

# Analysis of the influence of input data uncertainties on determining the reliability of reservoir storage capacity

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**Abstract:** The paper contains a sensitivity analysis of the influence of uncertainties in input hydrological, morphological and operating data required for a proposal for active reservoir conservation storage capacity and its achieved values. By introducing uncertainties into the considered inputs of the water management analysis of a reservoir, the subsequent analysed reservoir storage capacity is also-affected with uncertainties. The values of water outflows from the reservoir and the hydrological reliabilities are affected with uncertainties as well. A simulation model of reservoir behaviour has been compiled with this kind of calculation as stated below. The model allows evaluation of the solution results, taking uncertainties into consideration, in contributing to a reduction in the occurrence of failure or lack of water during reservoir operation in low-water and dry periods.

**Keywords:** Uncertainties; Reliability; Reservoir storage capacity; Monte Carlo method; Mean monthly flows; Evaporation; Elevation–volume curve; Elevation–area curve.

## INTRODUCTION

The current knowledge in the field of climatology indicates a gradual change in hydroclimatic conditions all over the world. Climate changes are reflected in the changes in the hydrological cycle due to the redistribution of precipitation during the year and they contribute to more frequent occurrences of extremes in the form of floods and dry periods.

Clear signs of climatic changes have appeared in the Czech Republic in recent years. It should be noted that, from the hydrological point of view, 2011 and 2012 were considered to be extremely dry (Zahradníček et al., 2014). The temperatures in the winter in 2014 were considerably above average. In that period, the water storage in snow cover was the lowest in the last twenty years. The consequences were extraordinary manipulations at some water reservoirs. It is apparent that the subject of advanced management and control of surface water resources is becoming more and more important. The manipulation rules of large open water reservoirs were approved in the period of construction of those waterworks and subsequently reviewed for the current hydrological conditions. It will be necessary to carry out a thorough review in the future in relation to their adaptability due to climate change and hydrological cyclic evolution. Therefore, the tasks of water management analysis of reservoirs for active reservoir conservation storage capacity will always be necessary and research in this field is valuable. In particular, the application of new optimization methods for water management analysis of reservoirs, new reservoir performance definitions and, last but not least, the introduction of analysis of uncertainties in these problems or combinations of the above mentioned applications and knowledge.

Under the given conditions, it is necessary to introduce input data uncertainties into the proposal for control of reservoir storage capacity. The procedures which will be described below refer to “The influence of uncertainties in the calculation of mean monthly discharges on reservoir storage” (Marton et al., 2011). This paper describes, in detail, the introduction of uncertainties of measurement in determining below average monthly

flows over the stage-discharge curve in a river and a number of measurements of hourly records of river stages in a hydrometric profile. For this sort of computation, the Monte Carlo method was used. One of the results was creating the random time series of mean monthly flows, which was affected by uncertainties of measurement in the hydrometric profile. The random series of mean monthly flows served as input data for the water management analysis of the reservoir storage capacity, when the spectrum of reservoir storage volumes for the maximum hydrological reliability of 100% were determined repeatedly using single-pass simulations of reservoir operation. The final spectrum of random reservoir storage capacities was evaluated statistically and the interval of possible values of reservoir storage volumes was found. The other work referred to in this paper is a paper by Marton et al. (2014) describing the calculation of reservoir storage capacity in the conditions of measurement uncertainties and extended to using the AR and ARMA models, generators of artificial streamflow series of mean monthly discharges. Random discharge series, in this case as data inputs for artificial streamflow series generators, were used, resulting in random samples of artificial streamflow series. These random series were evaluated using a reservoir simulation model. The calculation result was a spectrum of reservoir storage capacities for maximum reliability of 100 %, which was statistically evaluated. Both papers have indicated that the current water volumes in reservoirs can be underestimated and, in dry periods, may result in an unexpected failure in surface water supply.

As regards current knowledge, uncertainty can be derived from set theory, but also uncertainty can be derived using statistics. From set theory, it is necessary to mention the application of uncertainty based on the theory of fuzzy sets (Zadeh, 1965) and the theory of possibilities (Klir, 2005). However, the first definition of uncertainty was by Knight (1921), nowadays known as Knightian uncertainty. The uncertainty concept is currently viewed from different aspects, with plenty of definitions and points of view, such as the uncertainty associated with the definition of risk, uncertainties applied in forecasting problems, and also the uncertainty of measurement. Uncertainties



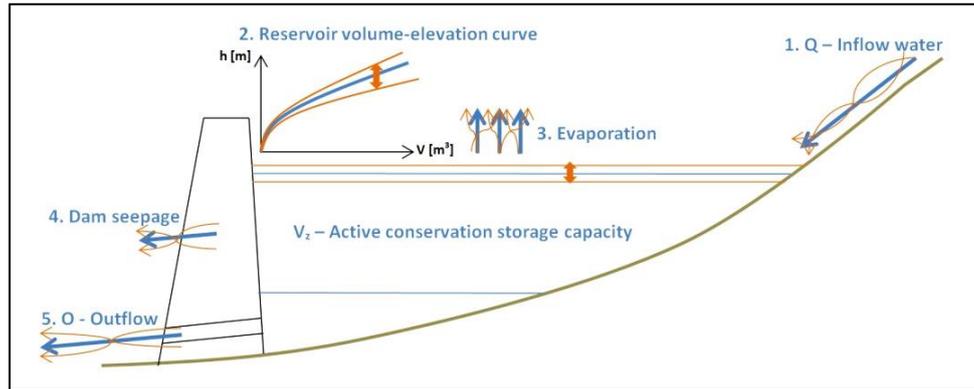


Fig. 2. Symbolic introduction of considered quantities affected with uncertainties.

