

INTERCOMPARISON OF GENERIC SIMULATION MODELS FOR MULTI-RESERVOIR WATER RESOURCE SYSTEMS

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ABSTRACT

Particularly under water scarcity conditions, simulation models provide an efficient way to predict the interaction and impacts, over time and space, of alternative operating rules in multipurpose multi-reservoir systems. There are a number of such generic models for simulating water resource systems. AQUATOOL (Valencia Polytechnic University), MODSIM (Colorado State University), RIBASIM (DELTARES), WARGI (University of Cagliari) and WEAP (Stockholm Environmental Institute) are representative of models used for preliminary analysis of alternative plans and policies. The proposed intercomparison do not identify all the features of each simulation model, but rather gives some general information on the given evaluations considering a complex water system (the Agri-Sinni water system in Southern Italy) and system management performances reached with the aid of these simulation models. In particular, the paper emphasis is on the flexibility and effectiveness of these simulation models that use different techniques to reproduce traditional operating rules.

1 INTRODUCTION

A large variety of generic simulation models within interactive graphics-based interfaces has been developed by public and private organizations. They all are designed to study water related planning and management issues in water systems and to satisfy the needs of those at different levels of planning and decision-making process (Assaf et al., 2008). Since the early 1960s, simulation models have been used to model complex water resource systems. Examples of recent implementations that have specifically addressed multi-reservoir simulations and have been applied to complex water systems include, among others, AQUATOOL (Valencia Polytechnic University) (Andreu et al., 1996), MODSIM (Colorado State University) (Labadie et al., 2000), RIBASIM (DELTARES) (Delft Hydraulics, 2006), and WEAP (Stockholm Environmental Institute) (SEI, 2005), WARGI-SIM (Sechi and Sulis, 2009).

The proposed intercomparison do not identify all the features of each simulation model, but rather it gives some general information and particularly it will focus on application and evaluation of management performances reached with the aid of these simulation models considering a complex water system (the Agri-Sinni water system in Southern Italy)

2 MODEL FEATURES AND COMPARISON

Each model presented in this paper has its own special characteristics; nevertheless a main feature makes a specific difference between them: AQUATOOL, MODSIM and WEAP are models where optimization methods are developed and applied on the single time period and results are used as an efficient mechanism for performing a simulation-like procedure, whereas RIBASIM and WARGI-SIM are simulation-only models based on a more conventional if-then approach. Technically speaking in MODSIM, the minimum cost network flow problem is solved so that water is allocated according to physical, hydrological, and institutional aspects. In WEAP, a standard linear program is used to solve the water allocation problem at each time step, knowing the values from previous time steps. Its objective is to maximize satisfaction of demand based on supply preferences and demand priorities. In AQUATOOL, the simulation and management of the surface system are made at once, solving a conservative flow network optimization problem for each month of the simulation period.

Each one of the five models presented in the paper has model's in-built capacity for water quality modelling, but most water quality modelling components and algorithms are relatively simple compared to the state of the art in water quality modelling. In addition to this capacity, MODSIM and WEAP can be linked to a more detailed higher dimensional model (e.g. US EPA QUAL2E modelling framework) in order to provide highly detailed and comprehensive modelling of water quality parameters. This integrated approach allows to jointly consider quality as well quantity as a fundamental prerequisite for an effective water resource management. As a result, the user can clearly identify tradeoffs among quality and quantity objectives or deeply evaluates reservoir operating rules for a system of lakes and reservoirs considering both quality and quantity issues. Also, MODSIM and WEAP can be linked with the MODFLOW model, a three dimensional finite difference groundwater model, to study how changes in groundwater levels affect the overall system and vice versa. However, this tight coupling between generic simulation models and MODFLOW is not a simple task as it requires an extensive calibration phase. In AQUATOOL the user can choose among a spectrum of models to represent groundwater realistically, ranging from a model of reservoir type to a distributed model of a heterogeneous aquifer of irregular shape.

The following quick look at the models' main features describes how computer simulation addresses the issue of modelling the complexities of real water systems.

