An assessment of the operational freeware management tools for multi-reservoir systems
Evangelos Rozos

ABSTRACT

Water resources management is one of the most challenging problems of the water sector. The complexity of this problem is mostly attributed to the dynamic nature of the natural hydrosystems, of which the inputs are characterized by stochasticity. The assessment of the impact of alternative decisions on such a system requires a probabilistic approach. It is evident that this is a very demanding task even for a single-reservoir system, not to mention multi-reservoir systems. For this reason, computer codes have been developed since the early 1970s to help with this procedure. Nowadays, these codes have evolved into decision support platforms that offer a user interface to assist the pre-processing and the post-processing. However, the majority of the available tools are commercial and require a considerable amount of money for a licence. Thankfully, a few freeware tools that are based on the simulation–optimization method and with a modern user interface exist. The objective of this study is to assess the performance of these freeware tools. The assessment is based both on an analysis of the theoretical basis and on an application of the models on a simplified representation of the Athens water supply system.

Key words | freeware, optimization, simulation, water resources management

INTRODUCTION

Water resources are complicated dynamic systems that are driven by both natural processes and human activities. Consequently, climate trends or increase in water demand may have a great impact on these systems making imperative the achievement of maximum efficiency and sustainability of water resources use (Stevović et al. 2017). In the case of a water supply system with multiple resources, optimum management includes decisions regarding the selection of the most suitable source at each time (Bertone et al. 2018).

The problem of the optimum management of water resources is not new. Back in the 1950s, Clark (1950) introduced the New York Control Curves, which helped decision makers to estimate the probability of the system reservoirs reaching certain levels in the subsequent months for various initial storage levels at each month of the year. This facilitated the management of the reservoirs so as to distribute the available water optimally and minimize the overflows.

In general, the minimization of overflows is desirable since it maximizes the available water during low inflow periods. For this reason, minimization of water losses is one of the major objectives of the management of multi-reservoir systems. The other major objective is the minimization of the operational cost (most notably the energy consumed for pumping). Other important objectives could be, in the case of multi-purpose reservoirs, the maximization of hydro-power production or the water supplied to irrigation or other sectors of the economy.

The problem of the management of a system of reservoirs is very complicated. The inputs of the system (rainfall
and runoff) are stochastic, hence characterized by uncertainty; whereas the outputs (releases to cover the demand), though more predictable, also exhibit a degree of uncertainty. For this reason, computer codes have been employed in the study of this problem for almost 50 years. The first computer model to be used extensively to support this kind of decision-making appeared in the early 1970s (the model was SUPER of the US Army Corps of Engineers Southwest Division). Today the list of available models dealing with this problem has close to one hundred entries (Wurbs 2005).

The list of the available models is so extensive because there are a variety of approaches to the problem of the management of multi-reservoir systems. One of the most popular approaches is Network Flow Programming (NFP) introduced by Ford & Fulkerson (1962). According to NFP, the optimization of a multi-reservoir system can be accomplished by representing the system with a network of links characterized by cost-flow functions. NFP is, in fact, Linear Programming (LP) applied to network-structured problems. Fourier was the first who provided a solution for LP problems (Sierksma 2001), but since LP is met in many disciplines, it was the Soviet economist Leonid Kantorovich who presented the, now widely used, analytical solution to the problem (Schrijver 1998).

Another popular method is Dynamic Programming (DP), introduced by Bellman (1957). In DP, the given problem is divided into stages. At each stage, the system is at some state, which is described by the set of the state variables (i.e., the storage of reservoirs). The state depends on the decisions made at the previous stages, which are described by the set of decision variables (i.e., the releases). A different sequence of decisions (releases) results in different states (storage levels) at the various stages (simulation time steps). A penalty function gives the cost at a stage for a specific storage/release pair. DP is based on a recursive algorithm that evaluates the cost of all possible alternative states of the various stages and then indicates the sequence of decisions that would achieve the minimum total cost. A lookup table with the costs of all possible combinations of storages/releases is employed to accelerate the decision-making process. The major drawback of DP is the ‘curse of dimensionality,’ as Bellman himself called it, the reason being that the computational load for $m$ time steps and $n$ reservoirs is proportional to $m^n$.

