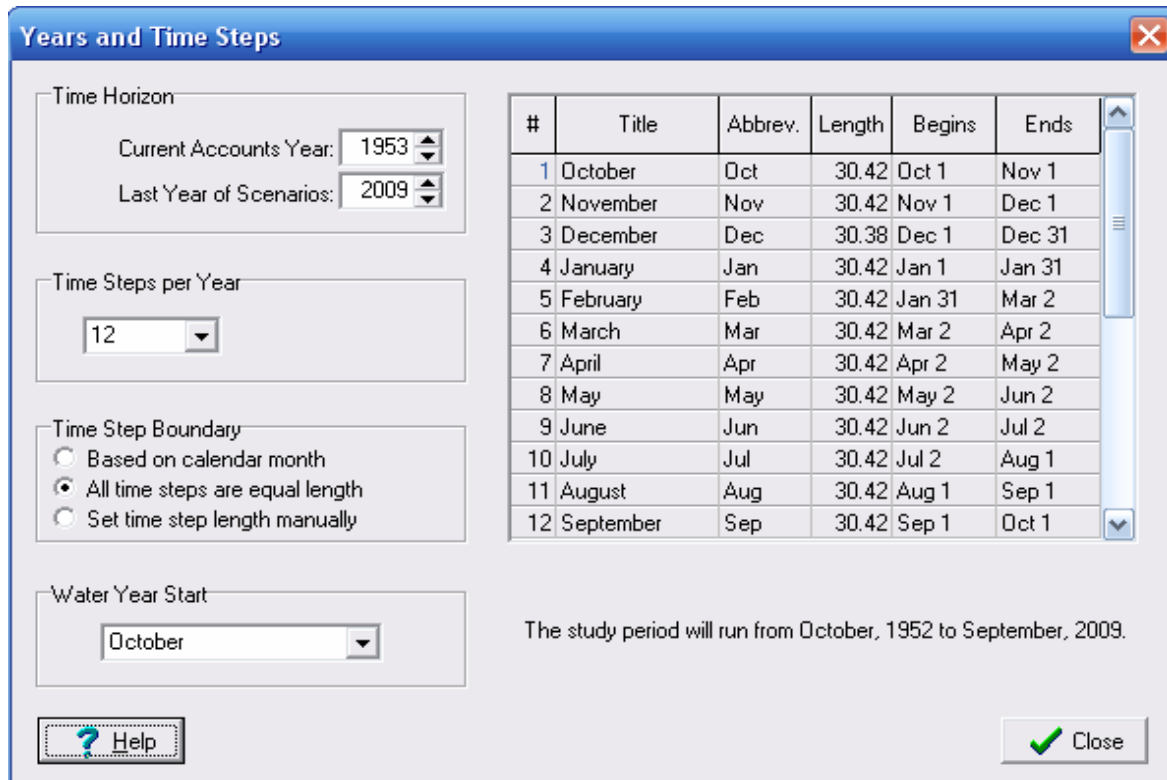


Figure 13. Used General Parameters settings

3.5.2.2 Adding elements to the Sorraia model

Reservoir elements

For the Sorraia model, two reservoirs were modeled: Montargil and Maranhão, as well as, two diversion dams: Gameiro and Furadouro Reservoir Montargil is given as an example, showing the type of data entered, which contains a series of data classified according to type, as follows.

Physical tab:

Storage Capacity sub-tab:

“**Storage Capacity**” represents the total capacity of the reservoir (Figure 14).

