

PAPER • OPEN ACCESS

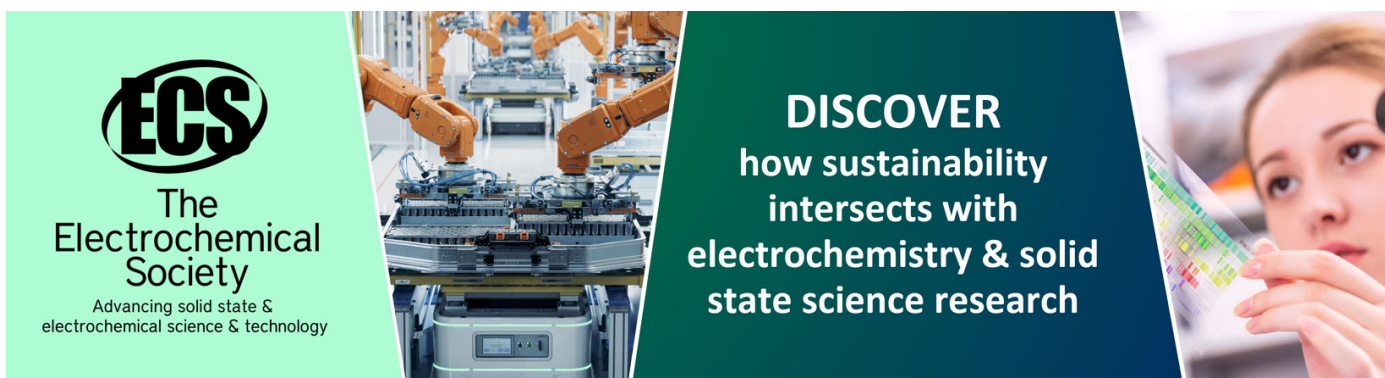
Optimizing Use of Water Management Systems during Changes of Hydrological Conditions

To cite this article: Roman Vyleta *et al* 2017 *IOP Conf. Ser.: Mater. Sci. Eng.* **245** 032075

View the [article online](#) for updates and enhancements.

You may also like

- [Climatological analysis of tropical cyclone impacts on hydrological extremes in the Mid-Atlantic region of the United States](#)
Ning Sun, Mark S Wigmosta, David Judi et al.
- [Human impact parameterizations in global hydrological models improve estimates of monthly discharges and hydrological extremes: a multi-model validation study](#)
T I E Veldkamp, F Zhao, P J Ward et al.
- [Diversity in the observed functionality of dams and reservoirs](#)
Jonghun Kam



ECS
The
Electrochemical
Society
Advancing solid state &
electrochemical science & technology

DISCOVER
how sustainability
intersects with
electrochemistry & solid
state science research

Optimizing Use of Water Management Systems during Changes of Hydrological Conditions

Roman Výleta ¹, Andrej Škrinár ¹, Michaela Danáčová ¹, Peter Valent ¹

¹ Department of Land and Water Resources Management, Faculty of Civil Engineering, Slovak University of Technology, Radlinského 11, 810 05 Bratislava, Slovakia

andrej.skrinar@stuba.sk

Abstract. When designing the water management systems and their components, there is a need of more detail research on hydrological conditions of the river basin, runoff of which creates the main source of water in the reservoir. Over the lifetime of the water management systems the hydrological time series are never repeated in the same form which served as the input for the design of the system components. The design assumes the observed time series to be representative at the time of the system use. However, it is rather unrealistic assumption, because the hydrological past will not be exactly repeated over the design lifetime. When designing the water management systems, the specialists may occasionally face the insufficient or oversized capacity design, possibly wrong specification of the management rules which may lead to their non-optimal use. It is therefore necessary to establish a comprehensive approach to simulate the fluctuations in the interannual runoff (taking into account the current dry and wet periods) in the form of stochastic modelling techniques in water management practice. The paper deals with the methodological procedure of modelling the mean monthly flows using the stochastic Thomas-Fiering model, while modification of this model by Wilson-Hilferty transformation of independent random number has been applied. This transformation usually applies in the event of significant asymmetry in the observed time series. The methodological procedure was applied on the data acquired at the gauging station of Horné Orešany in the Parná Stream. Observed mean monthly flows for the period of 1.11.1980 - 31.10.2012 served as the model input information. After extrapolation the model parameters and Wilson-Hilferty transformation parameters the synthetic time series of mean monthly flows were simulated. Those have been compared with the observed hydrological time series using basic statistical characteristics (e. g. mean, standard deviation and skewness) for testing the quality of the model simulation. The synthetic hydrological series of monthly flows were created having the same statistical properties as the time series observed in the past. The compiled model was able to take into account the diversity of extreme hydrological situations in a form of synthetic series of mean monthly flows, while the occurrence of a set of flows was confirmed, which could and may occur in the future. The results of stochastic modelling in the form of synthetic time series of mean monthly flows, which takes into account the seasonal fluctuations of runoff within the year, could be applicable in engineering hydrology (e. g. for optimum use of the existing water management system that is related to reassessment of economic risks of the system).



