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Intercomparison of Generic Simulation Models for Water Resource Systems

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Abstract: Particularly in water resource systems that frequently experience severe drought events, generic simulation models provide useful information for the definition of drought mitigation measures. Among them, AQUATOOL (Valencia Polytechnic University), MODSIM (Colorado State University), RIBASIM (DELTARES), WARGI-SIM (University of Cagliari) and WEAP (Stockholm Environmental Institute) are here considered for the preliminary analysis of alternative plans and policies. This paper is about modelling in practice more than in theory: the emphasis is on the application of these simulation models to a multireservoir and multiuse water system in Southern Italy where frequent droughts in the last two decades have required the adoption of unsustainable temporary user-supply restrictions. While each model has its own characteristics, the proposed application comparison does not identify all the features of each model, but rather gives general information on the identification and evaluation of operating policies with the aid of these simulation models.

***Keywords**:* Decision Support Systems, Water Resources Management, Simulation.

1. INTRODUCTION

Generic simulation models provide information and understanding to improve water system management and planning processes. Particularly under water scarcity conditions, simulation models provide an efficient way to predict source-demand interactions and the impacts of rule modifications, over time and space, in order to set the more appropriate drought mitigation measures. Appropriate intervention can reduce the impact of water scarcity, resulting in mitigating economic, social, and environmental consequences of droughts in actual systems. Current intervention is largely crisis driven. There is an urgent need (SEDEMED, 2003) for more risk-based management approaches to drought planning and the definition of drought mitigation measures becomes the central aspect in managing water systems that frequently experience severe drought events. In this context, generic simulation models provide an efficient way to predict effectiveness and efficiency of alternative mitigation measures. Frequently, generic simulation models are the core of complex decision support systems (DSS). The DSS can assist at different levels of details ranging from simple screening models for guiding data collection activities, to more complex tools requiring high levels of expertise. These computer-based prediction models can be combined in a mixed optimization-simulation approach to anticipate the occurrence of water scarcity considering different hydrological scenarios (Sechi and Sulis, 2009). Despite the potential of using scenario optimization in the search for efficient alternatives, full integration between simulation and optimization has not yet been achieved and real-world applications are frequently applications of generic simulation models.
Generally speaking, there are five steps in simulation modelling (Loucks and van Beek, 2005):

1. Identify the information to provide;
2. Model the system's behaviour;
3. Put 1 and 2 together and identify a means of entering inputs and obtaining outputs;
4. Calibrate and validate the model;
5. Use the model to produce information.

Despite the large amount of literature and models available, there is much that could be added to how well and how poorly planners, managers, modellers and analysts have already done. One step ahead would be to extend the thoughts of those described the gap between theory and practice in water resources planning and management more than a decade ago (Loucks, 1992; Simonovic 1992). All models produce simplified representations of real-world systems. What features are incorporated into the model depend in part on what the modellers have thought is important. Models are all based on some assumptions, and some of these may lead to significant approximations of reality.
This paper illustrates five of such generic models for simulating water resource systems: AQUATOOL-SimWin (in the following named AQUATOOL) (Valencia Polytechnic University) (Andreu et al., 1996), MODSIM (Colorado State University) (Labadie et al., 2000), RIBASIM (DELTARES) (Delft Hydraulics, 2006), WARGI-SIM (University of Cagliari) (Sechi and Sulis, 2009) and WEAP (Stockholm Environmental Institute) (SEI, 2005).
They are representative of simulation models used for preliminary analysis of alternative plans and policies. Those popular generic simulation models have been implemented world-wide in a large number of water systems and incorporate most of the desirable attributes of a simulation model.
This paper is about modelling in practice more than in theory. In the following, after a short presentation and comparison of characteristics and main features of the simulation models, the emphasis is placed on the application of these simulation models to a multireservoir and multiuse water system in Southern Italy where frequent droughts in the last two decades have required the adoption of unsustainable temporary user-supply restrictions.