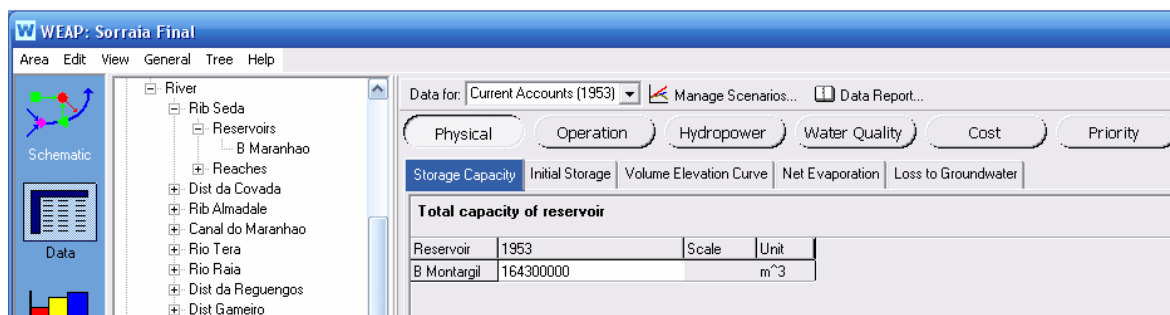


Figure 14. Montargil physical data entry sheet: Storage capacity

“**Initial Storage**” is the amount of water initially stored in the reservoir at the beginning of the first month of the **Current Accounts** year. Arbitrary initial volume, according to capacity volume, was entered for the two reservoirs, (100 for Montargil and 130 for Maranhão). No initial storage was set for the two diversion reservoirs.

The “**Volume-Elevation Curve**” represents the relationship between the reservoir volume and elevation. In this sub-tab (Figure 15), the volume-elevation curve data is entered. The values in the fields of elevations and volume must always be increasing. For this study, cota and volume data was used for Montargil and Maranhão reservoirs and no data was entered for the diversion dams.

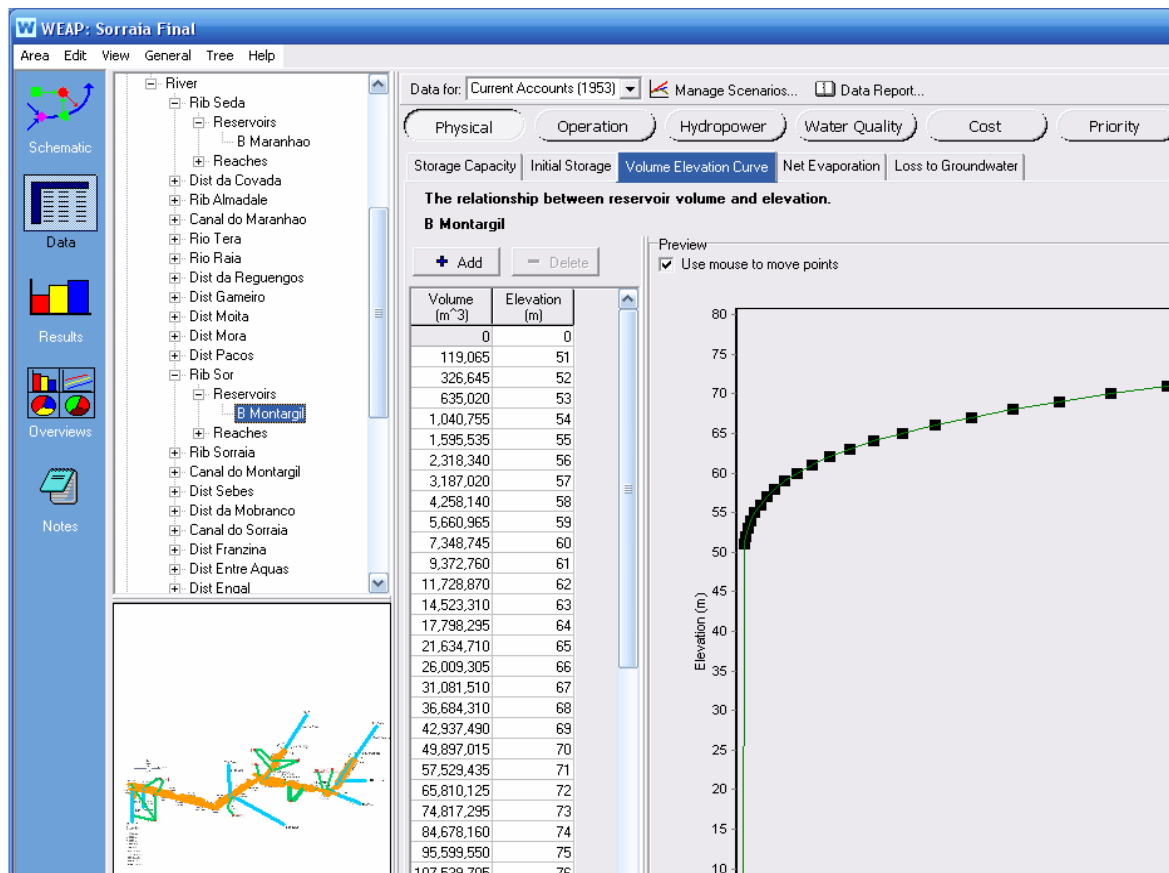


Figure 15. Montargil physical data entry sheet: Volume-Elevation Curve

For “**Net Evaporation**” evaporation rate data from SNIRH was used for Montargil and Maranhão and no evaporation data was entered for the diversion dams.