1. Introduction

Water management in Slovakia has been organized since the second half of the last century. Need for advanced and sustainable water management in the landscape and the urbanized area increases with an increasing demand for use of water resources, along with the rate of deterioration of their quality and decrease of usable water resources. This phenomenon is caused by non-stationarity of natural processes, induced by changes in the conditions of runoff creation nowadays and in the future due to changes in land use and climate [1, 2, 3].

Water reservoirs have an irreplaceable role in water management due to the uneven distribution of water sources in relation to the places or time periods where and when they are demanded. Water reservoirs and their systems are able to accumulate excess water during periods of higher flows and release it during dry periods when the water is needed. They are part of our environment and are used in many ways resulting from the various demands for water for agricultural land and for the protection and creation of our environment. In Slovakia's physiographical conditions more than 50 large and 200 small water reservoirs have been constructed. Most of them were designed to provide water for agriculture [4]. Some of them were even built to support mining activities centuries ago and are still operational [5].

This paper deals with optimizing the use of water management system of the Horné Orešany Reservoir under changed hydrological conditions, which was built to provide the water requirements of the crops grown in the area of Horné Orešany located in Western Slovakia. During the life of the water management system, the hydrological conditions, which served as a basis for its proposal, have changed. Management of the reservoir may lead to its non-optimal use. Therefore it is necessary to use a stochastic modelling to establish the synthetic hydrological series of flows that have the same statistical properties as the time series observed in the past. In addition, they will include a set of diverse hydrological situations that could occur in the future. In general, there is a range of methodological approaches created to solve this problem, and a detailed overview of this issue is reported, for example, by Nacházel [6], or Procházka [7].

The Thomas-Fiering model with use of Wilson-Hilferty transformation of independent random number has been applied in our work for modelling the synthetic series of mean monthly flows serving as the input for processing the water management balance of the reservoir in monthly step, simulation of possible water withdrawals and development of their different variants and reliability.

2. Methodology

The water reservoir of Horné Orešany, which is situated in the western Slovakia in the village of Horné Orešany (Figure 1), was selected as a study water management system for optimization.

The water reservoir was built on the Parná Stream on the 25th river km and the area of the catchment contributing to the reservoir is 45.6 km². The water reservoir has been in operation since 1992, with the primary purpose of providing water needs for the irrigation of adjacent agricultural land. The area of original proposed irrigation, which has never been implemented, had a size of 3420 ha of agricultural land specified by the State amelioration management in 1977 [8].

The reservoir had been designed for the maximum capacity of 3.8 mil. m³ (corresponds to an area of 50 ha), of which 3% represents the permanent volume, 88% represents the usable volume and remaining 9% represents the retention volume [9]. Nowadays, it can be described as multi-purpose water reservoir, which is used for transforming the flood waves, augmentation of the minimum flows, sport fishing and for electricity generation.

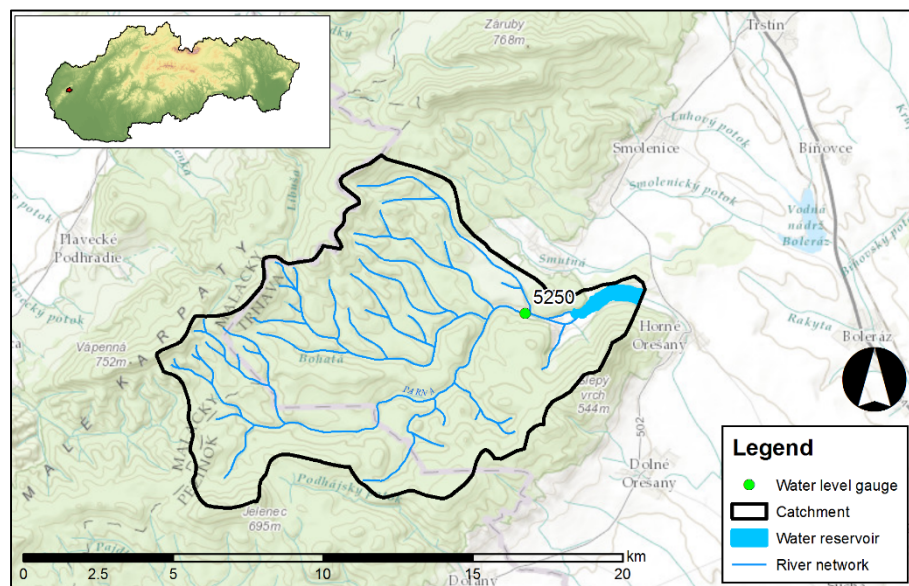


Figure 1. Location of gauging station and water reservoir of Horné Orešany within Slovakia.