2.1 AQUATOOL

2.1.1 Description

AQUATOOL is a generalized DSS developed at the Universidad Politécnica de Valencia (UPV), Valencia, Spain. The model was designed for operational management and planning stages of decision-making in complex basins comprising multiple reservoirs, aquifers and demand centres. Implemented within the Microsoft Windows Environment, AQUATOOL has been coded in different programming languages such as C++, Visual Basic and FORTRAN.

2.1.2 Appropriate use

The DSS has been upgraded and expanded and currently it consists of several modules, among which a simulation module (SimWin), a management module of water

resource system considering the risk of drought (SimRisk) that works based in SimWin, an optimization module with monthly passage of time (OptiWin) less detailed than SimWin, and a simulation module of groundwater by means of the eigenvalues method (AquiVal) to simulate groundwater distribution. The simulation in SimWin is made on a monthly basis and it allows adequately shaping the non linear processes as evaporation and infiltration. SimWin distinguishes five types of oriented connections that allow the user to reproduce losses of water, hydraulic connections between nodes, reservoirs and aquifers and flow limitation based on elevation.

2.1.3 Training required

For an effective use of all SimWin features, good skills and experience in resource modelling is required.

2.1.4 Documentation

Some documentation is available through the UPV website (<http://www.upv.es/aquatool/>).

2.1.5 Cost

The user should contact UPV Group for more detailed documentation and for licence cost.

2.2 MODSIM

2.2.1 Description

MODSIM is a generic system management DSS originally conceived in the late 1970s at the Colorado State University (CSU), US, and continuously maintained. MODSIM is developed in the .NET Framework that provides a powerful environment for customization without requiring recoding. MODSIM simulates water allocation in the system at each time step through sequential solution of a network flow optimization problem where nonlinearities (i.e. evaporation, groundwater return flows, channel losses etc.) are assessed within a successive approximations solution procedure. The problem is solved with the Lagrangian relaxation algorithm RELAX-IV. Reservoir balancing routines that allow division of reservoir storage into several operational zones can be used to control spatial distribution of available reservoir storage. Additionally, operating rules on reservoir regulation and demand allocation can be conditioned on user defined hydrologic state variables.

2.2.2 Appropriate use

MODSIM has been linked with MODFLOW for the analysis of the conjunctive use of groundwater and surface resources, as well as QUAL2E for assessing the effectiveness of pollution control strategies. MODSIM can be applied in an implicit stochastic optimization framework where optimal rules for integrated operation are obtained using the generalized dynamic programming software package CSUDP.

2.2.3 Training required

The use of the main module requires moderate training, whereas external modules are quite hard to be used without skills in modelling.

2.2.4 Documentation

Detailed documentation is available through the CSU website (<http://modsim.engr.colostate.edu/>).

2.2.5 Cost

MODSIM can be downloaded free through the CSU website.

2.3 RIBASIM

2.3.1 Description

RIBASIM is a generic model package for simulating the behaviour of river basins under various hydrological conditions developed by DELTARES, former DELFT Institute, Delft, The Netherlands. Different scenarios can be easily compared based on user-defined objectives through the powerful graphical interface. The analysis of water demand is extensive (demographic, economic, crop water requirement), and the current and future demands at different horizons can be compared. Crop production and crop damage due to water shortages can be assessed. RIBASIM provides fixed operating rules based on target storage volumes and multiple zoning.

2.3.2 Appropriate use

RIBASIM particularly address the hydrological and hydrographical description of the river-basins and links the hydrological water inputs at various locations with the specific water-users in the supply system. It allows the user to define operating/planning scenarios where each scenario is characterized by a particular operating rule and/or water supply projection.

2.3.3 Training required

While RIBASIM is intuitive and easy to use, it requires significant data to perform detailed analysis.

2.3.4 Documentation

Documentation and can be required to DELTARES (<http://www.wldelft.nl/soft/ribasim>).

2.3.5 Cost

Information on the licence can be required to DELTARES (<http://www.wldelft.nl/soft/ribasim>).