2. MODEL CHARACTERISTICS AND COMPARISON

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). Each model presented in this paper has its own special characteristics; nevertheless a main feature makes the difference between them: AQUATOOL, MODSIM and WEAP are models where optimization methods are developed on the single time period and results are used as an efficient mechanism for performing simulations, 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 in the simulation period. On the other hand, the application to complex water systems of simulation-only models as RIBASIM and WARGI-SIM could give lower values of performance system indexes (e.g., vulnerability or reliability at user-defined water supply levels). Nevertheless, RIBASIM and WARGI-SIM surely better fit the real word operating policies defining what should be done when it is not possible to satisfy system ideal conditions.
There is a large variety of operating policies presented in the literature. Operating policies vary from traditional operating policies that define very precisely how much water to release from reservoir for all possible combination of hydrologic and reservoir storage conditions, to operating policies that are defined by means of supply preferences and demand priorities. Operating policies in AQUATOOL, RIBASIM and WARGI-SIM are fixed whereas operating policies in MODSIM and WEAP are defined as a combination of system states and hydrologic conditions. In particular, the most recent versions of MODSIM are developed under the MS .NET Framework that allows user to customize MODSIM for any specialized operating rules without having to modify the original source code. While the generic simulation models presented here vary in the type and detail of operating policies they can reproduce, they all include the concepts of priorities and preferences.

Each 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 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 conditions in the system, whose constituents modelled include ammonia, nitrate, organic and inorganic phosphorus, algae, sediment, pH and pathogens. 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.

3. MODEL FEATURES

3.1 AQUATOOL

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. 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. For an effective use of all SimWin features, good skills and experience in resource modelling is required. Some documentation is available through the UPV website (http://www.upv.es/aquatool/). The user should contact UPV Group for more detailed documentation and for licence cost.

3.2 MODSIM

MODSIM is a generic system management DSS originally conceived in the late 1970s at the Colorado State University (CSU), US, and continuously maintained. 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. MODSIM is developed in the .NET Framework that provides a powerful environment for customization without requiring recoding. 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. 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. The use of the main module requires moderate training, whereas external modules are quite hard to be used without skills in modelling. Detailed documentation is available through the CSU website (http://modsim.engr.colostate.edu/) where MODSIM can be downloaded free.

3.3 RIBASIM

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. 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. 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. While RIBASIM is intuitive and easy to use, it requires significant data to perform detailed analysis. Documentation and information on the licence can be required from DELTARES (http://www.wldelft.nl/soft/ribasim).

3.4 WARGI-SIM

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), a reservoir quality optimization module (WARGI-QUAL), and a module of scenario optimization (WARGI-SCEN). To improve the definition of drought mitigation measures and the effective linking of these measures with drought indicators, the WRG recently developed a full integration of WARGI-SIM and WARGI-OPT. WARGI has been also implemented in a GRID environment to satisfy the requirement of massive simulation-optimization runs for the analysis of complex water system under drought condition. 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. WARGI-SIM is a relatively simple model that enables non-experts to understand the main issues and problems of complex water systems. Requests for a non-commercial license and detailed documentation can be addressed to the authors.

3.5 WEAP

WEAP is a generic simulation model developed at the Stockholm Environment Institute, Boston, Massachusetts. It 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. WEAP model simulations are constructed as a set of scenarios with different simulation time steps. The physical hydrology model updates the hydrologic state of the system at each time step, and thus provides mass balance constants used in the allocation phase within the same time step. A groundwater module in WEAP allows for the water transfer between stream and aquifer. The main point of the water management analysis in WEAP is the analysis of water demand configuration. 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. WEAP requires significant data for a detailed analysis. Detailed documentation is available online at SEI website (http://www.weap21.org).

4. THE AGRI-SINNI WATER SYSTEM APPLICATION COMPARISON

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 10^6 m^3) and Pertusillo (capacity of 159 10^6 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, Sarmento, 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 10^6 m^3/yr, 12.6 10^6 m^3/yr, and 240 10^6 m^3/yr.