Figure 2. View of the reservoir of Horné Orešany

To optimize the water management system of Horné Orešany water reservoir it is necessary to know the hydrological regime of the Parná Stream, which is the main water source of the reservoir.

There is a permanent gauge of Horné Orešany (Number 5250) situated above the reservoir in the Parná Stream (at the river km 26.8) and administered by the Slovak Hydrometeorological Institute (SHMI). The value of minimum biological flow is $0.083 \text{ m}^3/\text{s}$. Mean daily flows in study gauging station from the period between 1961 and 2013 were available. Since the water gauge is situated upstream of the reservoir, the flow observations had to be corrected to account for the remaining input from the catchment area between the water gauge and the dam crest (Figure 1). These corrected data were subject to further analysis, since it is essential to know the hydrological regime, distribution, seasonality and development of water bearing in the study locality, as well as to update the design values for water balance of the reservoir. In Slovakia, the regional analysis of design variables and their interrelationships were addressed e.g. by Szolgay et al. [10], or Gaál et al. [11].

2.1. Data analysis

The mean annual flow at the station of Horné Orešany for the period of 1961-2013 is $0.359 \text{ m}^3/\text{s}$. The minimum and maximum flow observed during this period was $0.025 \text{ m}^3/\text{s}$ and $7.653 \text{ m}^3/\text{s}$, respectively. For development of water bearing within the study area an analysis of the mean, minimum and maximum annual flows was performed for the observed period between 1961-2013 showing, that the time series comprises a statistically significant decreasing trend (Figure 3). Its occurrence was tested using a Mann-Kendall statistical test at the 95% confidence level [12, 13].

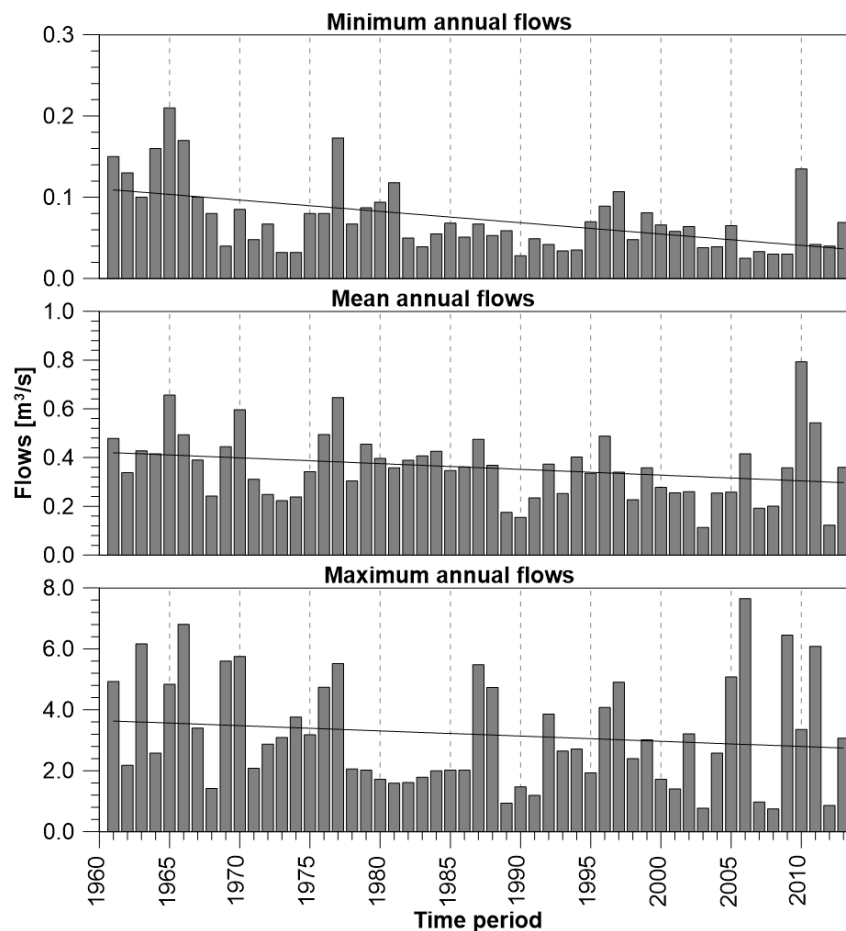


Figure 3. The results of the trend analysis of the minimum, mean and maximum annual flows at the Parná Stream in the time period of 1961 - 2013.