2.4 WARGI-SIM

2.4.1 Description

WARGI is a user-friendly tool specifically developed to help users understanding interrelationships between demands and resources for multi-reservoir water systems under water scarcity conditions, as frequently occur in the Mediterranean regions. Since the middle of 1990s, WARGI has been extended and new modules have been developed by the Water Research Group (WRG) at the Department of Land Engineering, University of Cagliari, Italy. The WARGI modelling capability includes several interrelated macro-modules, the main ones being a simulation-only module (WARGI-SIM), a deterministic optimization module (WARGI-OPT), the reservoirs quality optimization module (WARGI-QUAL), and a module of scenario optimization (WARGI-SCEN). The water allocation in WARGI-SIM is simulated using user-defined preferences and priorities. Also, the user can define reserved volumes as a fixed function of the period of the year and withdrawn from reserved zone is decreased to satisfy user-selected high priority demands.

2.4.2 Appropriate use

To improve the definition of drought mitigation measures and the effective linking of these measures with drought indicators are defined through a full integration of WARGI-SIM and WARGI-OPT and the requirement of massive simulation-optimization runs for the analysis of complex water system under drought condition are satisfied in a GRID environment.

2.4.3 Training required

WARGI-SIM is a relatively simple model that enables non-experts to understand the main issues and problems of complex water systems.

2.4.4 Documentation

Requests for a detailed documentation can be addressed to the authors.

2.4.5 Cost

Requests for a non-commercial license can be addressed to the authors.

2.5 WEAP

2.5.1 Description

WEAP is a generic simulation model developed at the Stockholm Environment Institute, Boston, Massachusetts. WEAP model simulations are constructed as a set of scenarios with different simulation time steps. These demand scenarios are applied deterministically to a linear programming allocation algorithm where each demand and source is assigned a user-defined priority. The linear program solves the water allocation problem trying to maximize satisfaction of demand, subject to supply preferences and demand priorities, and using reservoir operating policies to minimize the distance to ideal conditions. The water allocation problem is solved at each time step using an iterative, computationally expensive approach. Traditional target storage levels, multiple zones, and reduced releases by a buffer coefficient are implemented in WEAP. Supply balancing within demand centres with the same priority is assured by that approach. A groundwater module in WEAP allows for the water transfer between stream and aquifer.

2.5.2 Appropriate use

The model integrates some physical hydrological processes with the management of demands and infrastructure to allow for multiple scenario analysis, including alternative climate scenarios and changing anthropogenic stressors. The main point of the water management analysis in WEAP is the analysis of water demand configuration.

2.5.3 Training required

WEAP requires significant data and a moderate experience for a detailed analysis.

2.5.4 Documentation

Detailed documentation is available online at SEI website (<http://www.weap21.org>).

2.5.5 Cost

US \$1000 for universities and government.

3 THE AGRI-SINNI WATER SYSTEM

The Agri-Sinni water system (Figure 1) is located in the Basilicata region (Southern Italy), and supplies water to the Puglia and Calabria regions as well. The main reservoirs in the system are Monte Cotugno (capacity of $556 \cdot 10^6 \text{ m}^3$) and Pertusillo (capacity of $159 \cdot 10^6 \text{ m}^3$) along the Sinni and the Agri Rivers, respectively. Marsico Nuovo and Cogliandrino are single purpose reservoirs (respectively for irrigation and hydroelectric use) with small regulation capacities. Four intake structures (Agri, Sarmiento, Sauro, and Gannano) were constructed on the main rivers for water diversion.

Based on the observed monthly inflows at Monte Cotugno and Pertusillo over the period 1983-2005, the inflows in other sections of interest in the basin were generated. The inflow series accurately represent the severe water scarcities in the Agri-Sinni that occurred in the years 1989-1990 and 2001-2002. Table 1 shows the main properties of the hydrologic series. Urban (Lucano Aqueduct and AQP in Figure 1), industrial (ILVA), and agricultural demands (C.B.) are respectively: $295.8 \cdot 10^6 \text{ m}^3/\text{yr}$, $12.6 \cdot 10^6 \text{ m}^3/\text{yr}$, and $240 \cdot 10^6 \text{ m}^3/\text{yr}$.