A more recent method, proposed by Nalbantis & Koutsoyiannis (1997), suggests employing parametric rules for describing the operational policy instead of providing individually step-by-step the releases from all reservoirs. The major advantage of this approach is the very limited number of parameters, two for each reservoir. Another advantage of this method is that it is capable of estimating the reliability of the proposed solution without additional computational burden or any reduction of the accuracy of the representation, which some stochastic DP approaches introduce.

The advantage of the three above methods is their utility in the simulation–optimization approach. That is, they can simulate the operation of the hydrosystem in parallel with the optimization by either incorporating or invoking a model of the hydrosystem. In this manner, the simulation procedure handles the physical constraints of the system, and provides a detailed representation of a real-world system’s performance. The advantages of this combined approach have rendered it as the standard method used by most of the successful commercial software packages like MIKEBASIN, RIBASIM, WEAP, etc. Unfortunately, the cost of these packages is quite high, in the range of several thousands of euros. Thankfully, freeware packages, some of them developed by reputable organizations and institutions, are available (e.g., HEC-ResPRM is developed by USACE) and are proving successful in application (e.g., Ashrafi et al. 2017; Fazlali & Shourian 2018).

The scope of this study is to provide a comparison among the available freeware generalized multi-reservoir management models that include a user-friendly interface and a CAD environment in which to design the network. A popular DP-based tool, CSUDP, was excluded from this comparison because it does not provide a CAD environment, and StateMod was excluded because it offers only priority-based simulation without optimization.

The literature review indicated that only four models meet the criteria mentioned above. These models are HEC-ResPRM, MODSIM, Hydronomeas, and UWOT. The characteristics of these models are presented separately in the following sections. Subsequently, the four models are tested in a hypothetical case study, which is a simplified
version of the Athens water supply system. The study concludes with a discussion on the advantages and disadvantages of each model, based both on the analysis of its theoretical basis and the assessment of its performance in the case study. The objective of this discussion is to provide a guideline for researchers who intend to use a freeware model in water management studies.

METHODS

HEC-ResPRM

HEC-PRM (‘Prescriptive Reservoir Model’) is a generalized computer program that performs deterministic network flow optimization of reservoir system operations (USACE 2011). HEC-PRM is developed in FORTRAN and is based on the NFP method. The optimization problem can be written as follows (Jensen & Barnes 1980):

\[
\text{minimize: } \sum c_i(f_i) \\
\text{subject to:} \\
\quad \text{continuity at nodes} \\
\quad \text{capacity of conduits and reservoirs}
\]

where \( f_i \) the storage of the \( i \) reservoir or the flow of the \( i \) conduit at time step \( t \), \( c_i \) is the penalty function of the \( i \) reservoir or conduit.

Equation (1) is the generalized minimum-cost network flow problem, which is solved employing the primal network simplex method, as described in Jensen & Barnes (1980). In the case of non-convex penalty functions, a restricted basis entry procedure (Hadley 1964) is used.

HEC-ResPRM is the coupling of the HEC-PRM model with HEC-Res (common interface to both HEC-ResSim and HEC-ResPRM), a modelling environment developed in Java for viewing and organizing model data. HEC-ResPRM comprises three modules. In the first module, the Watershed, the user defines the hydrosystem topology and configuration. In the second module, the user defines the hydraulic properties and features of the hydrosystem, i.e. the reservoirs (penalty functions, label of inflow timeseries, constraints), the reaches (penalty functions, constraints), and the diversions to water demands (penalty functions, constraints). The penalty functions are defined by providing pairs of storage-cost (for reservoirs) or flow-cost (for conduits). In this module the user creates also the Alternative Scenario that defines the set of timeseries to be used and the initial water storage in the reservoirs. The timeseries should be provided in DSS format prepared with the HEC-DSS tool (implemented as an MS Excel plug-in). Finally, in the third module, the network optimization is performed. Tools to visualize the results are available in this last module.