The basic principle of generating random positions of points in the two-dimensional coordinate system  $(NX_i, NY_i)$  is identical to the theory described above. The dissimilarity is given by plotting a point which requires plotting two Monte Carlo generators independent of each other. Each generator produces a random position of point  $NX_i$  (e.g. water level elevation  $Nh_i$ ) and with it a random value  $NY_i$  (water volume in reservoir  $NV_i$ ). The result on the reservoir elevation–volume curve is then a random point coordinate  $(NV_i, Nh_i)$  of the reservoir elevation–volume curve. See Fig. 1.

As observed, the reservoir inflow, water surface evaporation, dam seepage and reservoir elevation–area and elevation–volume curves are considered to be hydrological and operating inputs. The principle of introducing uncertainties into the calculation of reservoir storage capacity is shown in Fig. 2.

The generated random curves of water inflows into the reservoir, water evaporation from the water surface, seepages and random area and elevation–volume curves serve as input values for a simulation model which, using single-pass simulation, simulates the behaviour of the reservoir in the conditions of data affected with uncertainty.

### Reservoir simulation model and reservoir performance calculation

The basis for a reservoir simulation model is an adjusted equation in the cumulative form converted to the following inequalities (1) Starý (2005).

$$0 \leq \sum_{i=0}^k (O_i - Q_i) \Delta t + (O_{i+1} - Q_{i+1}) \Delta t \leq V_{z,max} \quad (1)$$

where  $O_i$  is the reservoir outflow,  $Q_i$  the reservoir inflow for  $i = 1, \dots, n$ , and  $\Delta t$  is the time step of calculation (one month).  $O_{k+1}$  is the outflow from the reservoir in the following time step, when in step  $i+1$  the value  $O_{i+1}$  is first replaced with the value of the required outflow  $O_p$ . The time course of the numbered sum simulates the course of emptying the reservoir storage by time steps  $i = 1, \dots, k$ . For  $i = 0$  it is necessary to enter the starting solution condition after the sum value. Inequality (1) is limited from both the left and the right. From the left it is limited by value 0 (full storage capacity) and from the right by value  $V_{z,max}$  (empty storage capacity) characterizing the reservoir storage capacity available for the reservoir. By calculating the value of the expression, the current emptying of the storage volume

$V'_{z,i+1}$  is obtained and it is then tested as to whether it lies in a particular interval  $(0, V_{z,max})$ . If not, it is necessary to find value  $O_{i+1}$  (for the sum of the expression to be equal to zero, idle discharge will occur, or if equal to  $V_{z,max}$  – a failure will occur).

The general definition of reliability was successively described by (Hashimoto et al., 1982; Klemeš, 1967; Kritskiy and Menkel, 1952). The classification of a failure in the reservoir storage capacity for the following calculation of reliability is as follows (2).

$$Z_{t,i} = \begin{cases} Z_{t,i} = 1, & O_i \geq O_p \\ Z_{t,i} = 0, & O_i < O_p \end{cases} \quad (2)$$

$Z_{t,i} = 1$  describes the reservoir storage capacity in a no failure situation (satisfactory state).  $Z_{t,i} = 0$  describes the reservoir storage capacity in a failure situation (unsatisfactory state). The required reliability can be further calculated from values  $Z_{t,i}$ . Generally, reliability is calculated by time-based reliability as temporal reliability and occurrence reliability, and volumetric reliability is calculated separately. The paper uses the formula for the calculation of temporal reliability  $P_T$  (3).

$$P_T = \frac{1}{k} \sum_{i=1}^k Z_{t,i} \quad (3)$$

where  $k$  is the number of months in the period being solved.