In all presented simulation models, demand nodes in the graph represent aggregations of urban, industrial or agricultural water requests. Water allocation is based on a priority ranking of demands from urban (highest priority) to agricultural (lowest priority). Reservoir priority numbers were entered in AQUATOOL, MODSIM and WEAP to determine a relative order of supplies to demand sites and filling reservoirs. In particular, priorities of filling of reservoirs were set lower than all competing demands. While in AQUATOOL all demand nodes connected with sources are supplied by those sources, all the other simulation models required that each demand had a hierarchical list of resources from which a supply flow could be activated. These lists were established according to the information provided by the system water Authority.

Table I. Statistical properties of the generated inflow series.

Stations	Mean ($\text{m}^3 \cdot 10^6 / \text{yr}$)	Stand. Dev. ($\text{m}^3 \cdot 10^6 / \text{yr}$)	Max ($\text{m}^3 \cdot 10^6 / \text{yr}$)	Min ($\text{m}^3 \cdot 10^6 / \text{yr}$)
Pertusillo	212.15	57.72	328.54	118.25
Monte Cotugno	277.60	106.61	494.14	118.45
Cogliandrino	89.76	32.12	147.13	33.95
Marsico Nuovo	7.82	3.04	12.91	2.53
Gannano	105.54	88.56	389.03	11.72
Agri	115.54	64.43	241.55	17.92
Sauro	50.46	25.50	101.31	11.93
Sarmiento	84.10	38.79	162.06	26.42

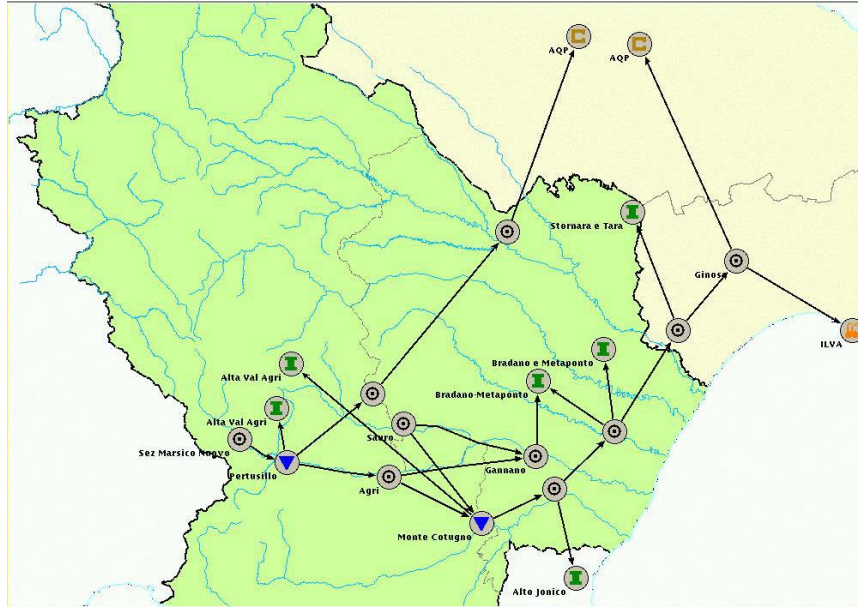


Figure 1. The Agri-Sinni water system in the WARGI Graphical Interface.

3.1 Model application and results

Reservoir operating rules in system configuration included the conservation and inactive zones in the Monte Cotugno and Pertusillo reservoirs. All models allow the modeling of advanced reservoir operation through the definition of these zones. In particular, MODSIM allows the conservation zone to be divided into several operational subzones. To allocate the water within the same priority proportionally to those demands, the conservation zone in each reservoir in MODSIM was divided into 100 multiple subzones.