A comparison of the mean monthly flows shows that the runoff regime is a combination of rainy and snowy with the highest flows at the end of winter in March, when the catchment is saturated with water from melting snow cover. On the other hand, the lowest flows can be observed at the end of summer period (August September and October) after long periods of draughts caused by little rainfall activity.

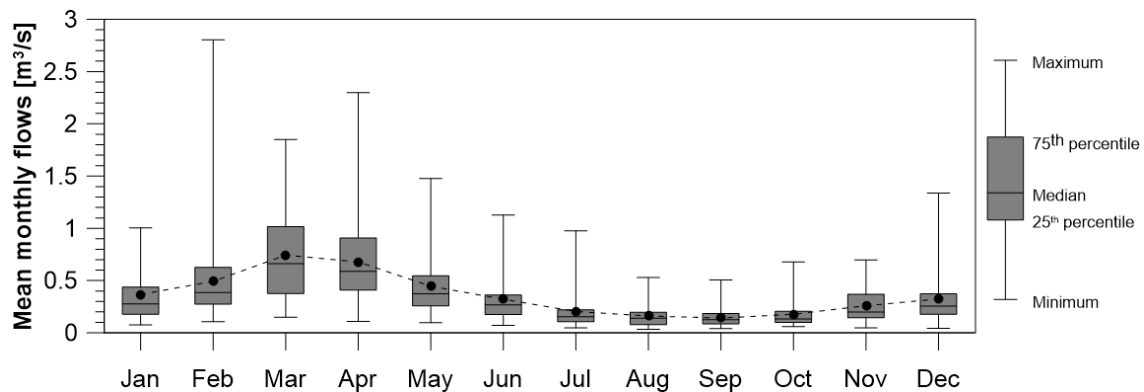


Figure 4. Variance in mean monthly flows at the station of Horné Orešany for the period of 1961-2013.

Variance in mean monthly flows is relatively large in months with more water bearing (the largest is in months with melting of the snow cover). On the other hand, minimum variances can be seen at the end of summer in August and September. Since the nonstationary of the flow time series could lead to an overestimation of accessible water quantity (discharges in last 30 years are smaller than the ones in the first 30 years), only the data for the last 32 years (period of 1981-2013) were used in further calculations.

2.2. Modified Thomas-Fiering model

In order to take into account the seasonal variations in runoff within the year considering the extreme events, the Thomas-Fiering approach of auto regression model [14] was used in this study with application of Wilson-Hilferty transformation of independent random number. A Thomas-Fiering model presents a set of 12 regression equations and can be given as the basic equation:

$$Q_{i+1} = \bar{Q}_{j+1} + b_j \cdot (Q_i - \bar{Q}_j) + t_i \cdot S_{j+1} \sqrt{(1 - r_j^2)} \quad (1)$$

Where:

Q_{i+1}, Q_i - modelled mean monthly flow in the $i+1$ and i -step respectively, counting from the beginning of the generated series,

$\bar{Q}_{j+1}, \bar{Q}_j$ - selective mean monthly flows in observed time series during the $j+1$ and j month respectively, while $j \in \langle 1, 12 \rangle$,

b_j - regression line slope for the estimation of $j+1$ month from the j month, b_j is given by:

$$b_j = \frac{S_{j+1}}{S_j} \cdot r_j \quad (2)$$

Where:

S_{j+1}, S_j - selective standard deviations of monthly values during $j+1$ and j months from the data observed,

r_{j+1}, r_j - selective correlation coefficient between the mean monthly flows in the $j+1$ and j months,

t_j - independent random variable with a normal distribution, zero mean and unit variance.

The principle of calculation may be chronologically described by the following scheme, where $Q_i = \bar{Q}_{nov}$ is defined as the beginning, while $i=1$. Subsequently, then following equations are valid:

$$Q_2 = \bar{Q}_{dec} + b_{dec/nov} \cdot (Q_1 - \bar{Q}_{nov}) + t_1 \cdot S_{dec} \cdot \sqrt{(1 - r_{dec/nov}^2)} \quad (3)$$

$$Q_3 = \bar{Q}_{jan} + b_{jan/dec} \cdot (Q_2 - \bar{Q}_{dec}) + t_2 \cdot S_{jan} \cdot \sqrt{(1 - r_{jan/dec}^2)} \quad (4)$$

⋮

$$Q_{i+1} = \bar{Q}_{j+1} + b_j \cdot (Q_i - \bar{Q}_j) + t_i \cdot S_{j+1} \cdot \sqrt{(1 - r_j^2)} \quad (5)$$

The asymmetry in observed time series is taken into account by the introduction of modification of independent random number with normal distribution in the basic model equations using Wilson-Hilferty transformation into independent random number with an asymmetrical distribution.