MODSIM

MODSIM is a generic river basin management decision support system originally conceived in 1978 at Colorado State University (Labadie & Larson 2010). The model engine is written in MS Visual C+++.NET and the user interface is developed in Visual Basic.NET. The timeseries are provided in xls, dbf or csv format, or just pasted into the application. MODSIM is based on the NFP method. Equation (1) is solved with the Lagrangian relaxation algorithm RELAX-IV (Bertsekas & Tseng 1994), which according to MODSIM developers is up to two orders of magnitude faster than the revised simplex method of LP. Seepage is assumed to be a linear function of average volume in the reservoir over each time step and the seepage loss rate is assumed to be constant.

MODSIM uses the priority number, an arbitrary value defined by the user, to derive the costs related to the system reservoirs, groundwater pumping and demands. The employed conversion formula is:

\[
c_i = -(50,000 - 10Pr_i) 
\]

where \( Pr_i \) is the priority number of the element \( i \). For reservoirs, this is an integer priority ranking from 1 to 5,000, with lower numbers indicating lower preference for a resource. For groundwater abstractions, this is a ranking number generally greater than 5,000 such that Equation (2) calculates a positive cost associated with pumping. For demands, it is an integer between 0 and 5,000, with lower numbers representing higher priorities.
Besides the cost derived by the previous formula, MODSIM allows also the user to assign incremental costs for different storage zones of a reservoir, and these costs (called Layer Priorities) need to be in ascending or descending order (the penalty values have to monotonically increase with the percentage of storage).

The user can define directly the cost of the links between elements. However, MODSIM accepts only integer values (an unhandled exception is raised when the user tries to set a real number for a link cost).

**Hydronomeas**

Hydronomeas is an operational software tool for the management of complex water resource systems developed by the ITIA research team of the National Technical University of Athens (Koutsoyiannis et al. 2002; Efstratiadis et al. 2005). Hydronomeas is based on the parametric rule approach (Nalbantis & Koutsoyiannis 1997) and is developed in Delphi. The timeseries should be prepared in hts format with Hydrognomon software. Hydronomeas represents the topology of the system with a digraph, of which the mathematical formulation is equivalent to Equation (1). The penalty functions of Equation (1) are automatically defined by Hydronomeas. For conduits this is accomplished by taking into account the energy required for pumping and the unit cost. For reservoirs, the penalty functions are formulated appropriately to ‘penalize’ the deviation of the reservoirs’ storage from the target storages, as defined by the parametric rule. Equation (1) is solved with the binary Simplex method (Chvatal 1983).

According to the parametric rule approach, for each reservoir Hydronomeas employs a linear equation with two parameters (intercept and slope) that relates the reservoir’s target storage with the total system storage. For each groundwater pump, Hydronomeas uses two threshold values (parameters) to decide whether a specific groundwater resource will be used with higher priority or not be used at all. These parameters define the parametric rule, which in effect represents the operational strategy. To identify the values of these parameters, Hydronomeas employs a global optimization scheme based on the evolutionary annealing-simplex (Efstratiadis & Koutsoyiannis 2002). The results of the optimization include, besides the parameter values, the probability of failure for each water use, the water and energy balance, as well as prediction curves for all hydrosystem fluxes.

Hydronomeas offers the option to use a third-degree polynomial to estimate reservoir seepage.