In a first phase of model application we did not introduce further components of reservoir operating rules. From simulation results, the releases simulated for the reservoirs present similar trends that reproduce the historical values whose available database ranged between 1994 and 2004 (Figure 2). In particular, all models simulated the severe supply restrictions occurred during the most serious drought (2001-2002) when releases were dramatically reduced. The annual mean of spilling was minimized by WARGI-SIM and WEAP (Table II). Nevertheless these models use different techniques for reproducing operating rules: the simulation algorithm of WARGI-SIM in each period tried to satisfied all demand sites to the same percentage according to assigned demand priorities and then tried to fill reservoirs with the surplus surface water; WEAP single period LP optimization treated reservoir conservation zones below the top of conservations like downstream demands and the OF maximized both coverage types (demand coverage and “coverage for demand” to fill reservoirs).

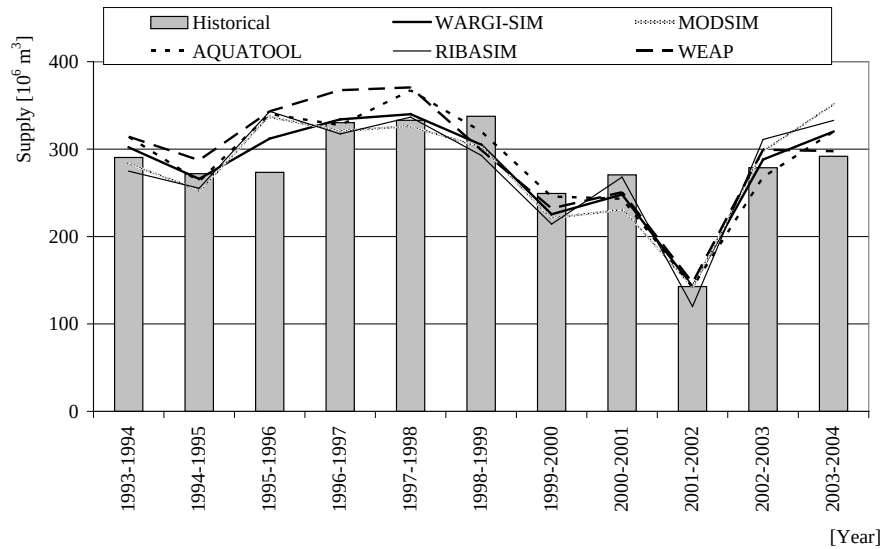


Figure 2. Time series of simulated and historical water supply volumes from reservoirs.

Table II. Annual mean volume of spilling.

	Spilling volume ($10^6 \text{ m}^3 / \text{year}$)
AQUATOOL	93.99
MODSIM	97.22
RIBASIM	98.26
WARGI-SIM	90.49
WEAP	90.69

Figure 3 shows the simulated time series of monthly storage volumes at Monte Cotugno. Time series are close, with a significant exception during the 1998-2002 period when releases from the Monte Cotugno reservoir simulated by AQUATOOL and also by MODSIM are higher than in RIBASIM, WARGI-SIM and WEAP. Also, it should be noted that storage volumes simulated by MODSIM approximate the storage balancing in the Agri-Sinni water system only in the case of introducing 100 multiple subzones in the conservation zones of Monte Cotugno and Pertusillo. In all model simulations, reservoir releases are not possible from the inactive zone beneath the buffer zone.

Here the vulnerability index was evaluated as the maximum monthly deficit of aggregated use and it was assessed to compare performances of different models. Even if time-series performance data resulting from simulation analysis needs a depth definition of the typical tradeoffs between reliability, resilience and vulnerability (Sechi and Sulis, 2009), the vulnerability-alone measure allowed to summarize and compare performances of these different models. Table III shows that simulation-alone algorithm of WARGI-SIM can give very close values of urban vulnerability compared with models having a network flow optimization algorithm engine to define the releases, as in MODSIM and AQUATOOL. Nevertheless, the management optimization of surface waters in the system are made once every period in MODSIM and AQUATOOL and deficit costs in the objective function are calculated from demand priorities. Also, MODSIM supplied different demands having the same priority from each reservoir zone simply by following the order of node insertion in the system graph, and an equitably share of water shortage among those demands during drought events was assured by introducing a really high number (i.e.: 100) of multiple subzones in the conservation storage zones of Monte Cotugno and Pertusillo reservoirs. In WARGI-SIM the available resources are allocated depending on priorities so that urban demands are allocated before industrial and agricultural demands. It is to be noted that supply performances provided by these two different approaches could be not the same when considering different systems. As expected, the use of allocation rules based only on a hierarchical order of demand priorities and the absence of any reservoir release rule determined maximum values of monthly deficits in the industrial and agricultural uses equal to 100%.