### PRACTICAL APPLICATION

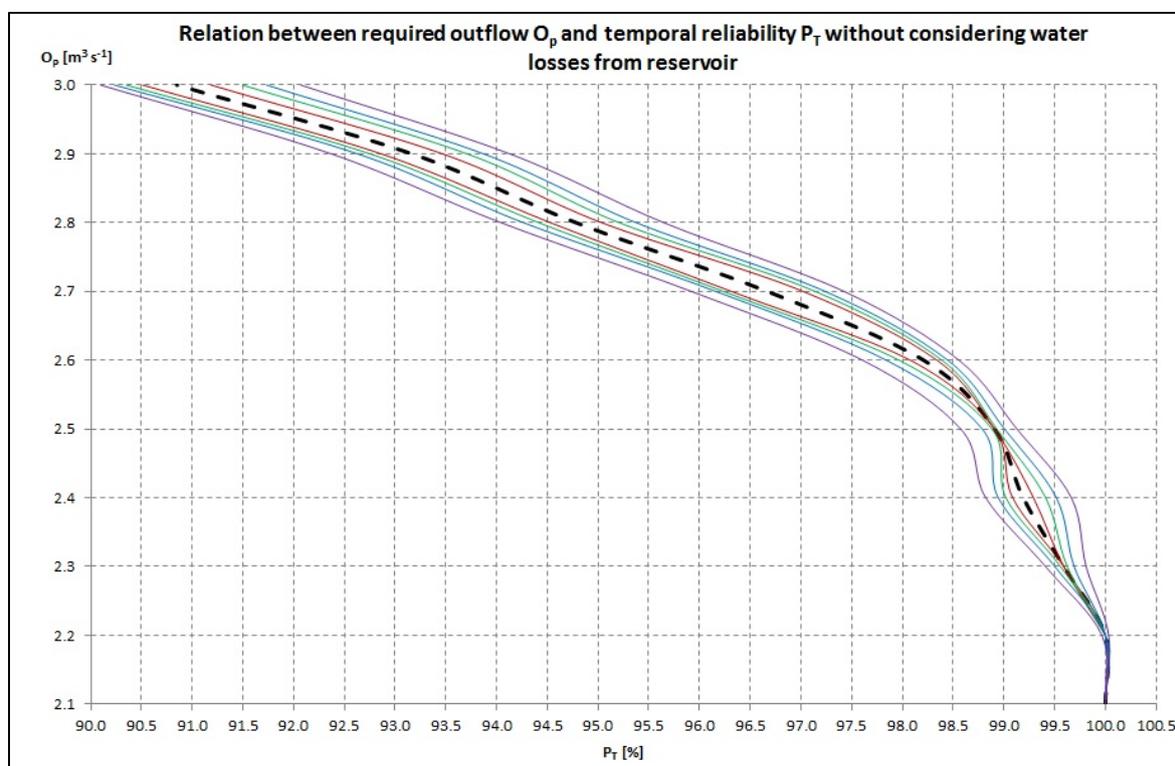
The model was applied in practice to the existing reservoir, Vír I, which is situated in the Vysočina Region, Czech Republic. This is a multi-use reservoir serving mainly as flood protection and surface water accumulation for water supply and hydroelectric purposes. The reservoir is built in the Svatka River basin and has been in operation since 1957. The Svatka is the main inflow into the reservoir. The mean long-term inflow into the reservoir  $Q_a$  is  $3.34 \text{ m}^3 \text{ s}^{-1}$ . Input values for the calculation were made up of a time series of mean monthly flows over 60 years with the measurement period from 1950 to 2010. The mean annual evaporation from the water surface  $E_{ANNUAL} = 613 \text{ mm}$ . The monthly evaporation values from water surface were derived in a simplified manner according to the percentage distribution of evaporation according to the ČSN 75 2405 Standard (2004) and from the mean annual evaporation values for Vír I reservoir, see Table 1.

**Table 1.** Monthly distribution of evaporation amount during the calendar year.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
$E_m$ [%]	6	9	12	14	16	15	11	7	5	2	1	2
$E_m$ [mm]	36.78	55.17	73.56	85.82	98.08	91.95	67.43	42.91	30.65	12.26	6.13	12.26

**Table 2.** Calculation without considering water losses from the reservoir. Measurement uncertainties are applied for water inflow into the reservoir.

$O_p$ [ $m^3 s^{-1}$ ]	Input data uncertainty $U_a = 3\sigma$							
	$\pm 3\%$		$\pm 6\%$		$\pm 9\%$		$\pm 15\%$	
	$\mu(P_T)$	$U_a(P_T)$	$\mu(P_T)$	$U_a(P_T)$	$\mu(P_T)$	$U_a(P_T)$	$\mu(P_T)$	$U_a(P_T)$
2.2	100.000	0.000	100.000	0.000	100.000	0.000	99.999	0.033
2.3	99.590	0.001	99.591	0.033	99.598	0.095	99.611	0.200
<b>2.5</b>	<b>98.907</b>	<b>0.001</b>	<b>98.906</b>	<b>0.024</b>	<b>98.896</b>	<b>0.109</b>	<b>98.852</b>	<b>0.277</b>
2.7	96.668	0.354	96.688	0.453	96.701	0.540	96.672	0.753
2.9	93.165	0.302	93.230	0.479	93.250	0.621	93.250	0.879
<b>3.0</b>	<b>90.849</b>	<b>0.338</b>	<b>90.923</b>	<b>0.573</b>	<b>90.984</b>	<b>0.749</b>	<b>91.084</b>	<b>0.987</b>



**Fig. 3.** Relation between required outflow  $O_p$  and temporal reliability  $P_T$  without considering.

The total reservoir volume is  $V_{TOTAL} 56.193 \times 10^6 m^3$ , active storage volume  $V_{Z,max}$  is  $44.056 \times 10^6 m^3$  and flood reservoir volume  $V_{FLOOD}$  is  $8.337 \times 10^6 m^3$ . The total dam height is 67.3 m. The ecological flow from the reservoir  $Q_{ECO}$  is  $0.53 m^3 s^{-1}$ . The value of seepage through the dam was derived from empirical observation and for the gravity concrete dam it is  $0.15 l s^{-1}$  per  $1000 m^2$ .