**UWOT**

UWOT has been developed in C and Python by the Urban Water Management and Hydroinformatics Team, National Technical University of Athens (Rozos & Makropoulos 2013; Rozos et al. 2016). It is an urban water cycle model that acknowledges every urban water flow as a result of a demand (it simulates demand signals instead of flows). UWOT distinguishes between two signal types: the push and pull signals. The push signals express a need to dispose a specific volume of water (e.g. the output of a washing machine). The pull signals express a demand for a specific volume of water (e.g. the water required for the operation of a washing machine). Water flows in the same direction with push signals whereas water flows in the opposite direction for pull signals. This results in a schematization where the network links have a direction from demand locations to water resources, which contradicts the typical network representation used by the other tools.

UWOT estimates the demand signals emitted from household appliances. These signals are aggregated up to household or higher level. The city-level demand signals can be routed to different water resources according to the qualitative and quantitative conditions of each resource. To accomplish this, UWOT employs a special component, the splitter, which splits the incoming demand signal into two streams. This component should be inserted, in the representation of the simulated hydrosystem, at each confluence of aqueducts. The demand is split into the two streams according to the equations:

\[
O_1 = \min \left\{ 0, \max \left\{ 0, a + \sum b_j S_j, 100 \right\} \right\} I / 100
\]

\[
O_2 = I - O_1
\]

where \(O_1, O_2\) are the demand signals going to the two output streams, \(I\) is the incoming demand, \(a\) the intercept parameter of the splitter, \(b_j\) the slope corresponding to
reservoir \( j \), \( S_j \) the relative storage (storage to capacity) of reservoir \( j \).

UWOT employs a linear relationship to estimate the seepage from a reservoir.

Figure 1 displays the flowchart of Hydronomeas and UWOT. The flowchart of HEC-ResPRM (which is representative for MODSIM also) can be found in Figure 2 of the HEC-PRM user manual (USACE 2003).

**CASE STUDY**

The water resources of the Athens Water supply system comprise two major reservoirs, a smaller one located close to Athens (Marathon, net capacity 33.5 hm\(^3\)), and two aquifers with installed boreholes (Mavrosouvala and Vassilika). The two major reservoirs are Mornos (in reality the major reservoirs are three, but for the sake of simplicity Evinos and Mornos are considered as a single reservoir with net capacity of 740 hm\(^3\)) and Lake Hyliki (net capacity 584 hm\(^3\)). Water flows from Mornos reservoir to Athens by gravity, hence this reservoir has the advantage of supplying water without consuming energy. However, Lake Hyliki has significant seepage, therefore water storage left indefinitely in this reservoir will eventually turn into water losses. A very prudent management, from a reliability point of view, would use this resource with higher priority, despite its cost (0.45 kWh/m\(^3\)), and with lower priority other resources in which water is secure. A similar decision should be made regarding the activation conditions of the energy-intensive (0.23 kWh/m\(^3\) for Vassilika and 1.5 kWh/m\(^3\) for Mavrosouvala) water abstractions from the aquifers. The capacity of the boreholes (70 hm\(^3\)/year) does not suffice to cover the Athens demand (412 hm\(^3\)/year). Therefore, in the case of drought, abstractions should be initiated well before the reservoirs get empty. The threshold of initiation of groundwater abstractions and the priority of using an expensive resource, like Lake Hyliki, depend on the desirable trade-off between cost and reliability, which is defined by the adopted operational strategy.

All four assessed models employ a constant coefficient to introduce losses or gains along the elements that transfer water. For a more realistic estimate of water losses, a virtual pressure-dependent demand should be introduced at the pressurized aqueducts. To estimate this virtual demand, which depends on the hydraulic head, the approach of Covelli et al. (2015) could be used. Covelli et al. (2016a, 2016b) have also provided a methodological approach on how to reduce this kind of water loss. In the present study, constant coefficient values that represent the average estimated water losses have been assigned to the aqueducts where losses take place (e.g., 4% at Mornos Aqueduct).

Besides resources availability, factors related to system reliability could also influence operational strategy. For example, Marathon is the only reservoir located close to Athens. For this reason, it has the additional role of an emergency backup resource (to supply Athens for a period up to a...
month). To be able to accomplish this role, the storage in Marathon should be kept above a certain level (27.7 hm³).

