Available online at www.sciencedirect.com
ScienceDirect
Procedia Engineering 89 (2014) 1478 – 1485
Procedia Engineering
www.elsevier.com/locate/procedia

16th Conference on Water Distribution System Analysis, WDSA 2014

Risk and Reliability Analysis of Open Reservoir Water Shortages Using Optimization

D. Marton[a,]*, Z. Kapelan[b]

[a]*Brno University of Technology, Faculty of Civil Engineering, Institute of Landscape and Water Management, Veveří 95 ,Brno 612 00, Czech Republic*
[b]*University of Exeter, College of Engineering, Mathematics and Physical Sciences, Centre for Water Systems, North Park Road, Exeter EX4 4QF, United Kingdom*

Abstract

The goal of this paper was to describe how to find optimal relations between water shortage and hydropower energy based on Risk and Reliability methods. Reservoir simulation model including water losses as well as risk (reliability) model of water demand has been built up. Using NSGA II optimization method the optimization of reservoir operation has been done. For problem solving was used Multi-Objective Optimization. This approach has been applied to a real-life water reservoir called Vir 1 in the Czech Republic. Results were presented in the form of Pareto curves and data sets of reservoir outflows.

Peer-review under responsibility of the Organizing Committee of WDSA 2014

Keywords: Risk, reliability; water resources; open reservoir; reservoir operation; genetic algorithm; Non-Dominated Shorting Genetic Algorithm; NSGA II; water demand; water shortage

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1. Introduction

More and more the slowly disappearing character of weather typical for the spring months is observed and shows that the climate is changing. The consequence can be a time redistribution of rainfalls during a year, slowly disappearing of seasonality in the annual hydrologic cycle and increasing occurrences of floods and droughts. All these meteorological and hydrological phenomena can be observed more frequently in the Central Europe. Relevant studies which were carried out for the Czech Republic indicate a significant reduction of long-term flows in the river network

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* Daniel Marton. Tel.: +420-541-147-773; fax: +420-541-147-771.
E-mail address: marton.d@fce.vutbr.cz

Peer-review under responsibility of the Organizing Committee of WDSA 2014
doi:10.1016/j.proeng.2014.11.433

and associated reduction of water resources yield, for example in [1]. Winter this year 2013/2014 can only strengthen these considerations. Water stored in a form of snow cover on the Czech mountains has reached minimum values over the last twenty years and the average air temperature in the March has reached maximum values over the last fifty years. Water levels of some open water reservoirs are far away under the water levels typical for this time of year and operations on them has been modified by special operational rules.

Pressure on effective management with the surface water resources will become stronger and stronger. Possibilities how to face these challenges are a lot. On the one hand there are the long term water management planning and policy, on the other hand the short term strategies in a form of reservoir operations using hydrologic forecasts exists as well. Most of open water reservoirs in the Czech Republic are using like a multipurpose water management constructions, designed and operated for a certain security level, which evaluated as a resistance towards failure or situations when system is in unsatisfactory state.

Generally performance evaluation of water resources system is specified as reliability, vulnerability, resiliency or risk. First definition which defined evaluation criteria of water resources reliability described Kritskiy, Menkel in [2].Then the reliability, resilience and vulnerability of water resources system in detail were described Hashimoto et al in [3]. For evaluation of hydrological security in the Czech Republic the title reliability is using and introduced it primarily by Votruba, Broža in [4]. If it talks about Risk, then the basic concept of Risk was described in beginning of 20 century by Knight in [5]. For water management purposes the concepts of Risk, Risk assessment and Risk analyses were described by Kaplan in [6]. Today water management industry the Risk and Risk analysis concepts are normally used.

Efficient and secure utilization of storage water in reservoir as well as effective water supply distribution and water resources planning are provided using a various simulation and optimization techniques which these kind of analyses used. These models are designed to find out the optimal operation strategy of water management systems during normal and extreme hydrologic or other unexpected situations. Applications and literatures which deal with these topics are a lot of in the scientific world and mostly differ only in a way of what kind of method was used. For example Hall at al. in [7] were shown the risk based water resources planning in England and Wales under a changing climate. Using water resources simulation model based on mass balance simulation of reservoir for water resources planning under severe uncertainty described Korteling et al. in [8].