The calculation of temporal reliability  $P_T$  for an increased outflow from the reservoir was analysed with and without considering water losses from the reservoir. When water losses were considered in the calculations of temporal reliability, the described procedures for generating uncertainty-affected hydrological, morphological and operating inputs were applied. The analysis was carried out for the values of increased required outflow  $O_p$  lying in the interval  $O_p \in (2.1; 3.0) m^3 s^{-1}$ . The selected num-

ber of repetitions using the Monte Carlo method was 300. Input uncertainties for the analysis ranged in intervals  $\pm 3$ ,  $\pm 6$ ,  $\pm 9$ , and  $\pm 15\%$ . The algorithm simulating the behaviour of the reservoir then calculated random discharges  $NO_i$  of water from the reservoir and temporal reliability of  $NP_T$ . Then, random courses of monthly filling and emptying of the reservoir storage capacity were calculated. For a better presentation of the results, these values were evaluated statistically. The mean value  $\mu(X)$  for each random set is considered to be the resultant value and the standard deviation  $\sigma(X)$  is considered to be the standard uncertainty related to a particular result. The total, extended uncertainty, type “ $U_a$ ” covering almost 100% or specifically 99.97% of occurrences of the monitored quantity, corresponded to value  $\mu(X) \pm 3\sigma$ . Sensitivity analysis was carried out for the calculation without considering water losses from the reservoir, when only

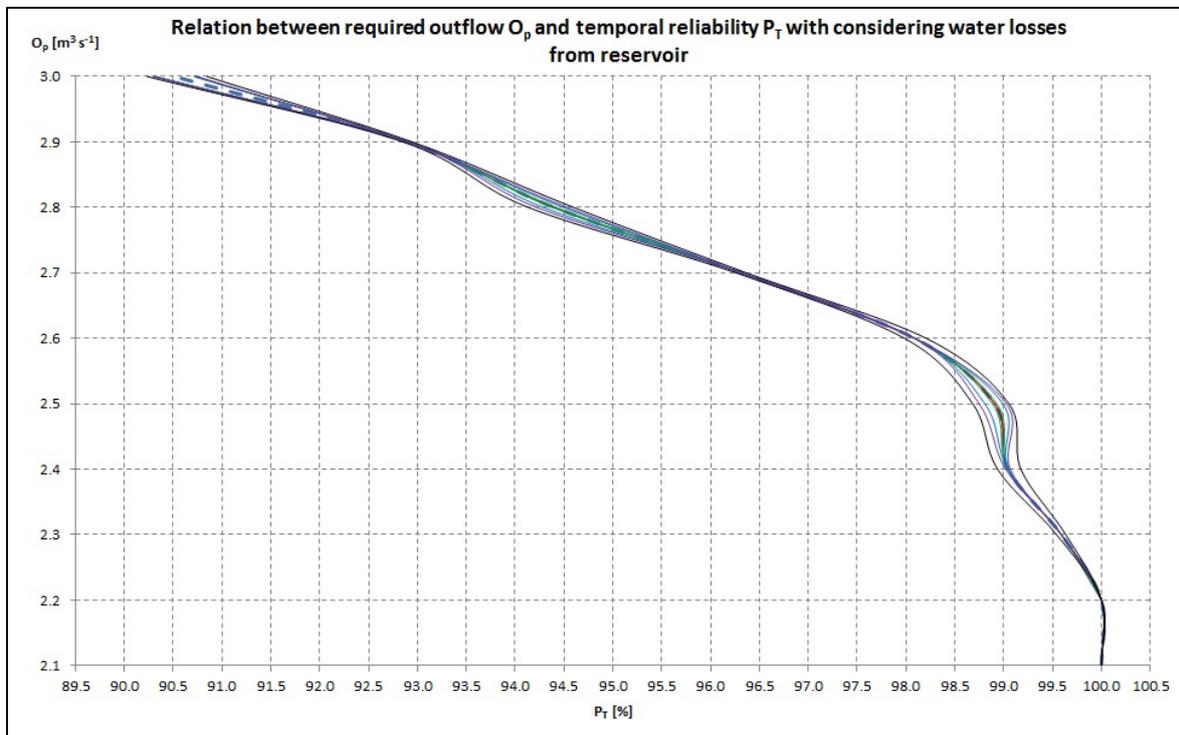
inflow into the reservoir was burdened with uncertainty, see Table 2 and Fig. 3. Calculations were also made while considering water losses from the reservoir. First, only the evaporation values, elevation–volume curve, elevation–area curve and seepage through the dam were affected with uncertainty, see Table 3 and Fig. 4. Then, reservoir inflow, evaporation, elevation–

volume curve, elevation–area curve and seepage through the dam were affected with uncertainty, see Table 4 and Fig. 5.

The shape of the curves in Figs. 3, 4, and 5 in the range from  $O_p = 2.3 \text{ m}^3 \text{ s}^{-1}$  to  $O_p = 2.5 \text{ m}^3 \text{ s}^{-1}$  is caused by a large time step in the calculations (1 month), and also by a step increase in the number of failure months, which is a small number in the given

**Table 3.** Calculation with considering water losses from reservoir. Uncertainties considered for evaporation, elevation–volume (area) curves and seepage through dam body combinations.