The monthly historical timeseries (net rainfall on the reservoirs and runoff of the corresponding drainage basin) for the period 1-Jan-1996 to 1-Dec-2010 were used for the simulation of the reservoirs' water budget. Water abstractions for irrigation (35.1 hm³/year from Lake Hyliki during the dry season) and releases for environmental purposes (constant release from Mornos equal to 2.6 hm³/month) were also taken into account in the simulation. As mentioned previously, Lake Hyliki exhibits significant seepage from its karstified bottom, which depends on the water level. However, since HEC-ResPRM does not support seepage simulation, it was approximated by assuming constant abstractions equal to 14.4 hm³/month. This is the seepage value estimated from equations (4.3) and (4.4) of the 2009 Master Plan (Efstratiadis et al. 2009) for the average lake water level of the hydrological period from 1977–78 to 2004–05.

After the simulation–optimization, the four models were compared using two metrics:

1. the minimum water storage (excluding the first time-steps of the simulation) of the simulation period (the time step of the minimum was the same for all models);
2. the energy consumed up to the moment of minimum storage.

The setup of each of the four models is described in the following lines.

HEC-ResPRM

In this study HEC-ResPRM 1.0 was used. The representation of the Athens water supply system in HEC-ResPRM is displayed in Figure 2.

In HEC-ResPRM the water demand is introduced by employing Diversion elements. This includes the demand for Athens water supply (different value for each month), the demand for irrigation (different value for each month), the demand for environmental flow (constant value), and the seepage from Lake Hyliki (constant value). Diversion elements are also employed to simulate the abstractions from reservoirs for the Athens water supply network. These elements have as upper bound the capacity of the downstream conduits. The Mavrosouvala and Vassilika boreholes are simulated employing a large virtual reservoir (corresponding to the aquifers) and a conduit with a penalty function that introduces the energy cost. A penalty function corresponding to the energy for pumping is also introduced in the first segment of the Hyliki aqueduct.

The employed penalty function for the storage of reservoir \( i \) has the following form (the penalty gets lower with the increase of reservoir storage):

\[ c_i(f_{\text{ai}}) = 1 - f_{\text{ai}} / (0.98 \text{Vmax}_i), \text{ for } f_{\text{ai}} < 0.98 \text{Vmax}_i \]
\[ c_i(f_{\text{ai}}) = 1, \text{ for } f_{\text{ai}} > 0.98 \text{Vmax}_i \]  

where \( \text{Vmax}_i \) is the capacity of the \( i \) reservoir.

Figure 2 | Athens water supply network representation in HEC-ResPRM.
Especially for Marathon, to introduce the target of the lowest acceptable storage in this reservoir (27.7 hm³), the penalty function has the following form:

\[ c(f_t) = \begin{cases} 
3 - 3f_t/27.7, & \text{for } f_t < 27.7 \\
0, & \text{for } 27.7 < f_t < 33 \\
1, & \text{for } f_t > 33 
\end{cases} \]  \hspace{1cm} (5)

Since energy consumption cannot be represented in HEC-ResPRM, this should be taken into account by appropriately formed penalty functions like:

\[ c_i(f_{it}) = p_i f_{it} \]  \hspace{1cm} (6)

where \( p_i \) is the specific energy in kWh/m³ of the element \( i \).

The weights of the penalty functions are selected according to the management strategy. For example, a conservative strategy (minimize risk of failure) would suggest employing a larger weight in the penalty of Mornos storage to render preferable the abstractions from Lake Hyliki (the optimization algorithm tries to minimize cost, and hence for the adopted form of penalty function will favour storage in the reservoirs with higher weight). This would reduce the storage of Hyliki, and consequently the seepage and the total hydrosystem losses. Similarly, the weight of the penalty functions for energy consumption is also an important parameter that defines the management strategy. The higher this weight (more specifically the higher the relative value of this weight compared with the other weights) the more ‘unwilling’ becomes the algorithm to use energy-intensive resources (e.g. groundwater). This would reduce the energy consumption, but it would result in an increase of the risk of failure as explained previously.

