8-1-2014

Optimizing Operating Rules Of Multiple Source Water Supply Systems In Terms Of System Reliability And Resulting Operating Costs: Survey Of Simulation-Optimization Modeling Approaches Based On General Purpose Tools

Jordi Meseguer

Gabriela Cembrano

Josep M. Mirats

Eduard Bonada

11th International Conference on Hydroinformatics
HIC 2014, New York City, USA

OPTIMIZING OPERATING RULES OF MULTIPLE SOURCE WATER SUPPLY SYSTEMS IN TERMS OF SYSTEM GUARANTEE AND RESULTING OPERATING COSTS: SURVEY OF SIMULATION-OPTIMIZATION MODELING APPROACHES BASED ON GENERAL PURPOSE TOOLS

JORDI MESEGUER (1), GABRIELA CEMBRANO (2) (1), JOSEP M. MIRATS-TUR (1) ,
EDUARD BONADA (1)

(1): CETaqua, Water Technology Center, Carr. Esplugues 75,Cornellà de Llobregat, 08940, Spain. Phone: +34-93-3124829, fax : +34 93 312 48 01 / e-mail: jmeseguer@cetaqua.com

(2): Institut de Robòtica i Informàtica Industrial(CSIC-UPC), Spain.

Management and operation of a multiple-objective multisource water supply system from the point of view of the conjunctive use of water sources is a very complex problem whose solution is not just obtained using analytical models but also through a negotiation process among stakeholders and in which Public Bodies have a main role. For these reasons, this problem has been addressed using conservative approaches based on simulation models or simulation – linear optimization models parameterized using few parameters which, in general, are already covered by existing generalized modelling tools using a longer or shorter trial and error process. However, these conservative approaches have drawbacks and constraints when dealing with certain complexities of water supply systems (i.e.: non-linearity, uncertainty or stochastic nature) that may prevent them of finding an optimal solution.

This paper identifies and tests suitable simulation-optimization approaches found in existing generalized modeling tools for optimizing operating rules of multisource water supply systems in terms of system guarantee and resulting operating costs. The main purpose is to find out whether these approaches are already covering the decision support needs of managers, Public Bodies or other stakeholders involved in the operation of these systems, or 'ad-hoc' tools may be needed

Keywords: Water Resources Management, Generalized Modelling System, Optimizing Operating Rules, Multiple-Source and Multiobjective Water Supply System.

1. INTRODUCTION

According to [1], the management and operation of multiple-objective multisource water-supply systems, typically exploiting multiple surface water and groundwater resources, tend to be extremely complex. The combination of supply sources and the associated complex hydraulic network that delivers water to various demand nodes are often too numerous [2]. The large number of variables involved, the nonlinearity of dynamics, the stochastic nature of future inflows, and other uncertainties of water resources systems render their management a difficult but imperative task [3]. Complexity further increases since the management of these systems usually involve many objectives and purposes which might compete among them [1] (i.e. maximizing water supply system reliability, meeting water demands, , maximizing hydropower generation, cutting operating costs).Based primarily on past experience, reservoir operators arrive at some feasible alternatives and mode of operation. In most instances, these alternatives are not necessarily optimal, resulting in loss of efficiency and benefits. Decision models can help this type of problem considerably by integrating all technical, environmental, economic, and social aspects relevant to decision making [4] and can lead authorities and the water utilities to undertake a structured and systematic analysis.

The main purpose of this paper is to identify and test suitable simulation-optimization approaches found in existing generalized modeling tools for optimizing operating rules of multisource water supply systems coupling integrated water resources management approach at the regional level (long-term management) based on water supply sustainability optimization (water supply guarantee) and selected operational objectives set for short-term operation in the water supply-system (mainly, minimizing water supply deficits and operating costs). The main goal is to identify strengths and weaknesses of these approaches and the current tendencies of these tools to overcome their drawbacks. A simple but representative case of study inspired in the Barcelona water supply system will be used.

In the paper reminder, past and current trend in water resource management modeling (methods and tools) is reviewed in *Section 2*. Then, simulation-optimization approaches found in existing generalized modeling are assessed using the case of study (*Section 3*). Finally, the conclusions are presented in *Section 4*.

2. WATER RESOURCE MANAGEMENT

2.1. Modeling approaches

The management and operation of multisource water-supply systems tend to be extremely complex demanding a conjunctive use[1] of the system's water sources [1] and the use of models to support the decision-making / operation process [4]. A number of mathematical models have been developed and applied over the last several decades which, mainly, are grouped into two large categories: optimization and simulation methods [5][6].