2.2.1. Wilson-Hilferty transformation. It is a transformation of values of independent random numbers with normal distribution (t) into random numbers (t_g) with approximate Gamma distribution according to relationships of McMahon and Mein [15]:

$$t_g = \frac{2}{\gamma} \cdot \left(1 + \frac{\gamma \cdot t}{6} - \frac{\gamma^2}{36} \right)^3 - \frac{2}{\gamma} \quad (6)$$

$$\gamma = \frac{C_s - r_1^3 \cdot C_s}{(1 - r_1^2)^{3/2}} \quad (7)$$

Where:

C_s - coefficient of skewness of mean monthly flows

r_1 - autocorrelation coefficient of the first order.

Instead of the random variable t with normal distribution used in each step i in the basic equation (1) of the model of Thomas and Fiering, a random number t_g with Gamma distribution is assigned. In this case the model should maintain the first three moments of the observed series along with the first-order autocorrelation coefficient and it should generate the flow series with approximate Gamma distribution. The transformation is valid for about $C_s < 3$ [16].

2.3. Water balance of the reservoir

Water balance of the reservoir was implemented in monthly time step by the BALVAN model (a computer software in the MATLAB[®] environment), that balances selected hydrological processes and reservoir operation and allows the simulation of withdrawals and outflow from the reservoir. Specific characteristics of the system examined are defined by the components of the balance relationship given in the volume scale as described in the basic balance equation:

$$S_i - S_{i-1} = (I_i - RR_i - E_i - IRN_i) \cdot \Delta t \quad (8)$$

where:

S_i, S_{i-1} - actual amount of water (volume) in the reservoir in the months i and $i-1$ [m³],

I_i - total volume of water calculated from the mean monthly flows (inflow) in the month i [m^3],

RR_i - required volume of water in month i defining the minimum biological flow and other existing water withdrawals, except of water for irrigation [m^3],

E_i - evaporation from the free water surface of the reservoir in the month i [m^3],

IRN_i - required (necessary) volume of water for the irrigation in the month i [m^3],

Δt - time step [month].

Input data to the water balance of the reservoir consisted of synthetic mean monthly flows of the Parná Stream, information about water operation in the reservoir, contracted withdrawals from the reservoir, value of minimum biological outflow from the reservoir and required irrigation withdrawals from the reservoir per each 1 ha. The average irrigation water amount was determined by the CROPWAT software depending on rainfall and temperature data to $1801 \text{ m}^3/\text{ha}$, and crops were selected based on data from the Statistical Office of the Slovak Republic referring to crops growing in the study area (potatoes, sugar beets, orchards and vegetables - smaller acreage). The water balance was calculated for four alternatives in the BALVAN model, which distinguished between each alternative in the area of irrigated land and in additional withdrawals from the reservoir. The individual alternatives took into account: i) various areas of irrigated land and all the current withdrawals (Alternative A); ii) various areas of irrigated land, all the current withdrawals, and an additional withdrawal of $0.025 \text{ m}^3/\text{s}$ (Alternative B); iii) The same as alternative A, plus an additional withdrawal of $0.035 \text{ m}^3/\text{s}$ (Alternative C), iv) the same as Alternative A, plus an additional withdrawal of $0.060 \text{ m}^3/\text{s}$ (Alternative D). The alternatives were compared among each other to calculate the reduction of potentially irrigated areas under various conditions.