Three sets of weight values were employed in the application of HEC-ResPRM. The first set was derived by calibration to reproduce the reservoirs’ operations suggested by the 2009 Master Plan of the Athens Water Supply Company (Efstratiadis et al. 2009, p. 82). The second set was derived by manual calibration to achieve an energy-saving system operation, whereas the third set achieved an operation with low risk of failure. These weights are shown in Table 1.

**Table 1** The three sets of weight values used the HEC-ResPRM penalty functions to derive the three operational strategies

<table>
<thead>
<tr>
<th></th>
<th>Set 1</th>
<th>Set 2</th>
<th>Set 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mornos storage</td>
<td>1.80</td>
<td>1.13</td>
<td>2.60</td>
</tr>
<tr>
<td>L. Hyliki</td>
<td>1.00</td>
<td>0.40</td>
<td>1.00</td>
</tr>
<tr>
<td>Marathon storage</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Energy</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
</tbody>
</table>

**MODSIM**

In this case study MODSIM 8.5.0 was used. The representation of the Athens water supply system in MODSIM is displayed in Figure 3.

![Figure 3](https://iwaponline.com/ws/article-pdf/19/4/995/593598/ws019040995.pdf)
MODSIM introduces demands to the system with the dedicated element Consumptive Demand. This element is used also to simulate abstractions from groundwater. Five Consumptive Demand elements are used in the representation of the Athens water supply system: two of them for the two pumped aquifers, one for the Athens demand, one for the irrigation demand and seepage, and one for environmental flow.

MODSIM, like HEC-ResPRM, cannot directly simulate energy consumption. For this reason, energy consumption is included as a cost in the appropriate elements. This cost is set equal to the specific energy consumption in kWh/100 m³. Furthermore, the cost assigned to the links that connect the reservoir with the network sinks is set equal to 1,000 (an arbitrary high value) to ‘penalize’ losses due to overflows. All demands have priority value equal to 100 whereas different priorities are assigned to the water resources (see Table 2).

It should be noted that MODSIM exhibited an abrupt step-like response to even slight changes of priority numbers. For example, changing the priority number of Vassilika pumps from 5,997 to 5,998 results in a drop of the pumped volume, over the simulation period, from 542.9 to 0 hm³.

The target storage of Lake Hyliki and Mornos was set equal to the corresponding reservoir capacity. The target storage of Marathon was set equal to the lowest acceptable storage under ordinary conditions (27.7 hm³).

**Hydronomeas**

In this case study Hydronomeas 4.9v was used. The representation of the Athens water supply system in Hydronomeas is displayed in Figure 4.

Hydronomeas employs dedicated elements, the Targets, to introduce demands. Four Targets were used to introduce: the Athens demand, the irrigation demand, the environmental flow, and the approximation of Lake Hyliki seepage. Targets can be also used to set desired storage levels at reservoirs. A Target was used to set the lowest acceptable storage at Marathon. Dedicated elements can be used to simulate the aqueducts where water is pumped, like Lake Hyliki Aqueduct. Hydronomeas has also a special type of node to simulate water abstractions. Two elements of this kind are used to simulate the abstractions from the two aquifers of the Athens water supply system (Mavrosouvala and Vassilika).