Traditionally, the management of multisource and multi-objective water supply systems is based on predetermined operation rules which are obtained through a negotiating / discussing process supported by simulation models [3]. In general, the following drawbacks can be pointed out in this process: many trials are required to test every possible operation rule combination, optimum solution could not be achieved. In spite of these drawbacks and the development and growing use of optimization techniques, simulation models remain the primary tool for reservoir planning and management studies in practice [3]. Simulation models allow a more detailed and faithful representation of a real-world system performance than optimization models do [4]. As mentioned, the main drawback of simulation is that it requires prior specification of the system operating policy. In consequence, the only way to locate an optimal policy is through subsequent trials. The studies of large scale systems [4] have

[1]The conjunctive use of a multiple-source system was described by Walsh (1971) as 'the joint use of two or more water resources according to a planned rule, leading to a cheaper supply than that gained by their independent use'

indicated that even with the use of simple optimization approaches (i.e.: Linear Programming optimization), valuable results can be obtained to simplify simulation. [7] presented an approach combining simulation and optimization modelling where operation rules of water sources are parameterized using few parameters which are estimated using optimization in order to obtain an optimal solution. In this scheme, simulation model is used to assess the goodness of the estimated parameter set.

[3] pointed out that due to the stochastic aspect of water resources systems, deterministic optimization methods such as linear and dynamic programming [8][9] cannot provide optimal solutions. To tackle these drawbacks, *Evolutionary algorithms* may be used as optimization models [10][11]: i.e. *Genetic algorithms* (*GAs*). The evolutionary computation (EC) approach has been tried out to overcome the complexities, such as, multi-objectives, uncertainty, nonlinearity, discontinuity and discreteness which limit the applications of analytical optimization methods in reservoir systems optimization.

2.2. Modeling tools

In general, modelling systems (tools) applied to water resource management can be classified into two groups: generalized modelling systems [6] and site specific (ad-hoc) systems [6]. Those systems belonging to the first group are built without considering a specific water supply system meaning that they can be applied to a large number of water systems using a certain customization. This group of models trends to offer a wide flexibility to the user trying to cover those general aspects common in a large number of cases of study. However, they may not cover some specific requirements of certain water supply systems. On the other hand, site specific or ad-hoc modelling tools are designed and built to be applied in a concrete water supply system following predefined objectives. This second approach let obtain very accurate solutions covering in details all the known requirements. However, the application of these tools to other cases of study may require a lot of re-programming effort. According to [6], the general trend in recent years has been to shift away from customized system-specific models to generalized models.

As mentioned in *Section 2.1*, existing generalized modeling systems are still based, mainly, on simulation methods [4][6]. The main reason is due to simulation approaches are more detailed, clear and therefore, faithful for water supply system managers [3]. Besides, decisions about operation rules of water sources are usually also based on a negotiating process among certain related stakeholders (i.e.: Public Body, Local operators and special users) where modeling tools are just used as decision support systems. Thereby, the main requirement for these modeling systems is that they can reproduce accurately the performance of water supply systems. In this sense, modeling systems are required to be capable of describing any water system operation rule. In some cases, modeling systems have a customizing environment to implement specific operation policies not included in their standard options and an own language syntax.
Nonetheless, as mentioned in previous section, a pure simulation approach can be very time consuming where the used trial and error process does not guarantee an optimal solution. As a response to this drawback, the trend in existing generalized modeling systems is to combine the simulation approach with a simple and deterministic optimization approach (Rani et al., 2010). In general, in this approach the optimization algorithm is parameterized using few parameters whose values must be identified by users to try to obtain suitable solutions.
Although this simple combined simulation – optimization approaches does not let obtain optimal solutions since they do not consider important aspects affecting to water resource systems (i.e.: stochastic, non-linear, complex nature) [3][10][11], existing generalized

modelling tools are not integrating more accurate modelling methods (i.e.: *GAs*). The main reason is that in general, generalized modelling tools try to cover a wide set of water resource management problems rather than focusing on a specific problem. In [6], the five types of generalized modeling tools representative of the existing state-of-the-art in reservoir/river system modelling capabilities are described.