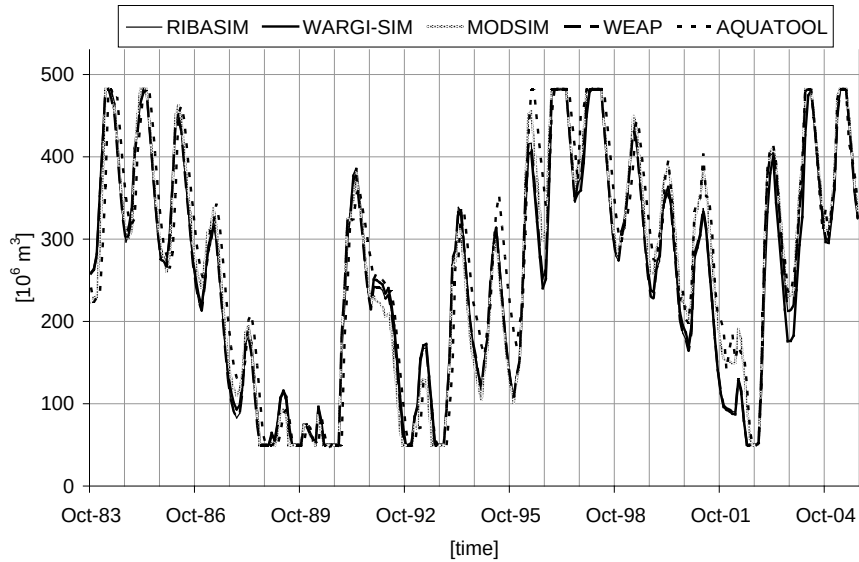


Figure 3. First phase results: Time series of simulated storage volumes at Monte Cotugno.

Table III. Comparison of results: Maximum values of simulated monthly deficits in urban uses expressed as % of original demands.

	First phase (without hedging rules)	Second phase (with hedging rules)
AQUATOOL	64.72	16.28
MODSIM	65.00	12.00
RIBASIM	100.00	56.70
WARGI-SIM	65.30	28.02
WEAP	68.94	39.41

A second application phase was developed in order to verify the suitability of water supply actions in the system management during the severe water scarcity event in 2001-2002. The Agri-Sinni system was again simulated by all software also considering additional components of reservoir operating rules. These water saving were introduced with the aim of minimizing the urban and industrial deficits. The new components included a hedging rule that reduced agricultural releases to save water for higher priority uses in the following periods. Each simulation model has its own way to reproduce this common requirement of reservoir operating. Briefly:

1. in AQUATOOL and RIBASIM at each arc entering in a demand node we associated an alarm indicator containing a monthly value equal to 0.7 as a monthly restriction coefficient for agricultural uses and a target volume of half conservation volume as trigger that restriction rule;
2. in WARGI-SIM when storage volume in a reservoir was within a reserved volume equal to half conservation volume, releases were decreased to supply only urban and industrial demands;
3. in MODSIM and WEAP, a conditional rule curve was introduced that defined reservoir releases as a function of existing storage volume (WEAP), and a function of existing storage volume and inflow into the reservoir (MODSIM), when storage volume is within the buffer volume equal to half conservation zone. The coefficients of these linear functions for each reservoir were obtained in a trial-and-error procedure.