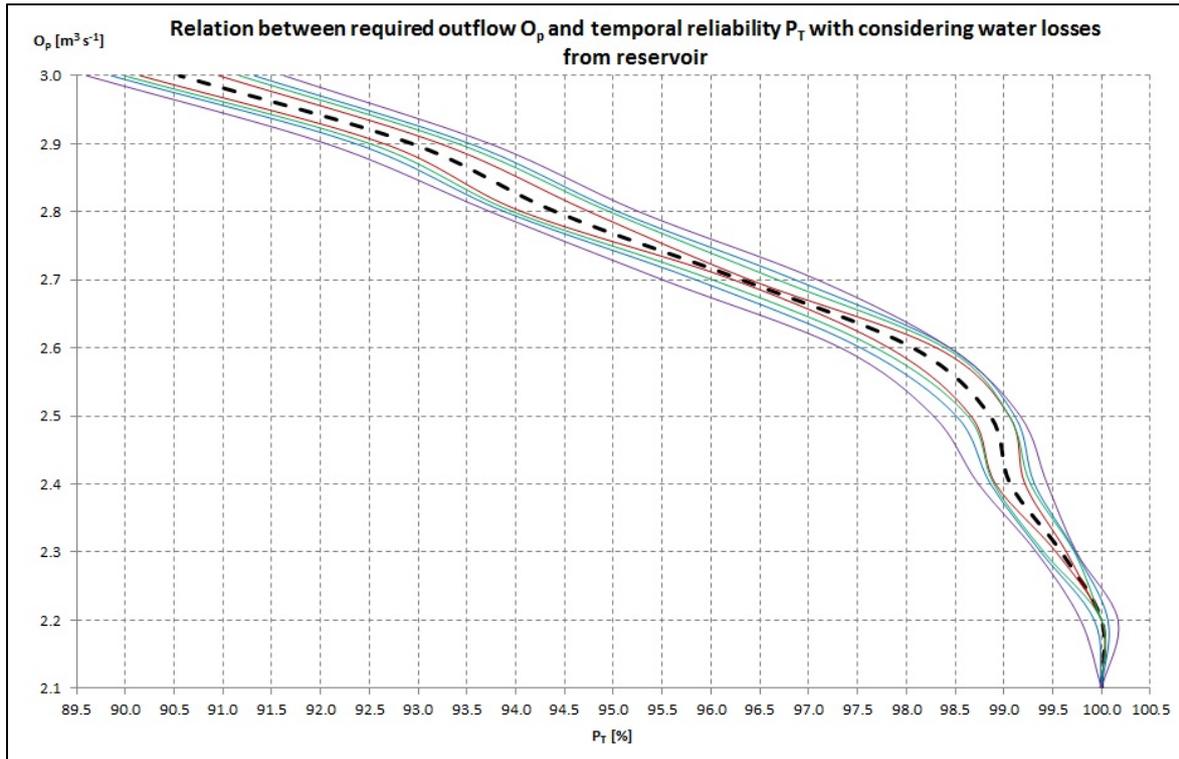
$O_p [\text{m}^3 \text{ s}^{-1}]$	Input data uncertainty $U_a = 3\sigma$					
	$\pm 6\%$		$\pm 9\%$		$\pm 15\%$	
	$\mu(P_T)$	$U_a(P_T)$	$\mu(P_T)$	$U_a(P_T)$	$\mu(P_T)$	$U_a(P_T)$
2.2	100.000	0.000	100.000	0.000	100.000	0.000
2.3	99.590	0.001	99.590	0.001	99.590	0.001
<b>2.5</b>	<b>98.906</b>	<b>0.024</b>	<b>98.899</b>	<b>0.092</b>	<b>98.889</b>	<b>0.140</b>
2.7	96.311	0.001	96.311	0.001	96.311	0.001
2.9	92.896	0.001	92.896	0.001	92.896	0.001
<b>3.0</b>	<b>90.516</b>	<b>0.203</b>	<b>90.514</b>	<b>0.204</b>	<b>90.522</b>	<b>0.224</b>