Nonetheless, current providers of generalized modeling tools are very aware of this constraint and therefore, a functionality that current modelling systems are starting to offer to overcome this drawback is its capacity to be linked with external software modules mainly implementing accurate optimization algorithms [12][13]. In this sense, current modelling systems also tend to offer a customizing environment where these systems can be customized for specific requirements when it is needed. As example, the *Aquator* generalized modeling tool [2] implementing a pure simulation approach can be linked to generalized multi-objective optimization module based on *GA* [13] [3]. On the other hand, [12] proposes an approach where *Aquatool* generalized modeling tool [14] which is based on a simple optimization[4] – simulation approach is linked to the PIKAIA GA-based optimization tool [15].

3. ASSESSMENT OF SIMULATION-OPTIMIZATION APPROACHES

3.1. Introduction

In *Section 3*, the following approaches will be considered: *Simulation – Linear Programing (LP*[5]*) Optimization*, *Simulation / LP Optimization – Genetic Algorithm (GA)*, *Simulation – Optimization based on a Genetic Algorithm*. These approaches are tested focusing on the water supply guarantee and operating cost optimization considering an illustrative case of study inspired in the regional water resource system that supplies Barcelona.

3.2. Case study description

The considered water supply system has two reservoirs and one desalination plant as water sources and supplies water to two demands nodes. Regarding reservoirs, the main properties of this type of water sources are: initial Storage (S_{ini}), minimum and Maximum storage (S_{min}, S_{max}), maximum reservoir outflow (Q_{max}), unitary operating cost (*Cost*). In regard to the desalination plant, the main properties of this type of water source are: maximum desalination plant outflow (Q_{max}), unitary operating cost (*Cost*). Regarding to the water supply system demands, the main considered properties are: demand time series (*Demand*), demand priority (*Priority*). In **Error! Reference source not found.**, a basic graph of the considered water supply system can be seen. The main difference between both reservoirs is the corresponding operating costs: *0.2* for *Rerservoir 2* while *0.1* for *Reservoir 1*. However, the desalination plant still has much higher operating costs (*0.4*) but its supply capacity at every time instant is also much more limited such as it occurs in the reality. Regarding the two existing demands, the main difference is that *Demand 1* has a higher priority than *Demand 2*. In **Error! Reference source not found.**, the considered reservoir inflows and demand time series (volum units) of a given period of time can be seen. Each period is divided into *10* time instants and repeats periodically. Thereby, the considered whole simulation time contains *6* periods of time with *10* time instants each. Regarding the values of these demand time series, all three water sources are required to supply the predicted demand.

---

2 http://www.oxscisoft.com/aquator/

3 See pag 19, newsletter *Circulation* Nº 112 of the British Hydrological Society

4 The optimization method implemented in Aquatool is based on linear programing (LP)/network flow programing (NFP)

5 Network Flow Programming has been used instead of Linear Programming since it is requires for the optimization of the systems efficiency (guarantee) during a given period of time. This method can be considered an extension of the known Linear Programming method

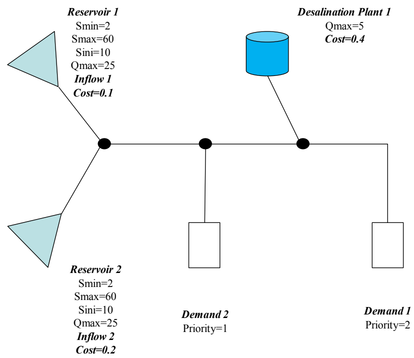

Figure 1 Basic scheme of the considered water supply system

Table 1[6] Reservoir inflows and demand time series

i	Inflow 1 (-)	Inflow 2 (-)	Demand 1 (-)	Demand 2 (-)
1	2	2	6.2	1
2	2	2	6.2	1
3	12	12	22.2	1
4	15	15	27	1
5	12	12	22.2	1
6	9	9	17.4	1
7	6	6	12.6	1
8	4	4	9.4	1
9	3	3	7.8	1
10	3	3	7.8	1