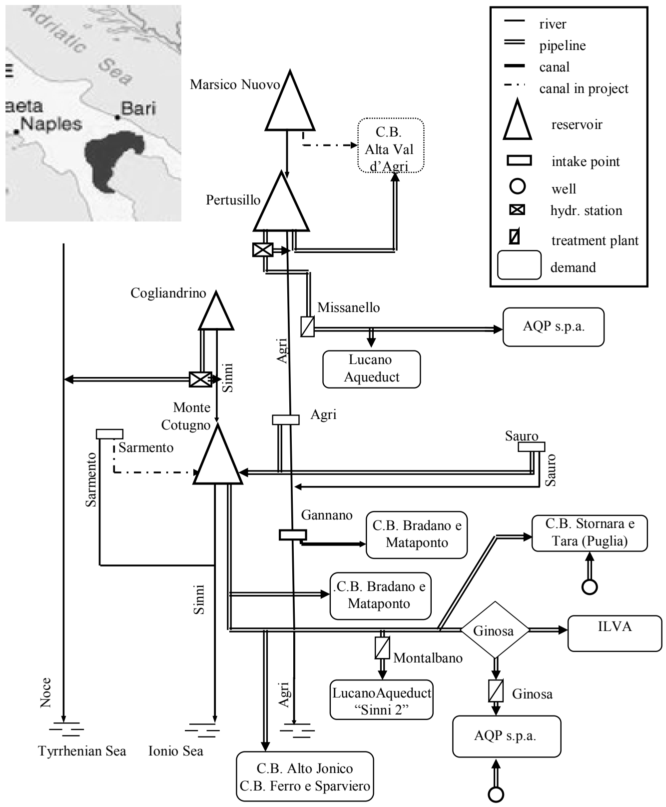

Figure 1. The Agri-Sinni water system

Stations	Mean ($m^3 \cdot 10^6$/ year)	Stand. Dev. ($m^3 \cdot 10^6$/ year)	Max ($m^3 \cdot 10^6$/ year)	Min ($m^3 \cdot 10^6$/ year)
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
Sarmento	84.10	38.79	162.06	26.42

Table 1. Statistical indexes of inflows in the period 1983-2005

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.

4.1 First model applications

In a first application of simulation models, no reservoir operating rules were introduced, and the only conservation zone and inactive zone were defined in the reservoirs. Figures 2 and 3 show the storage volume-time behaviour obtained in the two main system reservoirs: Monte Cotugno and Pertusillo. While AQUATOOL and MODSIM present similar trends, in WARGI-SIM the average of storage volumes in both reservoirs is the lowest between all simulation models. As reported in Table 3, the annual mean of spill volumes is minimized by WEAP, while RIBASIM and WARGI-SIM have higher similar values (+14%, +16%). These results reflect the use of different techniques for reproducing operating rules based on priority for reservoir filling; specifically optimization procedures act well in balancing the available resource between reservoirs at each single period as well as in trying to minimize spilling. Simulation models with optimization procedures such as those in WEAP could give better performance but less realistic flow configurations.