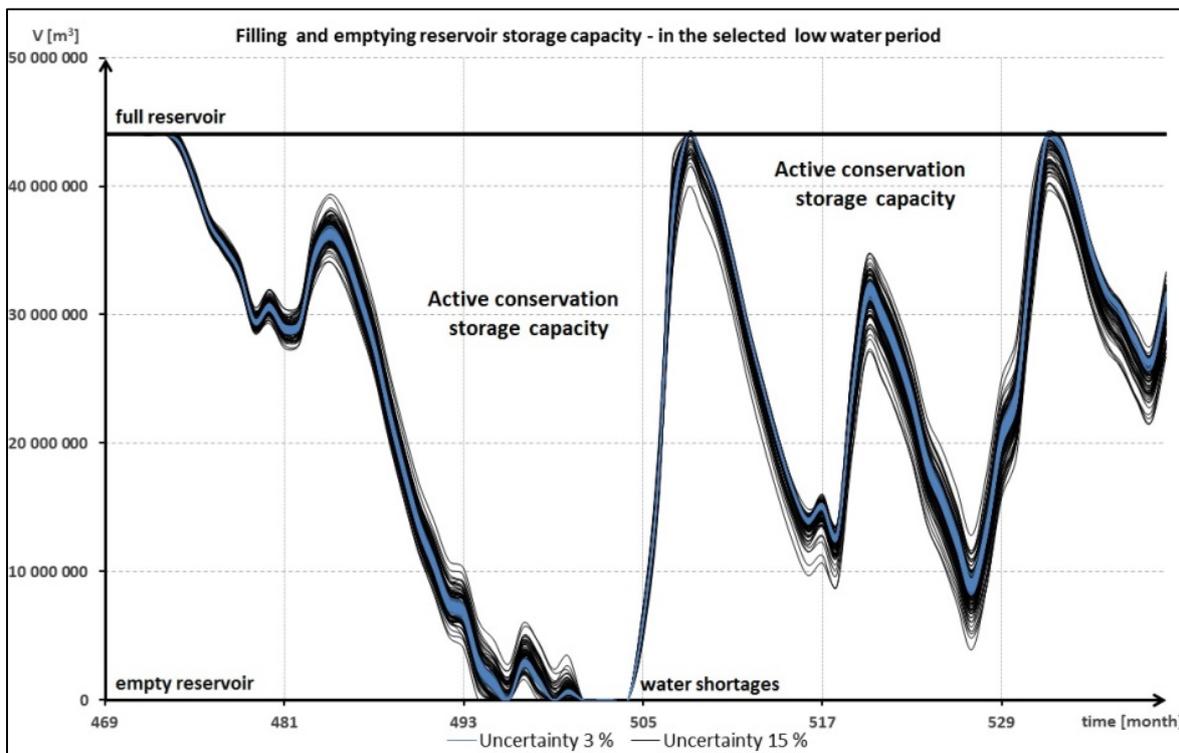
**Fig. 4.** Relation between required outflow  $O_p$  and temporal reliability  $P_T$ , with considering water losses from reservoir for input uncertainties  $\pm 6$ ,  $\pm 9$ ,  $\pm 15$ ,  $\pm 30\%$  and evaporation, elevation–volume(area) curves, dam seepage combinations.

**Table 4.** Calculation with considering water losses from reservoir. Uncertainties considered for all inflow, evaporation, elevation–volume (area) curves, seepage through dam body combinations.

$O_p [\text{m}^3 \text{ s}^{-1}]$	Input data uncertainty $U_a = 3\sigma$							
	$\pm 3\%$		$\pm 6\%$		$\pm 9\%$		$\pm 15\%$	
	$\mu(P_T)$	$U_a(P_T)$	$\mu(P_T)$	$U_a(P_T)$	$\mu(P_T)$	$U_a(P_T)$	$\mu(P_T)$	$U_a(P_T)$
2.2	100.000	0.000	100.000	0.000	99.996	0.070	99.978	0.191
2.3	99.587	0.057	99.566	0.155	99.555	0.179	99.539	0.204
<b>2.5</b>	<b>98.859</b>	<b>0.196</b>	<b>98.843</b>	<b>0.215</b>	<b>98.811</b>	<b>0.293</b>	<b>98.721</b>	<b>0.451</b>
2.7	96.316	0.084	96.348	0.338	96.350	0.510	96.300	0.797
2.9	92.939	0.290	92.957	0.454	92.943	0.584	92.896	0.838
<b>3.0</b>	<b>90.556</b>	<b>0.402</b>	<b>90.575</b>	<b>0.591</b>	<b>90.589</b>	<b>0.734</b>	<b>90.608</b>	<b>1.038</b>



**Fig. 5.** Relation between required outflow  $O_p$  and temporal reliability  $P_T$ , with considering water losses from reservoir for input uncertainties  $\pm 3$ ,  $\pm 6$ ,  $\pm 9$  a  $\pm 15\%$  and an inflow, evaporation, elevation-volume(area) curves and dam seepage combination.



**Fig. 6.** The course of filling reservoir storage capacity in the conditions of entered input data uncertainties  $U_a = \pm 3\%$  a  $\pm 15\%$  for the selected low water period.

range of required outflow from the reservoir  $O_p$ . For values  $O_p = 2.6 \text{ m}^3 \text{ s}^{-1}$  and higher, there is an apparent increase in the failure months, due to which the curves are smooth. The more significant interval of spacing in the curves in Fig. 5, unlike Figs. 3 and 4, in the field of required outflow from the reservoir  $O_p = 2.2 \text{ m}^3 \text{ s}^{-1}$  is caused by the number of failure months occurring in the evaluated set. The process contingency applied when uncertainties are introduced into all input data of the solution results in a significant increase in the number of failure months compared to the solution in which only uncertainties of reservoir inflow or uncertainties for evaporation, elevation–volume (–area) curves and seepage through the dam combination are applied. The analysis also included values of filling the reservoir storage capacity. Fig. 6 then shows the course of filling the reservoir for a particular number of repetitions and for the selected low water period.