3.3. Simulation – Linear Programing (LP) Optimization

When considering a multi-objective optimization considering maximizing water supply system guarantee (efficiency) while minimizing resulting operating costs as optimization objectives, the obtained objective function has the following aspect:

$$\text{Min}(-W_G G_{SYS} + W_C C_{SYS}) \quad (1)$$

where G_{SYS} and C_{SYS} are the resulting system guarantee and operating costs, correspondently being W_G and W_C their corresponding weights. On the other hand, this objective function is subject to a set of constraints determined mainly by system mass balance equations, constraints related to S_{ini}, S_{min}, S_{max} and Q_{max}, etc. Additionally, it must be taken into account that this optimization problem is not solved for every time instant but considering all the simulation time (*600* time instants) since this is a requirement when performing system guarantee or efficiency analysis.. In the following, the described simulation-optimization method is solved considering the case of identifying all system feasible operation points in terms of system guarantee / efficiency and resulting operating costs ($W_G \neq 0$ and $W_C \neq 0$) using an iterative (trial and error) process where $W_G=1$ while W_c is being valued using different values ranging from $W_C=0$ *until* $W_C=25$ *using a step of 0.1* (**Error! Reference source not found.**). This iterative process let determine an estimation of the *Pareto Optimal* solutions. In the following, more details are given about the most important operation points shown in **Error! Reference source not found.**. *Point 1*: this is the system operation point obtained $W_C=0$ obtaining the maximum system guarantee value (*100%*). *Point 2*: this operation point is obtained when the use of those more expensive water sources are starting to be penalized ($W_C=0.1$): it can be considered as an estimation of the optimum operation point (maximum efficiency at the minimum operating costs[7]). *Point 3*: its main characteristic is that the demand with lower priority (*Demand 1*) is not supplied anymore. *Point 4*: in this operation point apart from not supplying *Demand* 1, that part of *Demand 2* that requires the use of the desalination plant is not supplied either.

3.4. Simulation / LP Optimization – Genetic Algorithm (*GA*)

The iterative process presented in previous section could not be so straightforward in more complex systems or when additional optimization objectives are considered. In this line, (Reis

[6] Numerical values of this case of study have been inspired by the reference: Savić, D. A., Bicik, J., & Morley, M. S. 2011 A DSS Generator for Multiobjective Optimisation of Spreadsheet-Based Models. Environmental Modelling and Software, 26(5), 551-561.

[7] A bigger reduction of the operating costs also implies a reduction of the system efficiency.

et al., 2005) suggests using a *Genetic Algorithm* (*GA*) linked to *Simulation – LP Optimization* method. This approach is tested in this section using the considered case of study where a potential solution is given by a set of values for W_G and W_C. The iterative process is mastered by *GA* and pursues finding an estimation of the *Pareto Optimal* solutions (*Pareto Front*). The steps that determine this iterative process are the following: ***Step 1**: Generating population of solutions (GA tool)* using *the solutions selected in a previous step an applying the GA native processes;* ***Step 2**: Evaluate fitness of every solution. The fitness of a certain solution is given by the corresponding values of* G_{SYS} *and* C_{SYS} *given by the Simulation – LP Optimization tool;* ***Step 3**: Evaluate whether the stopping criteria of the iterative process is reached (GA tool). If it is not reached, then a new iteration starts jumping into Step 1.* Otherwise, the process ends obtaining an estimation of the Pareto Optimal solutions (*GA tool*). The obtained *Pareto Optimal* solutions (*Pareto Front*) can be seen in **Error! Reference source not found.** which are very similar to the ones obtained in previous section (**Error! Reference source not found.**)[8] with the exception of *Point 1* which cannot be found since it is not a *Pareto Optimal* solution.

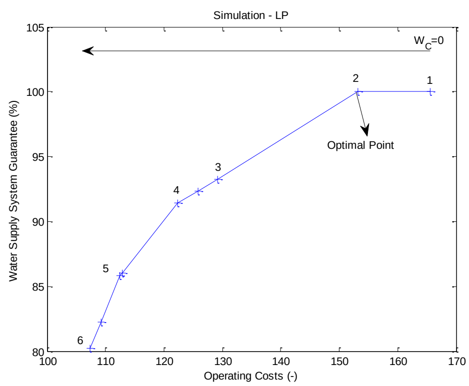

Figure 2 Evolution of the system guarantee / efficiency regarding the resulting operating costs.

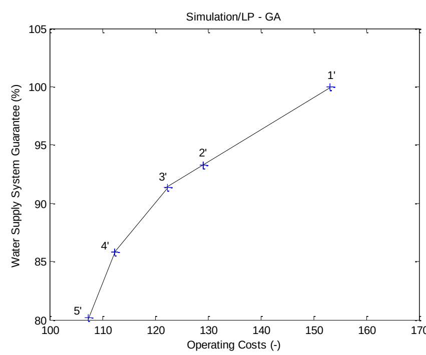

Figure 3 Evolution of the system guarantee / efficiency regarding the resulting operating costs: *Pareto Optimal* solutions.