Table III summarizes results for the vulnerability values for urban uses. The hedging rule in RIBASIM and WEAP did not reduce adequately the urban vulnerabilities. Moreover, even if AQUATOOL and MODSIM could better save water for urban demands, only WARGI-SIM minimized both urban and industrial demands. AQUATOOL, MODSIM, RIBASIM and WEAP showed maximum percentages of industrial deficit higher than 85.00%, whereas WARGI-SIM reduced it at least to the same amount of urban uses. It should be noted that releases in MODSIM and WEAP were reduced in the total amount and the reduced supplies were allocated to the demands according to their priorities. This procedure did not allow saving water in order to decrease the vulnerability of industrial demands. Finally, the application of the proposed hedging rule in RIBASIM did not efficiently restrict the supply to agricultural

uses and the maximum percentage of agricultural deficit (78.70%) was significantly lower than values obtained using other simulation models.

Figure 4 shows the simulated time series of monthly storage volumes at Monte Cotugno when releases were temporarily decreased by the hedging rule during the severe drought events. As expected, time series of all models are close with significant exceptions during drought events in 1988-1990, 1992-1993 and 2001-2002: in those cases the surplus surface water in Monte Cotugno reservoir emphasizes the use of different techniques for reproducing operating rules for reducing reservoir releases when storage volume is within the buffer zone. In particular, the most conservative rules were those implemented in AQUATOOL and RIBASIM that use static hedging coefficients whereas the release reduction in MODSIM and WEAP were adaptive. This could justify the fact, noticeable in Figure 4, that reservoir storage in reservoir still remains considerably high even during drought when considering AQUATOOL values. Nevertheless a finer definition of parameters was not in the aim of this work that mainly analyzed the different approaches adopted by these generic simulation models and their potential uses and we cannot exclude that better results could be obtained in a more accurate tuning of parameters for the specific system.

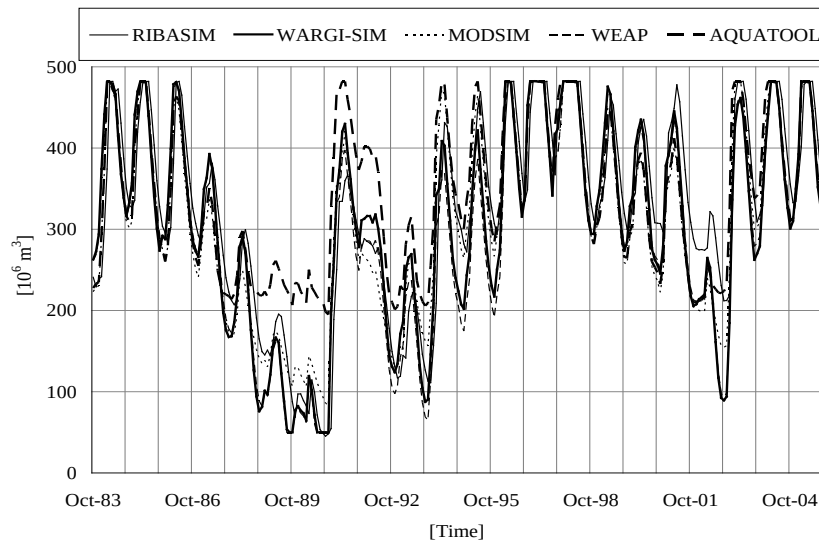


Figure 4. Time series of simulated storage volumes at Monte Cotugno with assigned hedging rules

4 CONCLUSIONS

Five popular generic simulation models are synthetically illustrated in this paper and their features analyzed and compared in the application to a complex water system in Southern Italy. While RIBASIM and WARGI-SIM use simulation-alone algorithms in a

traditional if-then approach, AQUATOOL, MODSIM and WEAP additionally employ optimization tools for the single period flows definition as an efficient mechanism for performing simulations. Demand priority is a common concept in all simulation models, and AQUATOOL, MODSIM and WEAP extend this concept also to reservoir filling. Results highlighted that a simulation-alone model as WARGI-SIM could give system performance indexes of a complex water system as good as simulation models aided by the use of single time-step optimization models but still remaining closely related to real water system management based on priorities and preferences criteria.

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