Operation tab:

Top of Inactive sub-tab:

Dead Volume used for Montargil and Maranhão for “**Top of Inactive**” (Figure 16).

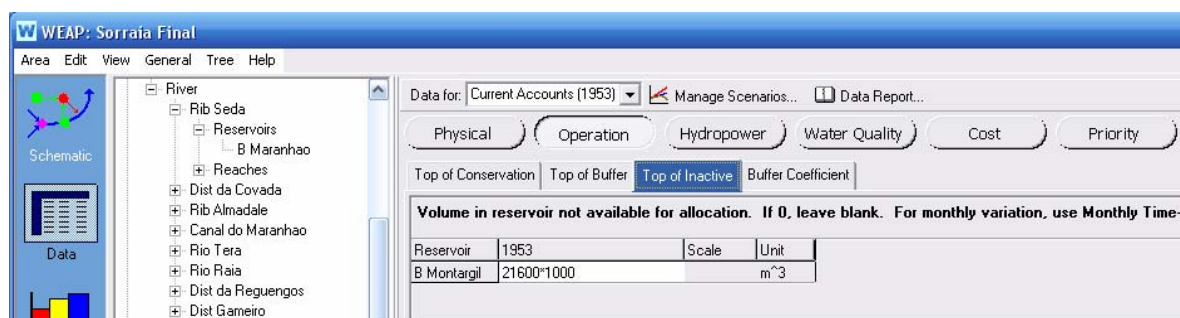


Figure 16. Montargil operation data entry sheet: Top of inactive

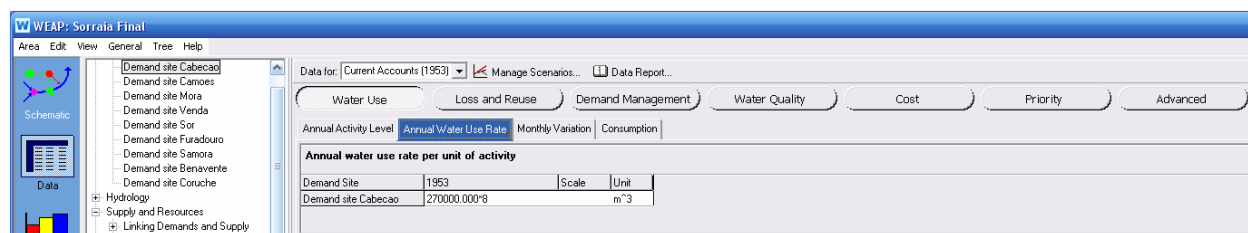
River elements

River elements (the equivalent of Intermediate inflows in AQUATOOL) are understood as water sources entering the system. To enter and edit data for the created river, it is necessary to enter data for “**Headflow**”. For this study the “Expression Builder” was used and the headflow data was entered using the command ReadFromFile(X.csv). This is a function which reads river headflow data from a file with extension .csv. This file is the equivalent of the .apo file in AQUATOOL. The observed monthly inflows in the rivers Tera, Sor, Seda, Erra, Trejoito, Divor, Almadale, and Sto Estevao were used for the period October 1952 – October 2009.

Demand site elements

Nine demand sites were identified and simulated in this study. During the months November, December, January and February there is no water demand.

For this study the “**Annual Water Use Rate**” was defined for each demand site (Figure 17):



The screenshot shows the WEAP software interface with the 'Annual Water Use Rate' data entry sheet. The 'Annual water use rate per unit of activity' table is visible, showing data for 'Demand site Cabecao' with a value of 270000.000 m³.

Demand Site	1953	Scale	Unit
Demand site Cabecao	270000.000	8	m ³

Figure 17. Demand site Annual Water Use Rate data entry sheet

“**Monthly Variation**” was also defined for each demand site to represent the months for which there is water demand and those months for which there is no water demand.