3. Results and discussion

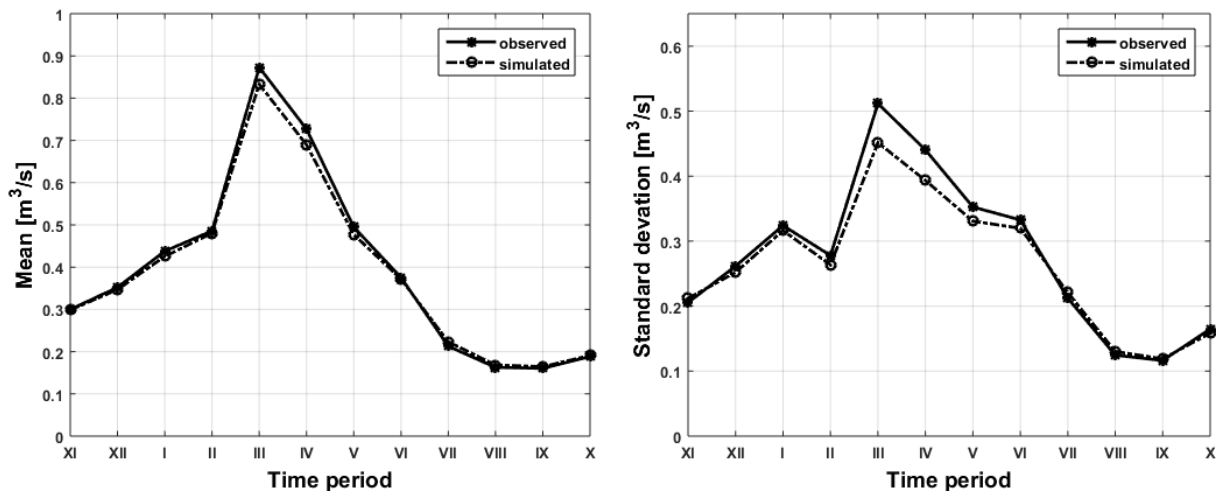
For calibration of the modified model of Thomas and Fiering the corrected mean monthly flows from gauging station of Horné Orešany for the period from 1.11.1980 to 31.10.2012 were used. It was necessary to estimate 36 parameters (specifically 12 means, standard deviations and correlation coefficients) between the neighbouring months and to calculate the regression coefficient between the neighbouring months (Table 1). The coefficient of skewness of mean monthly flows ($C_s = 1.859$), the autocorrelation coefficient of the first order ($r_1 = 0.614$) and the γ value of 2.904 were estimated within the Wilson-Hilferty transformation.

Table 1. Estimated values of the parameters of the Thomas-Fiering model.

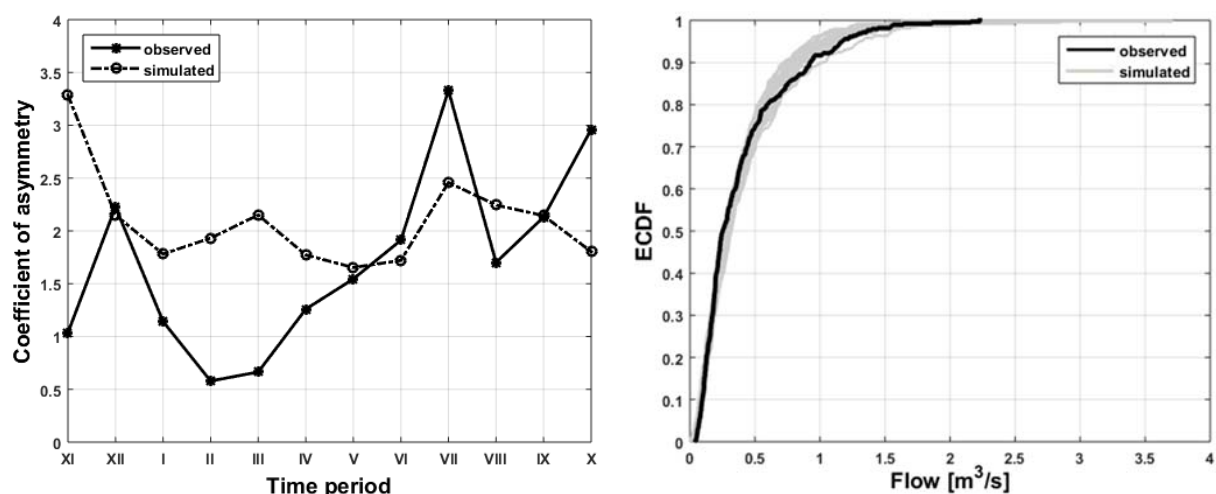
Month	Parameter of the T-F model			
	r	b	S	$\bar{Q}$
XI	-0.13	-0.16	0.21	0.30
XII	0.64	0.82	0.26	0.35
I	0.73	0.90	0.32	0.44
II	0.43	0.37	0.28	0.49
III	0.43	0.79	0.51	0.87
IV	0.53	0.46	0.44	0.73
V	0.65	0.52	0.35	0.49
VI	0.81	0.77	0.33	0.38
VII	0.42	0.27	0.21	0.21
VIII	0.44	0.26	0.12	0.16
IX	0.37	0.35	0.12	0.16
X	0.72	1.01	0.16	0.19

After estimating the parameters of the modified model of Thomas and Fiering the series of synthetic mean monthly flows for 800 years were generated. These series were compared with the observed mean monthly flows of Horné Orešany gauging station for the hydrological period of 32 years (1981-2012) using basic statistical data - mean, standard deviation and the coefficient of skewness in particular calendar months (Figures 5 and 6).