![Figure 4](https://iwaponline.com/ws/article-pdf/19/4/995/593598/ws019040995.pdf)

**Figure 4** Athens water supply network representation in Hydronomeas.
The releases from the reservoirs and the abstractions from the two aquifers are defined by the parametric rule, which at each time step gives the target storage. Normally, when Hydronomeas is used for supporting decisions, it is run employing long synthetic timeseries and the parameters of the parametric rule are optimized (single objective optimization) to minimize various metrics like energy consumption, risk of failure, total cost, etc. In this case study, the parameters were calibrated to reproduce the reservoirs’ operation suggested by the 2009 Master Plan. To simplify the calibration procedure, the coefficient $a$ of each reservoir was set equal to the ratio of the reservoir’s capacity to the total system capacity and was not optimized. This simplification gives the homogeneous rule (Nalbantis & Koutsoyiannis 1997) in which the coefficient $b$ of each reservoir is the ratio of the reservoir’s target storage to the total system storage. The values of the parameters obtained from the calibration are given in Table 3.

### UWOT

The representation of the Athens water supply system in UWOT is displayed in Figure 5. In this study UWOT 1.00.0.53 was used.

UWOT offers a variety of dedicated components that simulate the various elements of the hydrosystem (e.g. reservoirs, aqueducts, groundwater pumps, etc.) and allows the

**Table 3**  
The parameter values of the Hydronomeas parametric rule: the intercept $a$, the slope of reservoir target storage $b$, the upper and lower threshold of activation of groundwater pumps

<table>
<thead>
<tr>
<th></th>
<th>$a$ coeff.</th>
<th>$b$ coeff.</th>
<th>Upper threshold</th>
<th>Lower threshold</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hyliki</td>
<td>0.43</td>
<td>0.51</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mornos</td>
<td>0.55</td>
<td>0.56</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Marathon</td>
<td>0.025</td>
<td>0.01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vassilika</td>
<td></td>
<td>1.00</td>
<td>0.86</td>
<td></td>
</tr>
<tr>
<td>Mavrosouvala</td>
<td>1.00</td>
<td>0.00</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Figure 5**  
Athens water supply network representation in UWOT.
user to define the specifications of each one. For example, the user can define the coefficient of water losses of an aqueduct, the specific energy, the capacity, etc. Water needs can be simulated by dedicated components, but in this study the demand signals were introduced to the network with four special components intended for this purpose (marked with ‘IN’ in Figure 5).

For the case study, four splitters were employed. These splitters are used in the confluences of the aqueducts of Hyliki/Mornos, Marathon/Hyliki, Mavrosouvala/Hyliki, and Mornos/Vassiliki. Their parameters were derived by calibration to have UWOT reproduce the flows simulated with HEC-ResPRM when using the first set of weights. The values of these parameters that achieved the best fit are given in Table 4.

It should be noted that UWOT does not offer the option to set a target storage to a reservoir. This can be seen in Figure 6 where only the simulated storage with UWOT drops below the lowest acceptable storage.

**RESULTS AND DISCUSSION**

In total, results of seven model runs were obtained, three corresponding to the three weight sets of HEC-ResPRM, two for MODSIM with priority values 5,997 and 5,998 for Vassiliki pumps, one for Hydronomeas, and one for UWOT. The simulated storage of the reservoirs of the Athens water supply system is shown in Figure 6.

The more conservative solutions (regarding the risk of failure) tend to keep the storage higher in Mornos and the storage lower in Hyliki. From Figure 6 it becomes apparent that the minimum system storage during the simulation period occurred in November 2008. It is the total storage of the system of this month that is used as one of the metrics to compare the models (the higher the better). The other metric is the total energy consumed up to this date for pumping water to Athens (the lower the better).

Figure 7 displays the storage–energy trade-off achieved by the various models. Figure 7 indicates that the three solutions of HEC-ResPRM appear to lie on a front. MODSIM solutions also lie on this front. However, the slight change in the priority number of Vassiliki pumps resulted in a