One of the usual optimization techniques are Genetic Algorithm methods (GA). Advantage of GA is its using as the multiobjective optimization method. In 1960 Ingo Rechenberg wrote first text and introduced Evolution Strategies and in 1975 the first Genetic Algorithm was developed by John Holland at University of Michigan [9, 10]. Then the GA applications were extended into the many scientific branches. Using GA optimization method for risk assessment of optimal drought management was described by Merabete et al in [11]. Genetic programing went through the evolution in 1994 was developed by N. Srinivas and Kalyanmoy [12] Nondominated orting genetic algorithm method (NSGA). The example using NSGA II method in water management for optimization of water supply reservoir in the framework of climate variation Tukimat N. N. A. and Harun, A. were described in [13]. Other related work link to reservoir operation and multiobjective GA optimization were presented by Vamvakeridou-Lyroudia L. S. et al. in [14]. Simulation and optimization models in water management industry and research are calling for these solutions and for specific kind of work are very needful.

Above mentioned problems as well as evolution in the world of IT technologies and mathematical science allows solved various complex problems in water resources planning and management. The aim of this paper is to describe the different approaches of water supply security based on risk and reliability of open reservoir water shortages. That means find the optimal relations between water demand and hydropower energy of multipurpose reservoir which will be helpful tool for decision makers and water management policy and for long-term water resources planning. This relation will be generally described by Pareto curves using reservoir multiobjective optimization.

2. Method

2.1. Optimization problem

Open reservoir active conservation storage capacity is volume of water normally redistributed in time for requests of their manager and customers. This volume is dependent on inflow and outflow water and on the optimal strategy of its water distribution. When it takes into account that open water reservoir is an operations system is it important to manage it on the minimum level of its failure. According all to requests onto the reservoir the operation of optimal relationships have been found. In this case the amount of water consumed for the supply and use of hydropower was tried to found. These requests were lead to use the multiple objective optimization technique. When objective function was defined as three objective.

- Optimization problem based on RISK than objectives: Minimize RISK $O_T(t)$, minimize RISK $O_{WS}(t)$, maximize $E_{ANNUAL}(t)$.
- Optimization problem based on RELIABILITY than objectives are: Maximize R_{TEMP} $O_T(t)$, maximize R_{TEMP} $O_{WS}(t)$, maximize $E_{ANNUAL}(t)$.

Decision variables were total outflow $O_{T,i}$ for i = 1, …, 12 which could be specific for each month of year. The range of each decision variable was given by range of hydrology bounds created by ecological outflow Q_{ECO} and long term annual inflow Q_A.

2.2. Risk Definitions

The document EIC 300-3-9 was taken for basic risk definition. Which clearly defined risk as combination of frequency or probability of occurrence and consequence of specified hazardous events. This concept of risk definition was divided into risk thee definitions called $RISK_1$, $RISK_2$ a $RISK_3$. Reason of it was to describe as well as understand the effects of water supply shortages if the different definition of risk was used. The Reliability is the most common parameter used for security evaluation of open water reservoir in the Czech Republic. From three types of reliability parameters Occurrence reliability, Temporal reliability and Volumetric reliability, the Temporal Reliability R_{TEMP} was chosen and in further text called Reliability.