A modified model of Thomas and Fiering takes into account the long-term mean monthly flows within calendar months, thus maintaining the mean monthly flows in observed series. Long-term values of the standard deviation of the mean monthly discharges in simulated series are taken into account in the model from June through February, while this statistical feature is somewhat underestimated in the period from March through May. The model failed to take well into account the long-term values of the coefficient of skewness of mean monthly flows in the observed series (fluctuating within months). However, it retained the ECDF line of observed flow series, which is compared with simulated series with a length of 800 years divided into 25 equally long series (32 years each).



a) b)
Figure 5. Long-term mean monthly flows (a) and their standard deviations (b) calculated for observed and simulated time series.



a) b)
Figure 6. Coefficient of asymmetry of observed and simulated mean monthly flows (a) and ECDF curves of observed and simulated time series of flows divided into 25 equally long series (b).

The main outcome of the quantitative water balance of the reservoir is the relationship between the irrigated area and the reliability of the water supplies. The calculations were performed based on the assumption that the 90% of reliability of the water supplies for irrigation is usually considered in the design practice. The results indicate that under the defined conditions, 2415 ha of the agricultural land could be irrigated in the case of alternative A, 2210 ha in the case of alternative B, 2125 ha in the case of alternative C, and 1905 ha in the case of alternative D. Figure 7 summarizes the maximum irrigated area for a 90% reliability of the water supplies for irrigation and for a 100% reliability that the biological flow will always be ensured. In case that ensuring of the biological flow under the reservoir is priority, the maximum irrigated area would be 1200 ha for alternative A, 1090 ha for alternative B, 890 ha for alternative C and 680 ha for alternative D.

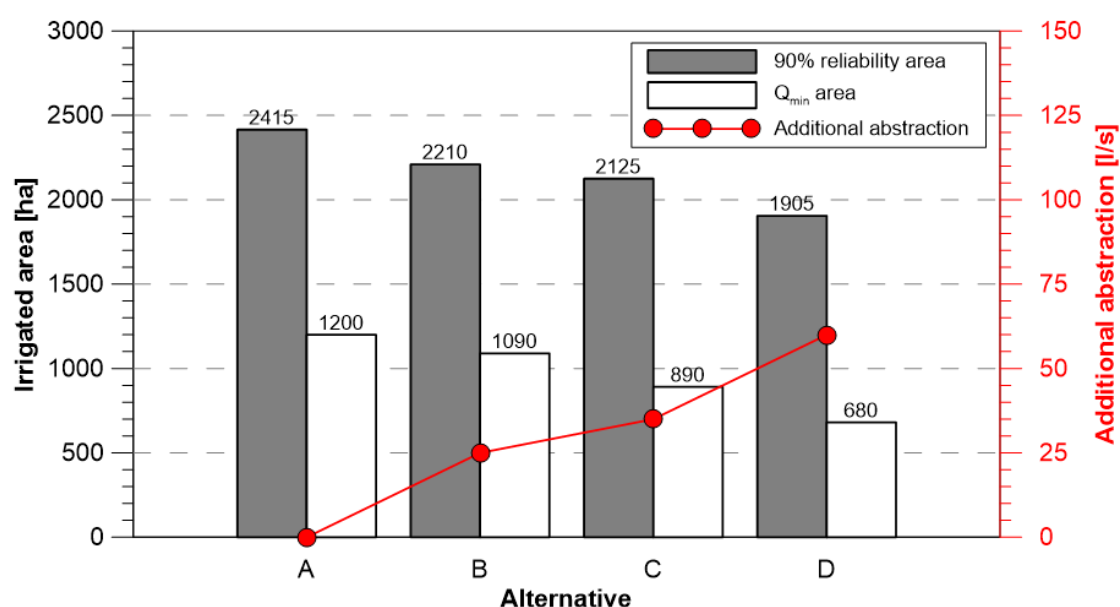


Figure 7. Comparison of various alternatives with different withdrawals for irrigation. The columns show the maximum irrigated area for a 90% reliability of the water supplies (the grey column) and a 100% reliability that the biological flow will be secured (the white column). The red dots represent various additional new withdrawals in the specific alternatives.

4. Conclusions

This study was focused on optimizing the use of the water management system of Horné Orešany Water reservoir due to changing hydrological conditions. The hydrological regime, distribution, seasonality and development of the water bearing in the study site were analysed in relation to the assessment of the water reservoir features. A modified model of Thomas and Fiering was used for modelling and imitation of the fluctuations in the interannual runoff with hydrological diversity of situations in the flow time series.