Demand intakes

Transmission links (the equivalent of demand intakes in AQUATOOL) are elements that supply water to demand sites. A demand site may be supplied by more than one intake. Only default settings were used for this study and the “**Supply Preference**” for all demand transmission links was set to be the same, equaling 1.

Diversion elements

For this study, nineteen diversions (the equivalent of type 1 channels in AQUATOOL), which represents canals and rivers, were identified and modeled in WEAP. The default settings were used for this study.

4. Results

In the application of AQUATOOL and WEAP for this modeling study no reservoir operating rules were introduced. For WEAP, the total annual capacity, initial storage, volume-elevation curve, monthly net evaporation rate and annual volume of inactive zone, were introduced. In AQUATOOL, the initial volume, the monthly volumes (min., max. and obj.) and monthly evaporation rates were introduced. Figures 18 and 19 show a comparison of the storage volume-time behavior of reservoirs Maranhao and Montargil, when modeled by AQUATOOL and WEAP. The results of WEAP are presented with tick line and those of AQUATOOL are presented with dashed line. The simulation period is October 1952 to October 2009. In the case of Maranhao, AQUATOOL and WEAP present similar trend, while in the case of Montargil the trend is the same, but WEAP presents higher reservoir storage volume figures. These results reflect the use of different optimization techniques for reproducing reservoir evaporation and operating rules based on priority for reservoir filling; specifically optimization procedures for balancing the available resource between reservoirs at each single period as well as in trying to minimize spilling to deliver water to water demand areas.

Table 4 presents the reliability of the Sorraia water supply system to deliver water. Reliability is defined as the percentage of the maximum monthly deficit which a demand site would experience related to its monthly demand. In this table, the number of failures represents the number of times there was not enough water to satisfy the water demand of a particular demand site. It is interesting to note that in both software products demand sites Venda and Sor have no number of failures. Both products present a very

similar number of failures and corresponding reliability figures. It must be noted that for Samora there are 102 failures in Aquatool and only 3 according to WEAP.