Definition $RISK_1$ was described by equation (1). Where Likelihood L was calculated as ratio between total sum of time of water deficit Σt_{WD} to total period of time T. Consequence C was calculated as ratio between sum of undelivered water volume in to system ΣV_{UW} to the total required volume of water in a system V_{RW}.

$$RISK_1 = L \cdot C = \frac{\sum t_{WD}}{T} \cdot \frac{\sum V_{UN}}{V_{RW}} \tag{1}$$

$RISK_2$ was derived as equation (2). Where $RISK_2$ was specified as sum of each event k when water shortage was occurred. The Likelihoods L_K was calculated as ratio between sum of time of water deficit for each event $\Sigma t_{WD,k}$ to total period of time T. The Consequence C_k was calculated like ratio between undelivered water volume in to system for each specific event of water shortage $V_{UW,k}$ to the total volume of required water in system V_{RW}. Where k is number of water deficit events for k = 1… N during all period.

$$RISK_2 = \sum_{k=1}^{N} (L \cdot C) = \sum_{k=1}^{N} \left(\frac{\sum t_{WD,k}}{T} \cdot \frac{\sum V_{UN,k}}{V_{RW}} \right) \tag{2}$$

$RISK_3$ was described by equation (3). Calculated on the same base like $RISK_1$ where Likelihood was multiplied by Consequence. Difference between $RISK_1$ and $RISK_3$ is how the likelihood was calculated. In this risk definition is likelihood calculated as ration between total sum of water deficit events Σt_{EVENTS} to total time T. That means the probability of frequency of system failure is defined. Consequence was calculated as ratio between sum of undelivered water volume in to system ΣV_{UW} to the total volume of required water in system V_{RW}.

$$RISK_3 = L \cdot C = \frac{\sum t_{EVENTS}}{T} \cdot \frac{\sum V_{UN}}{V_{RW}} \tag{3}$$

Reliability R_{TEMP} was described like system reliability as ratio of time of satisfactory state of system to total time. Reliability represents probability that the system has not entered to the unsatisfactory state until a given time. Reliability R_{TEMP} was described by equation (4). Where Σt_{WD} is total sum of time of water deficit and T is total time. Generally R_{TEMP} can be express $R_{TEMP} = 1 - C$.

$$R_{TEMP} = \frac{T - \sum t_{WD}}{T} \tag{4}$$

For evaluating of $RISK_{1,2,3}$ a R_{TEMP} the reservoir simulation model has been built up. This model is able to simulate the operation of reservoir as well as to calculate the length and depth of water deficit.

2.3. Reservoir Simulation model

For reservoir simulation model has been used successively balance method, described by Votruba, Broza in [4] and further elaborated and specified by Stary in [15]. The basis of the simulation model is the equation calls basic equation of the open reservoir in the summing form. To evaluation of risk and reliability employing by simulation model the basic equation was modified into the following mathematical expression (5).

$$V_{Z,\max} \geq \left(O_{T,k} - Q_k\right) \cdot \Delta t + \sum_{i=0}^{k-1} \left(O_{T,i} - Q_i\right) \Delta t \geq 0 \tag{5}$$

Where $V_{Z,\max}$ is maximal reservoir active conservation storage capacity (full reservoir storage capacity), $O_{T,i}$ is total outflow water from reservoir and Q_i is inflow water to reservoir for i = 0, …, k-1. $O_{T,k}$ is total outflow water from reservoir and Q_k is inflow water to reservoir in the current step k. Δt is time step (hour, day, month, year). Initial condition was full active storage capacity in reservoir and boundary condition were water inflows into reservoir. Total outflow was calculated as follows (6).

$$O_{T,k} = -\sum_{i=0}^{k-1} \left(O_{T,i} - Q_i\right) + Q_k \tag{6}$$

Generally the total outflow value O_T is decision variable in the simulation model. Each change of O_T leads to change in the risk or reliability of storage water in reservoir as well as risk or reliability of water supply. Unsatisfactory state or water deficit of total outflow is described as state when active conservation storage capacity in reservoir exceeds value of $V_{Z,\max}$. The total outflow O_T is split up to river outflow O and water demand O_{WS}. River outflow O is used as hydropower inflow Q_E and ecological outflow Q_{ECO}. Hydropower was assessed by annual amount of generated energy E_{ANNUAL}[kWh], which is defined as (7).

$$E_{ANNUAL} = \sum_{i=1}^{n} \left(\left(\rho \cdot g \cdot Q_i \cdot H_i \cdot \eta\right) \cdot \Delta t \right) \tag{7}$$

Where ρ is density of water, g is gravity, Q_i is discharge and is a same value as river outflow O_i for given month i, H_i is height of water level in given month i, η is coefficient of efficiency ranging from 0 to 1. Δt is time and i = 1… n for n = 12.