Results of the balance calculations of Horné Orešany Water reservoir provide the information on possible withdrawals from it, while this option was verified by retrospective balance, based on the conditions in the period of 1981-2013. The study includes a probative fact that flows were declined compared to those that were provided by the initial engineers designing the reservoir and irrigation in the 70s of the 20th century, as well as other facts arising from climate change: gradual warming and lengthening the occurrence of the number of dry days in a row, causing a reduction in the area of possible irrigation, which can be supplied from the reservoir.

It is necessary to note that any additional new withdrawals from the reservoir have to be evaluated in relation to their effect on water available for irrigation, which was the reservoir's original and sole purpose. Any new water balance calculations have to be performed under the actual hydrological and climatic conditions. The results of this study could be used in practice in the process of the optimization of the usable volume of the reservoir in order to maximize either new withdrawals or the area of irrigated land.

Acknowledgment(s)

This study was supported by the Slovak Research and Development Agency under the contract no. APVV-15-0425 and by the Scientific Grant Agency of the Ministry of Education, Science, Research and Sport of the Slovak Republic under the contract no. VEGA 1/0891/17.

References

- [1] K. Hlavčová, M. Lapin, P. Valent, J. Szolgay, S. Kohnová, and P. Rončák, "Estimation of the impact of climate change-induced extreme precipitation events on floods," *Contributions to Geophysics and Geodesy*, vol. 45(3), pp. 173-192, 2015.
- [2] P. Rončák, K. Hlavčová and T. Látková, "Estimation of the effect of changes in forest associations on runoff processes in basins: case study in the Hron and Topľa river basins," *Slovak Journal of Civil Engineering*, vol. 24(3), pp. 1-7, 2016.
- [3] J. Mind'áš, and J. Škvareninová, "Biodiversity and climate change: consequences for upper tree line in Slovakia," *Forestry Journal*, vol. 62(3), pp. 181-185, 2016.
- [4] K. Kalúz, Š. Rehák, K. Hlavčová and J. Szolgay, "Water management in landscape," Slovak agricultural university in Nitra, 314 pp., 2010. (in Slovak)
- [5] I. Belčáková, "Water technical monuments of Banská Štiavnica - a vision for a cultural heritage UNESCO site," *Landscapes in Flux: Eclac conference*, Tartu: Estonian University of Life Sciences, pp. 198—200, Tartu, Estonia, 2015.
- [6] K. Nacházel, "Stochastic models of outflow fluctuations during the year and their use in designing the water reservoirs," *Vodohospodársky časopis (Water Management magazine)*, vol. 24(2), pp.105-117, 1976b. (in Czech)
- [7] M. Procházka, "Mathematical modeling of mean monthly flows," *VÚV Praha*, pp. 50, 1989. (in Czech)
- [8] State amelioration management, "The study of set of irrigation structures using the Horné Orešany Water reservoir," 1977. (in Slovak)
- [9] Slovak Water-Management Enterprise, "Operational regulation for Horné Orešany Water reservoir," Piešťany, pp. 19, 2009. (in Slovak)
- [10] J. Szolgay, L. Gaál, T. Bacigál, S. Kohnová, K. Hlavčová, R. Výleta, J. Parajka and G. Blöschl, "A regional comparative analysis of empirical and theoretical flood peak-volume relationships," *Journal of Hydrology and Hydromechanics*, vol. 64(4), pp. 367-381, 2016.
- [11] L. Gaál, J. Szolgay, S. Kohnová, K. Hlavčová, J. Parajka, A. Viglione, R. Merz and G. Blöschl, "Dependence between flood peaks and volumes: a case study on climate and hydrological controls," *Hydrological Sciences Journal - Journal des Sciences Hydrologiques*, vol. 60(6), pp. 968-984, 2015.
- [12] H. B. Mann, "Non-parametric test against trend," *Econometrica*, vol. 13, pp. 245-259, 1945.
- [13] M. G. Kendall, "Rank Correlation Methods (4th edition) Charles Griffin," London, 1975.
- [14] H. A. Thomas and M. B. Fiering, "Mathematical synthesis of stream flow sequences for the analysis of river basins by simulation," *Design of Water Resources Systems*, Chapter 12. Harvard University Press, Cambridge, Mass, 1962.
- [15] T. A. McMahon and R. G. Mein, "Reservoir capacity and yield," *Elsevier*, Amsterdam, pp. 213, 1978.
- [16] R. Srikanthan, and T. A. McMahon, "A review of lag-one Markov models for generation of annual flows," *Journal of Hydrology*, vol.37, pp.1-12, 1978