## SUMMARY

The final comparison is from selected required outflow from the reservoir  $O_p = 2.5$  and  $O_p = 3.0 \text{ m}^3 \text{ s}^{-1}$ , where the influence is clearly graded. In the variant without applying water losses from the reservoir, the temporal reliability for  $O_p = 2.5 \text{ m}^3 \text{ s}^{-1}$  is in interval  $P_T \in (98.906\%; 98.908\%)$ , i.e.  $P_T = 98.907\% \pm 0.001\%$  for input uncertainty  $\pm 3\%$  and in interval  $P_T \in (98.575\%; 99.129\%)$   $P_T = 98.852\% \pm 0.277\%$  for input uncertainty  $\pm 15\%$ . The interval of temporal reliability for the  $O_p = 3.0 \text{ m}^3 \text{ s}^{-1}$  range in interval  $P_T \in (90.511\%; 91.187\%)$  is  $P_T = 90.849\% \pm 0.338\%$  for input uncertainty  $3\%$  and  $P_T \in (90.097\%; 92.071\%)$   $P_T = 91.084\% \pm 0.987\%$  for input uncertainty  $15\%$ . In the variant without applying all combinations, i.e. considering uncertainties in both inflow and water losses from the reservoir, the interval of temporal reliability was in  $P_T \in (98.663\%; 99.055\%)$   $P_T = 98.859\% \pm 0.196\%$  for input uncertainty  $\pm 3\%$  and for uncertainty  $\pm 15\%$  in interval  $P_T \in (98.27\%; 99.172\%)$   $P_T = 98.721\% \pm 0.451\%$ . For  $O_p = 3.0 \text{ m}^3 \text{ s}^{-1}$  the interval of temporal reliability acquired values  $P_T \in (90.154\%; 90.958\%)$   $P_T = 90.556\% \pm 0.402\%$  for input uncertainty  $3\%$  and  $P_T \in (89.57\%; 91.646\%)$   $P_T = 90.608\% \pm 1.038\%$  for input uncertainty  $15\%$ . The above mentioned results show a logical conclusion that with increasing input data uncertainty, the uncertainty in temporal reliability also increases. Converted to the number of failure months, increased discharge  $O_p = 2.5 \text{ m}^3 \text{ s}^{-1}$  in the solution without considering uncertainties and with considering reservoir water losses, corresponds to eight failure months, and for  $O_p = 3.0 \text{ m}^3 \text{ s}^{-1}$  to 70 months. When considering input uncertainties  $\pm 3\%$ , the number of failure months is from 8 to 9 months for  $O_p = 2.5 \text{ m}^3 \text{ s}^{-1}$  and 66 to 72 months for  $O_p = 3.0 \text{ m}^3 \text{ s}^{-1}$ . For the input data uncertainty of  $\pm 15\%$ , the number of possible failure months is 8 to 12 for  $O_p = 2.5 \text{ m}^3 \text{ s}^{-1}$  and 60 to 76 months for  $O_p = 3.0 \text{ m}^3 \text{ s}^{-1}$ . The presented results show how uncertainties can influence the increase in failure months and which intervals the temporal reliability can then acquire.

## CONCLUSIONS

In the manipulation rules for the Vír I reservoir, the stated temporal reliability for the hydrological period 1931 to 1991 is  $P_T = 99.59\%$  for a required reservoir outflow  $O_p = 2.5 \text{ m}^3 \text{ s}^{-1}$ . This means that the current state is underestimated by approximately 1% compared to the calculations which were undertaken for that reservoir. Underestimation can be explained by the length of the input streamflow series introduced to the calcula-

tions, which were not updated until 2010. In addition, there were few low water years in the first half of the 1990s. For example, in the presented analysis, there is the apparent effect of underestimation of temporal reliability for the value of the required outflow from the reservoir  $O_p = 2.3 \text{ m}^3 \text{ s}^{-1}$ , which is, with the amount of temporal reliability, nearest to temporal reliability according to the manipulation rules of the reservoir for the solution including considering input data uncertainties, and thus the reservoir is classified inappropriately in the significant class (A –  $P_T \geq 99.5\%$ , B –  $P_T \geq 98.5\%$ , C –  $P_T \geq 97.5\%$ , D –  $P_T \geq 95\%$ ) according to ČSN 75 2405. For the uncertainty of  $\pm 6\%$ , the mean value of temporal reliability was  $P_T = 99.566\%$ , which corresponds to the significance of the reservoir A –  $P_T \geq 99.5\%$ . In considering uncertainty, the lower interval of temporal reliability corresponded to value  $P_T = 99.411\%$  and thus also the reservoir significance would fall to a lower significant class corresponding to class B –  $P_T \geq 98.5\%$ . From this point of view, there is space for future reviews of the manipulation rules of reservoirs and possible amendment to the ČSN 75 2405 standard which should take input data uncertainties into consideration. In that case, it will be necessary to take the value of temporal reliability  $P_T$  as the lower limit of the resultant interval and thus to incline more to the safe side in the solution. Currently, the results cannot be generalized, but the computational algorithm is written in general terms and it can be applied also to other reservoirs. When carrying out the sensitivity analysis, the same value of uncertainties was always counted for all input data. Under these conditions it was shown that water inflow was the most significant source of uncertainties. However, other input measurement uncertainties also have an influence on the result, which must be taken into account. At the present time, the authors are not aware of which values the elevation–volume (–area) curves can acquire, when their stated actual course is affected by sedimentation of the reservoir and other effects. Here it is possible to assume that higher uncertainties of elevation–volume (–area) curves can affect the results more. From this point of view, the results may be different and thus also the intervals describing the occurrence of the calculated temporal reliability  $P_T$  may be different.