Risk and reliability parameters of water demand into supply system were calculated by further computation. The known parameters was required water supply outflows $O_{WS,REQ}$. When the value of water demand was smaller than the $O_{WS,REQ}$ and river outflow was under threshold required ecological outflow then the reservoir is in unsatisfactory state which was defined by water deficit time t_{WD} and water deficit volume (undelivered water volume) V_{UW}. Water reservoir losses are implemented into the simulation model in form of evaporation losses and seepage losses. Created simulation model was linked to optimization model and optimized using GA method.

2.4. Optimization Method

Reservoir simulation model was built in MS Excel software based on above mentioned methods and the GANetXL [16] optimization tool was used for optimize above specified optimization problem. GANetXL is addition tools into MS Excel and is based on spreadsheet platform. For optimization problem, the single or multiple objective optimization NSGA II method was used. Results of multiple objective solutions are presented in a form of Pareto curves relations between risk/reliability of water supply and reservoir hydropower energy.

3. Case Study

3.1. Description

For application of above mentioned method the open water reservoir Vir 1 has been chosen, which fits with its technical parameters into the required requests. Reservoir has been built and is operated in the Czech Republic in Vysocina Region 150 kilometers to the south from capital city Prague and 50 kilometers to the north east from Brno city. The main purposes why the reservoir is operated are water supply and producing of hydropower energy. Operator and manager of the Vir 1 reservoir is a government company called Morava River basin (Povodi Moravy) State Enterprise. Basic hydrologic information about watershed above the reservoir are these. Reservoir is built on Svratka river basin and the Svratka river is main inflow into the reservoir. Watershed area above reservoir is about 367 km^2. Average long term inflow Q_A is 3.34 m^3 s^{-1}, ecological flow the drought threshold defines as Q^{355} value and is 0.44 m^3 s^{-1}. As input data for computation were used the time series of mean monthly flows 60 years length and time period 1950 – 2010. Basic information about Vir 1 reservoir is as following. Total volume in the reservoir is V_{TOTAL} 56.193 million m^3, the active conservation storage capacity $V_{Z,max}$ is 44.056 million m^3 and flood control volume V_{FLOOD} is 8.337 million m^3. Total height of dam is 67.3 m. Ecological outflow Q_{ECO} is 0.53 m^3 s^{-1}. There is the hydropower plant with two Francis turbines with total installed power 7.15 MW and maximum turbine discharge Q = 14.1 m^3 s^{-1} situated at bottom the of dam construction. Values of required water demand distributed into the Brno water supply system was taken over in [17].

GANetXL configuration of reservoir simulation model was following. Population size was 250 genes. Crossover Probability was set like the Uniform Random and Crossover Rate was 0.95. Mutation type was set as Simple by Gene with probability of mutation 0.05. Number of chromosomes (decision variables) was entered 12 with range of bounds 1.90 m^3 s^{-1} for lower bound and 3.3 m^3 s^{-1} for upper bound. Solution was set as multiple objective optimization problem. Number of objectives were 3. First objective function was set to minimize RISK or maximize Reliability of total outflow from reservoir. Second objective function was to minimize RISK or maximize Reliability of undelivered water demand into the water supply system. Last objective function was to maximize the total hydropower energy. Number of generation size was chosen to 500. Some examples of how your references should be listed are given at the end of this template in the 'References' section, which will allow you to assemble your reference list according to the correct format and font size.

3.2. Results and Discussion

The results of optimization of open reservoir simulation model are in the graphical and the numerical form. Graphical form is presented by Pareto curves and numerical form is characterized in the form of Pareto curve data sets. Then the each line of these data represents a possible values of total outflows (decision variables), water demands and total annual energy. All these values can by applied for reservoir operation, produce of hydropower energy and water supply management.