3.5. Simulation – Optimization based on a Genetic Algorithm

In this section, considering that the stochastic and non-linear nature of water resource systems may prevent the application of the methods presented in *Section 3.2* and *Section 3.3*, a Simulation – Optimization method based on *GAs* (*Simulation – GAs*) will be used to identify the optimal outflows associated to every water source to meet the existing water demands. In this case, it is assumed that the outflows of a water source for a certain period will repeat periodically for the other periods of the simulation time. As a consequence, the unknowns that must be solved by this method are the ones shown in **Error! Reference source not found.**. In this *Simulation – GAs* approach, a potential solution is given by a set of values of the unknowns determined by **Error! Reference source not found.**. Then, the 3 steps of the iterative process explained in *Section 3.4* can also be applied in this case using the simulation tool to obtain the fitness values (G_{SYS}, C_{SYS}) associated with every solution. Then, at the end of this iterative process, an estimation of the *Optimal Pareto* solutions (*Pareto Front*) will be obtained (**Error! Reference source not found.**).

---

[8] *Point 1'=Point 2, Point 2'= Point 3, Point 3' = Point 4, Point 4' = Point 5 and Point 5' = Point 6*.

Regarding the obtained *Pareto Optimal* solution curve, three main linear segments can be identified proposing a conjunctive used of the water sources ordered from the cheapest one (*Reservoir 1*) to the most expensive one (*Desalination Plant*). *Res.1*: this segment is just determined by the use of *Reservoir 1; Res.1+Res.2*: this segment use intensively *Reservoir 1* and partially, *Reservoir 2; Res.1+Res.2+DP:* in this case, both reservoirs are used intensively while using partially, the desalination plant ending when the system efficiency reaches *100%*. The obtained results are very similar to the ones of previous sections. Nonetheless, this method can be used when considering non-linearities or stochastic nature of the system.

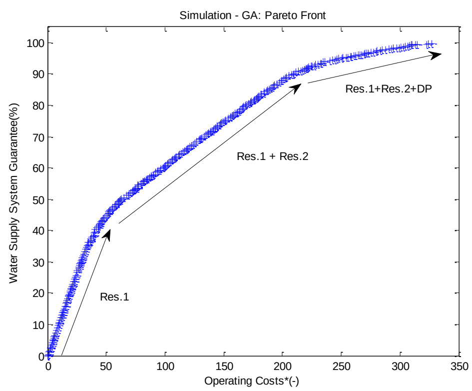

Figure 4 Evolution of the system guarantee / efficiency regarding the resulting operating costs: estimation of the *Pareto Optimal* solutions[9].

Table 2 Unknowns related to every water source

i	*Reservoir 1 (-)*	*Reservoir 2 (-)*	*Desal. Plant (-)*
1	X1	Y1	Z1
2	X2	Y2	Z2
3	X3	Y3	Z3
4	X4	Y4	Z4
5	X5	Y5	Z5
6	X6	Y6	Z6
7	X7	Y7	Z7
8	X8	Y8	Z8
9	X9	Y9	Z9
10	X10	Y10	Z10

4 . CONCLUSIONS

The main purpose of this paper is to identify and test suitable simulation-optimization approaches found in existing generalized modeling tools for optimizing operating rules of multisource water supply systems in terms of system guarantee and resulting operating costs. The general trend in modeling tools has been to shift away from customized system-specific tools to generalized modeling tools in which simulation models or simulation – linear optimization models parameterized using few parameters remain the primary methods since they are more detailed and clear and therefore, faithful. However, this approach may not always let obtain optimal solutions since they do not consider important aspects (i.e.: stochastic, non-linear, complex nature). Therefore, a functionality that current modelling tools are starting to offer to overcome this drawback is its capacity to be linked with external software modules implementing accurate and complex optimization methods (i.e.: Evolutionary Algorithms).