Finally, it must be stated that the presented sensitivity analysis was only carried out for one reservoir and the results cannot be generalized. It can be assumed that different results will be obtained for other reservoirs and all reservoir systems with different sizes of reservoir storage capacity, various sources of inflows and flood altitude. In this respect, there is space for further research, for example using software based on the paper by Menšík et al. (2015), as well as cooperation with waterworks administrators.

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## REFERENCES

- Beven, K., 2007. Towards integrated environmental models of everywhere: Uncertainty, data and modelling as a learning process. *Hydrol. Earth Syst. Sci.*, 11, 460–467.
- Beven, K.J., Binley, A.M., 1992. The future of distributed models: Model calibration and uncertainty prediction. *Hydrological Processes*, 6, 279–298.

- Campos, J.N.B., Souza Filho, F.A., Lima, H.V.C., 2014. Risks and uncertainties in reservoir yield in highly variable intermittent rivers: Case of the Castanhão Reservoir in semi-arid Brazil. *Hydrological Sciences Journal*, 59, 6, 1184–1195.
- Coxon, G., Freer, J., Westerberg, I.K., Wagener, T., Woods, R., Smith, P.J., 2015. A novel framework for discharge uncertainty quantification applied to 500 UK gauging stations. *Water Resour. Res.*, 51, doi:10.1002/2014WR016532.
- ČSN 75 2405 Standard, 2004. Water Management Analysis of Reservoir, ICS 93.160; 13.060.10, The Czech Office for Standards, Metrology and Testing, Prague.
- GUM, 1993. Guide to the expression of uncertainty in measurement. 1st ed. International Organization for Standardization, Geneva, 101 pp. ISBN 9267101889.
- Hashimoto, T., Stedinger, J.R., Loucks, D.P., 1982. Reliability, resiliency, and vulnerability criteria for water resource system performance evaluation. *Water Resources Research*, 18, 1, 14–20.
- ISO GUIDE 99998 Standard, 2004. Guide to the expression of uncertainty in measurement (GUM) – Supplement 1: Numerical methods for the propagation of distributions. International Organization for Standardization, Geneva.
- Klemes, V., 1967. Reliability estimates for a storage reservoir with seasonal input. *Journal of Hydrology*, 7, 2, 198–216.
- Klir, G.J., 2005. *Uncertainty and Information: Foundations of Generalized Information Theory*. John Wiley & Sons, Inc., Hoboken, NJ, 499 pp.
- Knight, F.H., 1921. *Risk, Uncertainty, and Profit*. Boston, Hart, Schaffner & Marx; Houghton Mifflin Company, Boston.
- Kritskiy, S.N., Menkel, M.F., 1952. *Water Management Computations*. GIMIZ, Leningrad. (In Russian.)
- Kuria, F.W., Vogel, R.M., 2014. A global reservoir water supply yield model with uncertainty. *Environmental Research Letters*, 9, 095006, doi: 10.1088/1748-9326/9/9/095006.
- LaBaugh, J.W., Winter, T.C., 1984. The impact of uncertainties in hydrologic measurement on phosphorus budgets and empirical models for two Colorado reservoirs. *Limnology and Oceanography*, 2, doi: 10.4319/lo.1984.29.2.0322.
- Marton, D., Starý, M., Menšík, P., 2011. The influence of uncertainties in the calculation of mean monthly discharges on reservoir storage, *Journal of Hydrology and Hydromechanics*, 59, 4, 228–237.
- Marton, D., Starý, M., Menšík, P., 2014. Water management solution of reservoir storage function under condition of measurement uncertainties in hydrological input data. *Procedia Engineering*, 70, 1094–1101, ISSN 1877-7058, <http://dx.doi.org/10.1016/j.proeng.2014.02.121>.
- Menšík, P., Starý, M., Marton, D., 2015. Water management software for controlling the water supply function of many reservoirs in a watershed. *Water Resources*, 42, 1, 133–145.
- WECC, 1990. *Guidelines for Expression of the Uncertainty in Calibrations*. Doc. 19-1990. International Organization for Standardization, Geneva, Switzerland.
- Winter, T.C., 1981. Uncertainties in estimating the water balance of lakes. *JAWRA Journal of the American Water Resources Association*, 17, 82–115. doi: 10.1111/j.1752-1688.1981.tb02593.x.
- Zadeh, L.A., 1965. Fuzzy sets. *Information and Control*, 8, 3, 338–353. doi: 10.1016/s0019-9958(65)90241-x.
- Zahradníček, P., Trnka, M., Brázdil, R., Možný, M., Štěpánek, P., Hlavinka, P., Žalud, Z., Malý, A., Semerádová, D., Dobrovolný, P., Dubrovský, M., Řezníčková, L., 2014. The extreme drought episode of August 2011–May 2012 in the Czech Republic. *Int. J. Climatol.*, doi: 10.1002/joc.4211.

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