The Pareto curves shows the relations between risk or reliability of water deficit and production of hydropower energy. The four solutions were created and named as follows.

- Solution A described relations between $RISK_1$ and annual hydropower energy E_{ANNUAL}.
- Solution B described relations between $RISK_2$ and annual hydropower energy E_{ANNUAL}.
- Solution C described relations between $RISK_3$ and annual hydropower energy E_{ANNUAL}.
- Solution D described relations between reliability R_{TEMP} and annual hydropower energy E_{ANNUAL}.

To effectively comparing the calculated results of each solution the recalculation to the same values of RISK were provided. As common parameter the $RISK_1$ was chosen and then results for each solution were recalculated. Recalculation was made backward using the optimized values of total outflow for $RISK_{2,3}$ and R_{TEMP}. Each set of total outflows was put it back to the reservoir simulation model and then these values were recalculated into the $RISK_1$ values. Pareto curves for solutions A, B, C, D are shown in the Fig. 1.

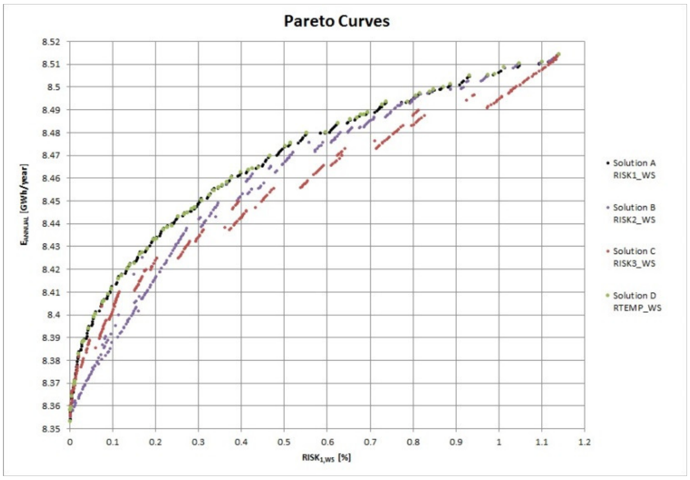

Fig. 1. Pareto Curves for solutions A, B, C, D.

As in the text above is written that for each Pareto curve the sets of decision variables of total outflows and water demands including total annual energy were obtained. Each point of Pareto curve was formulated as one specific solution with own set of optimal results for given solution. That means the twelve optimal values of total outflows corresponds for each point of Pareto curve defined by coordinates of $RISK_{1,WS}$ and annual energy.

Green points of recalculated Pareto curve corresponds to the solution D. Shape of this curve is similar as Pareto curve of solution A made by black points. Differences between both curves are obvious in a density of occurrences of black and green points. Results of solution D have taken into account only likelihood of water shortages. This is the reason why results of solution D created more sparse shape of Pareto curves. Description for this, is that some sets of decision variables are different but not so much to change the size of likelihood of water shortages. When increasing amount of decision variables (total outflows) exceed the time of unsatisfactory state which was corresponding for one size of likelihood then the likelihood were changed and new green point was created. Curve of solution A is specified more in details. It is made from more specific solutions represented by each point. That means the risk definition takes into account the consequences of water shortages. In this case it means that likelihood for some sets of decision variables are same but the consequences were changing and changing the risk value. In the results of Pareto curves of solution C has been seen that the points created several groups. This is caused by likelihood of water shortages which take into account only the number of unsatisfactory (water deficit) events not time of unsatisfactory state. For one group of pareto curves points in the solution C is likelihood same and consequences were changing and changing risk values.