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**Table 4**

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Hyliki/Mornos</th>
<th>Marathon/Hyliki</th>
<th>Mavrosouvala/Hyliki</th>
<th>Mornos/Vassiliki</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>a</em> coeff.</td>
<td>23.69</td>
<td>79.96</td>
<td>20.39</td>
<td>93.51</td>
</tr>
<tr>
<td><em>b</em> coeff.</td>
<td>−33.91 (Mornos)</td>
<td>76.18 (Marathon)</td>
<td>−18.74 (Hyliki)</td>
<td>−103.46 (Mornos)</td>
</tr>
</tbody>
</table>
jump from the rightmost end of this front (the highest storage during drought, hence lowest risk) to the leftmost end (the lowest energy consumption). Hydronomeas and UWOT solutions are sub-optimal. Regarding both models’ solutions, the same energy consumption could have secured more water at the driest month of the simulation period with more careful management. HEC-ResPRM and MODSIM achieved this better management by suggesting higher releases from the Marathon reservoir (almost 100 hm³ higher than Hydronomeas and UWOT), which is an energy-free resource. Hydronomeas was probably hampered by the storage targets of Marathon, which override the parametric rule. Hence, Marathon releases could not be increased no matter what parameter values were selected. On the other hand, UWOT was most probably hampered by the storage targets of Marathon, which override the parametric rule. Maier et al. (2014) have compiled a list of metrics that could be used to quantify the optimization difficulty of UWOT parameters. A better problem formulation, i.e., a more efficient parametric rule, could emerge from this analysis.

Table 5 summarizes the specifications and the characteristics of the four models that were discussed previously plus three characteristics regarding how easy it is to familiarize with and configure the model, the model expandability (e.g. MODSIM offers the Custom Code Editor for creating customized versions of MODSIM developed from user-supplied code written in VB.NET, UWOT allows new components to be easily added, though the code is not publicly available), and the quality of the available model documentation.

**CONCLUSIONS**

This study compares freeware water resources management models that are based on the simulation–optimization approach, namely HEC-ResPRM, MODSIM, Hydronomeas, and UWOT. The comparison includes an analysis of the theoretical basis and the case study (a simplified representation of the Athens water supply system). The advantages and disadvantages of each of the four models are presented briefly below.

1. **HEC-ResPRM.** HEC-ResPRM offers high flexibility in representing operational strategies by allowing the user to define the penalty functions and their weights. The impression obtained from HEC-ResPRM was that, with

![Figure 7](https://iwaponline.com/ws/article-pdf/19/4/995/593598/ws019040995.pdf)
proper selection of penalty functions and weights, it can yield an optimum managerial decision regarding the acceptable risk. The disadvantages of HEC-ResPRM are that it does not simulate groundwater pumping, it does not simulate seepage from reservoirs, and it has a rather complicated user interface.

2. **MODSIM.** MODSIM has the simplest user interface, and it provides solutions that are as good as those provided by HEC-ResPRM. The main disadvantage of MODSIM is that the slightest change in the priorities can result in a completely different operational strategy, which means that the user cannot explore in detail the trade-off between system reliability (water storage) and operational costs (consumed energy).

3. **Hydronomeas.** The greatest advantage of Hydronomeas is the straightforwardness of its parametric rule. In fact, once the rule is defined, it can be used without running Hydronomeas since the rule can be represented even as a nomogram. Hydronomeas simulates energy production and consumption, which can be used as separate metrics in the optimization procedure. The only disadvantage of Hydronomeas is that the storage targets can prevent the model from suggesting an optimum solution.

4. **UWOT.** UWOT has the advantage of being able to simulate not only the water resources and their operation but also the generation of the water demand, starting from the lowest level (i.e., the complete urban water cycle). UWOT can simulate the energy consumption and production, even from renewable resources (not examined in this study). However, UWOT does not allow the user to define the storage targets. Also, the parametric rule it employs does not seem to represent all the available solutions (i.e., every possible operational strategy) properly.

A final comment regarding the tested tools is that since none of them is open source, the scientific community cannot scrutinize the code and adapt it to the specific needs of their various studies. Some of the disadvantages described above could be resolved if the code were available in a public repository to allow a broader involvement in its further development. The adoption of such a distribution policy would not only improve the quality of the software but would also raise it to the industrial standard (see MODFLOW).

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