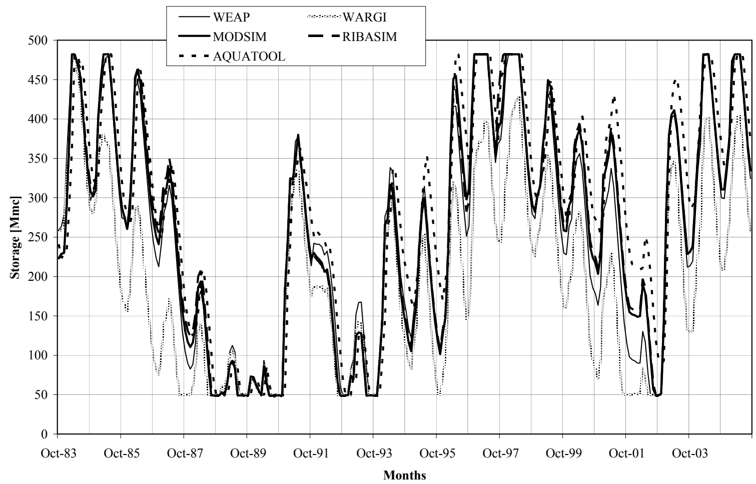

Figure 2. Monte Cotugno storage volumes

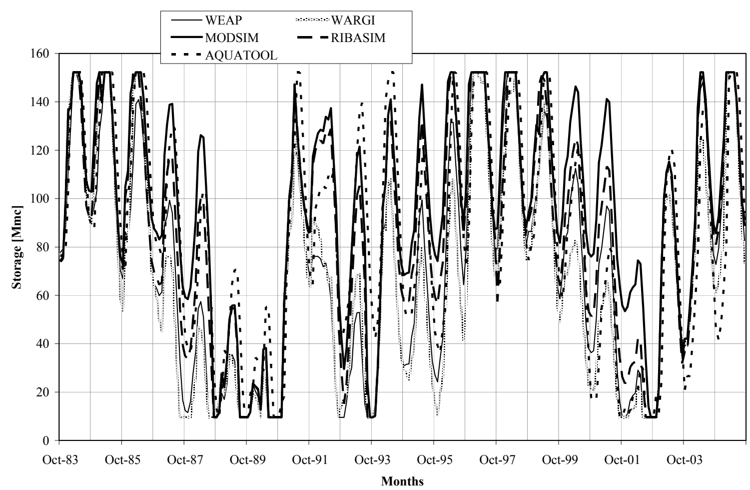

Figure 3. Pertusillo storage volumes

	Agri ($m^3 \cdot 10^6$/ year)	Sinni. ($m^3 \cdot 10^6$/ year)	Total ($m^3 \cdot 10^6$/ year)
AQUATOOL	73.50	20.49	93.99
MODSIM	83.27	13.95	97.22
RIBASIM	46.88	51.38	98.26
WARGI-SIM	80.24	20.06	100.30
WEAP	75.82	10.48	86.30

Table 2. Annual mean volume of spilling

Table 3 summarises the supply time series performance. Vulnerability value, that is the percentages of maximum monthly deficit for single use on the total value of the corresponding monthly demand, is reported for urban, industrial and agricultural uses. All simulation models associated urban, industrial and irrigation uses to decreasing priorities and vulnerability values in those supplies were coherently reproduced with the exception of RIBASIM where agricultural deficit was lower than urban and industrial values. The urban vulnerability values obtained by AQUATOOL, MODSIM and WEAP were very close, and WARGI-SIM gave a value of 79.41%, significantly lower than RIBASIM (100.00%). It should be noted that in MODSIM different demands having the same priority are supplied by each reservoir zone following the order of node insertion in the system graph. 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.

	Urban (% of demand)	Industrial (% of demand)	Agricultural (% of demand)
AQUATOOL	64.72	100.00	100.00
MODSIM	65.00	100.00	100.00
RIBASIM	100.00	100.00	91.30
WARGI-SIM	79.41	100.00	100.00
WEAP	68.94	100.00	100.00

Table 3. Maximum percentages of monthly deficit for different uses

4.2 Second model applications

During the two severe water scarcity events in the Agri-Sinni system (1988-’90 and 2001-’02), all software reproduced an unsustainable condition in the urban use where maximum deficit exceeded the 50% of the monthly demand. Consequently, a second models application was done introducing operation rules to reduce drought impacts. To minimize the urban and industrial deficits, a hedging rule was introduced in all software that reduces agricultural releases to save water for higher priority uses in the following periods. Each simulation model has its own way to reproduce this reservoir operating rule. 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.

Procedures were in some cases extremely sensitive: Table 4 summarizes results for the vulnerability values in different uses. In these results, only AQUATOOL and WARGI-SIM minimized both urban and industrial demands, whereas the hedging rule in RIBASIM and WEAP did not reduce significantly the urban and industrial vulnerabilities and MODSIM only could save water for urban demands. In particular, MODSIM, RIBASIM and WEAP showed maximum percentages of industrial deficit higher than 85.00%. 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 supply to agricultural uses and the maximum percentage of agricultural deficit (78.70%) was significantly lower than values obtained using other simulation models.

	Urban (% of demand)	Industrial (% of demand)	Agricultural (% of demand)
AQUATOOL	5.51	0.00	97.00
MODSIM	12.00	100.00	97.80
RIBASIM	56.70	100.00	78.70
WARGI-SIM	28.02	0.00	100.00
WEAP	39.41	85.00	90.58

Table 4. Maximum percentages of monthly deficit for different uses, considering the reservoir hedging rules

5. CONCLUSIONS

Five popular generic simulation models are synthetically illustrated in this paper and their features compared in the application of a complex water system in Southern Italy. While RIBASIM and WARGI-SIM use simulation-only algorithms in a traditional if-then approach, AQUATOOL, MODSIM and WEAP additionally employ optimization methods for the single period as an efficient, but not strictly realistic, 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. In the second application, the hedging rule was introduced in different ways to reduce releases and save water for high priority demands during the drought periods. Results highlighted that, even if the optimization models can assure better system performance indexes, their efficiency in water allocation is not realistically achievable in real world management of water systems.

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