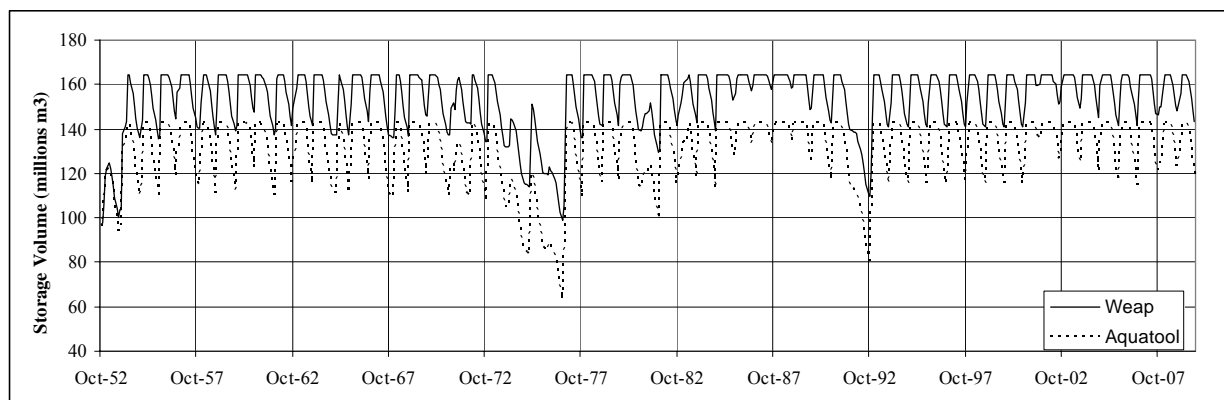


Figure 18. Montargil storage volumes

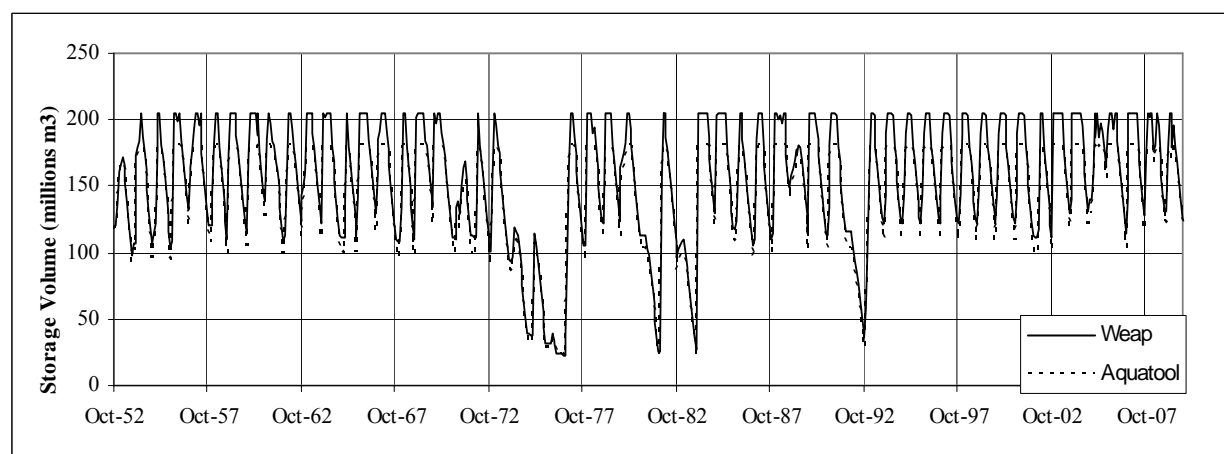


Figure 19. Maranhão storage volumes

Table 4. Sorraia water supply reliability

AQUATOOL				WEAP			
Demand site	No. failures	Average monthly reliability	Annual reliability	Demand site	No. failures	Average monthly reliability	Annual reliability
Cabecao	8	98.83%	98.86%	Cabecao	3	99.56%	99.07%
Camoes	8	98.83%	98.81%	Camoes	5	99.27%	99.07%
Mora	4	99.42%	99.16%	Mora	3	99.56%	99.07%
Furadouro	4	99.42%	99.23.60%	Furadouro	3	99.56%	99.07%
Venda	0	100.00%	100.00%	Venda	0	100.00%	100%
Sor	0	100.00%	100.00%	Sor	0	100.00%	100%
Coruche	8	98.83%	98.75%	Coruche	5	99.27%	99.07%
Benavente	6	99.12%	99.02%	Benavente	3	99.56%	99.07%
Samora	102	85.09%	84.31%	Samora	3	99.56%	99.07%

5. Conclusion

This paper presents analysis and implementation experience with two DSS software products for water allocation by comparing and applying them to the Sorraia water in Portugal. In this comparison modeling study, AQUATOOL and WEAP present both the concept of optimization for a single period of

simulation. Both products employ the concept of priority ranking for demand sites and reservoirs. In this study, water allocation was implemented in which the same demand sites' and reservoirs' priorities were assigned in both products. The results demonstrate that with some limitations AQUATOOL and WEAP present similar trends in the reservoir storage volumes, as well as, in the reliability of the Sorraia water system. It is also evident that both products can be used to simulate water allocation and can act as tools for sustainable water supply modeling. Finally, the successful implementation of the products depends on the availability of data from SNIRH, as well as, on the availability of data describing the physical elements comprising the water demand-supply system, preferably including their spatial relationships.

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Kaloyan N. Kenov has a M.Sc. degree in Integrated Water Resources Management by the Swedish University of Agricultural Sciences. He was a researcher in the scientific domains of water, renewable energy, nature disasters (flooding), computer simulations of reservoir operations, water flows on a catchment level and of the performance of urban drainage systems.
E-mail address: kenken171@gmail.com



Helena M. Ramos has a Ph.D. degree and is Professor at Instituto Superior Técnico (from Technical University of Lisbon - Portugal) at Department of Civil Engineering. Expert in different scientific domains: Hydraulics, Hydrotransients, Hydropower, Pumping Systems, Leakage Control, Energy Efficiency and Renewable Energy Sources, Water Supply, Vulnerability. More than 250 publications being 1 book in Small Hydro, 52 in Journals with referee and 102 in International Conferences; Supervisor of several post-doc, PhDs and MSc students and author of 8 innovative real solutions in the domain of Civil Engineering - hydropower and hydraulic system control.
E-mail address: hr@civil.ist.utl.pt / hramos.ist@gmail.com