The effect of water deficit depth is further shown and compared for same production of total annual Energy E_{ANNUAL} = 8.4 GWh/year. Depth and intensity of unsatisfactory state for first period of 30 months is derived on ratio of calculated water demand Q_{DEF} to required water demand Q_{REQ} and is shown in Fig. 2.Then in Table 2 is shown the recalculated values for solutions A, B, C, D of water shortage for same value of annual energy E_{ANNUAL}

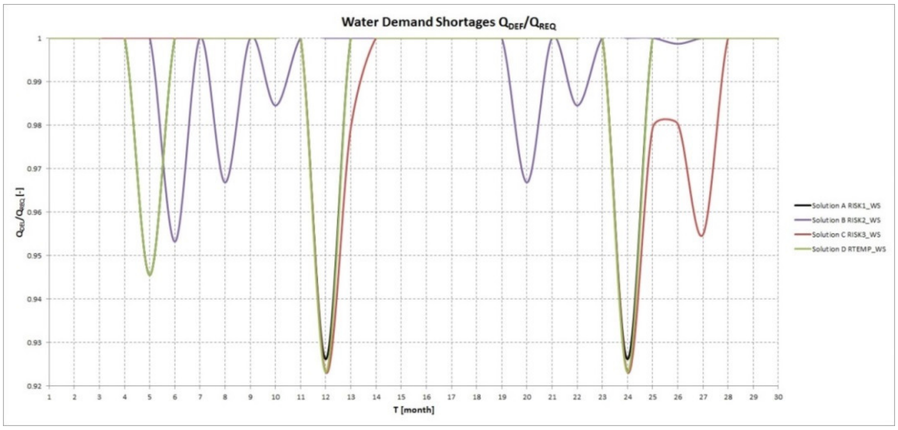

Fig. 2. Water Demand Shortages for solutions A, B, C, D – Same E_{ANNUAL}.

In the Fig. 2 the intensity of water shortages is noticeable of short period of time (30 months) but is very similar for whole time period. Solutions A and D are characteristic by short number of water shortages occurrences but with its big depth or with bigger undelivered volume of water in to the water supply system. That mean this kind of water deficit events are less frequently on the one hand but on the other hand can be more dangerous for all water supply system. Solution B is characteristic with high frequency of water shortages with small depth of water shortages. Character of water shortages in the solution C is close to solutions A and D but length and size of water shortages of this solution are more distributed over the time as well as water deficit volumes are more intensive. The results are shown in the table 2.

Table 1. Values of Risk and Reliability for solutions A, B, C, D

Month	Solution A $RISK_{1,WS}$	Solution B $RISK_{2,WS}$	Solution C $RISK_{3,WS}$	Solution D $R_{TEMP,WS}$
$RISK^1$[%]	0.055	0.125	0.085	0.056
E_{ANNUAL} [GWh/year]	8.4	8.4	8.4	8.4

4. Summary and Conclusions

The combination of different approaches was created. First the reservoir simulation model was built included the water losses model. This simulation model is able to solve the long term calculation of optimal outflow strategy. For optimization of this model the multiple objectives NSGA II optimization was used. Then the RISK based approach as secure parameters of reservoir operation was used as well. For security analysis the occurrence, temporal and volumetric reliability are normally used in the Czech Republic. The combination of Risk approach and multiple objective optimization method have been never used in the Czech Republic.

Using multiple objective optimization approach to creating the Pareto curves and databases of satisfactory total outflows and water demand could be guaranteed the bases of work with long term water management policy and planning on the different levels of hydrologic security. Each point of Pareto curves is the specific solution for operation of reservoir outflow as well as the specific draft for hydropower planning. That means this results can be used for decision makers for effective water management in long term period of time and to improve the handling guides of open water reservoirs.

Based on given above presented results Risk definitions which have been used for solutions B and C are more dangerous for water supply system. The intensity of water deficit for these solutions creates more unsatisfactory states characterized by higher frequencies of water shortages and higher volumes of undelivered water in to water supply system. From this point of view the solutions B and C are the least suitable for using and solutions A, D resulted as much more appropriate.