On the other hand, a basic but representative case of study inspired in the Barcelona water supply system has been used to test those methods. First, a *Simulation – Linear Programing (LP) Optimization approach* has been tested. In this case, the user must set up the optimization problem using a trial and error process in order to obtain a suitable solution. It may not be suitable for complex systems or when considering additional linear optimization objectives. Besides, when considering non-linear optimization objectives or the stochastic nature of water resource systems, this optimization method is not appropriate. Then, the *Simulation / LP Optimization – Genetic Algorithm (GA)* approach has been tested which speeds up the user trial

[9] the *Operating Costs** variable used in *x-axis* is not equal to system operating costs but it has been obtained as a weighting sum of the operating cost of every water source such that the use of cheaper water sources are stimulated

and error process of finding the suitable settings of the *Linear Programming* algorithm. Thereby, this method is suitable when this trial and error process is not very straightforward (i.e.: complex systems, considering additional optimization objectives, etc). Finally, the *Simulation – Optimization based on GAs* has been considered. This method is especially suitable when non-linear optimization objectives/ water resource system stochastic nature are considered. Regarding the use of *GAs* in this approach, they are more sensitive to their initialization and setting values than they are in the previous approach. Nonetheless obtained results are suitable.

ACKNOWLEDGMENTS

The authors wish to thank the support received by the WR1203 project funded by R+I Alliance (Suez environnement) and by the EFFINET grant FP7-ICT-2012-318556 of the European Commission.

REFERENCES

[1] Vieira, J., Cunha, M.C., Nunes, L., Monteiro, J.P., Ribeiro, L., Stigter, T., Nascimento, J., Lucas, H., (2011). 'Optimization of the Operation of Large-Scale Multisource Water-Supply Systems'. Journal of Water Resources Planning and Management 137, 150.

[2] Barros, M.T.L., Zambon, R.C., Barbosa, P.S.F., Yeh, W.W.-G., (2008). 'Planning and Operation of Large-Scale Water Distribution Systems with Preemptive Priorities'. Journal of Water Resources Planning and Management 134, 247.

[3] Koutsoyiannis, D., Efstratiadis, A., Karavokiros, G., (2002). 'A Decision Support Tool for the Management of Multi-reservoirs Systems'. Journal of the American Water Resources Association 38, 945–958.

[4] Rani, D. and Moreira, M. M., (2010).'Simulation–Optimization Modeling: A Survey and Potential Application in Reservoir Systems Operation', Water Resources Management, vol. 24, no. 6, pp. 1107–1138, Jul. 2009.

[5] Labadie JW., (2004) Optimal operation of multireservoir systems: state-of-the-art review. J Water Resour Plan Manage—ASCE 130(2):93–111

[6] Wurbs RA., (2005). 'Comparative evaluation of generalized river/reservoir system models'. TR-282. Texas Water Resources Institute, Texas A&M University.

[7] Nalbantis, I. and D. Koutsoyiannis, (1997). 'A Parametric Rule for Planning and Management of Multiple-Reservoir Systems'. Water Resources Research 33(9):2165-2177.

[8] Loucks, D. P., J. R. Stedinger, and D. A. Haith, (1981). 'Water Resource Systems Planning and Analysis'. Prentice-Hall, Englewood Cliffs, New Jersey.

[9] ReVelle, C., (1999). 'Optimizing Reservoir Resources'. John Willey and Sons, New York, New York.

[10] Reis, L.F.R., Walters, G.A., Savic, D., Chaudhry, F.H., (2005). 'Multi-Reservoir Operation Planning Using Hybrid Genetic Algorithm and Linear Programming (GA-LP): An Alternative Stochastic Approach'. Water Resources Management 19, 831–848.

[11] Reddy MJ, Kumar DN., (2006). 'Optimal reservoir operation using multi-objective evolutionary algorithm'. Water Resources Management. 20(6):861–878.

[12] Lerma N.,Paredes-Arquiola J., Andreu J. & Solera A. (2013): Development of operating rules for a complex multi-reservoir system by coupling genetic algorithms and network optimization, Hydrological Sciences Journal, DOI:10.1080/02626667.2013.779777

[13] Savić, D. A., Bicik, J., & Morley, M. S. (2011) A DSS Generator for Multiobjective Optimisation of Spreadsheet-Based Models. Environmental Modelling and Software, 26(5), 551-561.

[14] Andreu, J., Capilla, J., and Sanchís, E., (1996). AQUATOOL: A generalized decision support-system for water-resources planning and operational management. Journal of Hydrology, 177, 269–291.

[15] Charbonneau, P. and Knapp, B., 1995. A user's guide to PIKAIA 1.0. Boulder, CO: National Center for Atmospheric Research, NCAR Technical note 418+IA