Currently number of decision variables used for optimization are 12 so that the reservoir simulation model has calculated with number of 12 total outflows. Simulation model is able to extended it to bigger number of decision variables like 24 until 120 decisions variables (longer period of total outflows) and then compare it if extended number of decision variables make sense for using or not. After other modifications the reservoir simulation model can be used as reservoir operation model. For effective utilization of this operation model the hydrologic predictions of river inflows have to be used or created. Other possibilities how to expand this work is testing the long term water management planning using by artificial time series, incorporate an uncertainty model into the solution.

Acknowledgements

This paper was supported by the project „CZ.1.07/2.3.00/30.0039 Excellent young researchers at Brno University of Technology„ of Brno University of Technology.

References

[1] L. Kašpárek, Estimation of reservoirs storage volumes required for compensation of river outflow decrease by impact of climate change, T. G. M. RWI Prague, Research Report, Prague, 2005.
[2] S. N. Kritskiy, M. F. Menkel, Water Management computation, Gidrometiyd, Moscow, 1952.
[3] T Hashimoto, J. R. Stedinder, D. P. Loucks, Reliability, Resiliency, and Vulnerability Criteria For Water Resource System Performance Evaluation, Water Resources Research, 18(1) (1982) 14-20.
[4] L. Votruba, V. Broža, Water Management in Reservoirs, Faculty of Civil Engineering of the Technical University of Prague, Elsevier ISBN 0-444-98933-1, Czechoslovakia 1989.
[5] F. H. Knight, Risk, Uncertainty, and Profit, Boston, MA: Hart, Schaffner & Marx; Houghton Mifflin Co., USA, Boston 1921.
[6] S. Kaplan, Risk Assessment and Risk Management – Basic Concepts and Terminology Risk Management: Expanding Horizont in Nuclear Power and Other Industries, ‚Hemisphere Publ. Corp., Boston, Masachusetts, USA. 1991, pp. 11-28,
[7] J. W. Hall, G. Watts, M. Keil, L. de Vial, R. Street, K. Conlan, P. E. O'Connell, K. J. Beven, C. G. Kilsby, Towards risk-based water resources planning in England and Wales under a changing climate, Water and Environment J., 26(1) (2012) 118–129.
[8] B. Korteling, S. Dessai, Z. Kapelan, Using info-gap decision theory for water resources planning under severe uncertainty, Water Resources Management, 27(4) (2013) 1149-1172.
[9] M. Mitchell, An Introduction to Genetic Algorithm, Massachusetts Institute of Technology, 1996.
[10] I. H. Holland, Adaptation in Natural and Artificial Systems. University of Michigan, Press. Ann Arbor. 1775.
[11] T. Merabtene, A. Kawamura, K. Jinno, J. Olsson, Risk assessment for optimal drought management of an integrated water resources system using a genetic algorithm. Hydrol. Process., 16(11) (2002) 2189–2208.
[12] N. Srinivas, D. Kalyanmoy, Muiltiobjective Optimization Using Nondominated Sorting in Genetic Algorithms. Department of Mechanical Engineering Indian Institute of Technology Kanpur, Evolutionary Computation 1994.
[13] N. N. A. Tukimat, S. Harun, Optimization of Water Supply Reservoir in the Framework of Climate Variation, International Journal of Software Engineering and Its Applications 8(3) (2014) 361-378.
[14] L. S. Vamvakeridou-Lyroudia, M. S. Morley, J Bicik., C. Green, M. Smith, D. A. Savic, AquatorGA: Integrated optimization for reservoir operation using multiobjective genetic algorithms, In proceeding of: INTEGRATING WATER SYSTEMS, London 2010.
[15] M. Starý, Reservoir and Reservoir system, Education Tutorial, Brno University of Technology, Faculty of Civil Engineering, Brno 2006.
[16] D. A. Savic, J. Bicik., M. S. Morley, A DSS Generator for Multionbjective Optimization of Spreadsheet – Based Model. Enviromental Modeling and Software. 26(5), 551-561.
[17] M. Starý, P. Doležal, Vir I Reservoir Utilization for the Brno Water Supply System Based on Hydrological Data Period 1931 – 1991. Brno University of Technology, Faculty of Civil Engineering, Research Report, Brno 1994.