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Water management solution of reservoir storage function under condition of measurement uncertainties in hydrological input data

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Abstract

The paper describes a possible procedure of the rate uncertainty implementation to the continuous water stage measurement and uncertainties of state - discharge rating curve point positions, which the stage -discharge rating curves were fitted into the uncertainties of the real discharge series members. Then the members of discharge series under uncertainty impact were tested on the calculated values of the reservoir storage volume. The next step was the implementation of the uncertainties of the real discharge series members on the generation of the artificial discharge series of mean monthly discharge using the AR and ARMA generators and the determination of their impact on the calculated values of the reservoir storage volume.

Keywords: Measurement Uncertainty; Sampling Water Stage; Stage - Discharge Rating Curve; Real Discharge Series; Artificial Discharge Series; Monte Carlo Method; Reservoir Storage Capacity; AR and ARMA Models.

1. Introduction

Access to water has determined the development of human society from ancient times. The problem of water supply solution has had a long tradition not only in the Czech Republic but also in the world. Water resources can be generally divided into two categories, i.e. surface water resources and groundwater resources. At present the water reservoirs are the most important as a storage of surface water. Water reservoirs serve for many purposes. It is especially a storage and flood protective purpose as well as a hydropower and recreation purpose and others.

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It can be expected that the significance of water supply with surface water sources will further strengthen in the future. The reason is the gradual decrease of reserves of groundwater resources which brings the gradual expansion of the areas affected by drought. In the Czech Republic this effect can be significantly observed mainly in the Southern Moravia region. There is currently more and more discussed the problem of reinforcement of the importance of surface water resources because groundwater resources are more and more unstable. The main reason is especially the gradual change in the climate system and the related distribution of rainfall during the hydrological year. However, the surface water resources are not completely safe. Changes in precipitation, air temperature and air humidity during the hydrological year will result in a gradual change in the hydrological regime in the watershed. According to the study Kašpárek et al. (2005), it is possible that the effects of climate change and the associated gradual changes in the hydrological regime in the watersheds, decrease long-range average discharge Q_a in the river network of 20 to 40 percent. Empowering strategic significance of water reservoirs on one hand and hydrologic stress on the other hand, lead to a revival of research tasks concerned with the supply and quality of water in the watershed. Tasks related to water management solution of storage reservoir function, or a reservoir system, as well as the issues of uncertainties of hydrological inputs are current and justified.

In the water management solution of the reservoir storage function the course of water inflow into the reservoir Q(t) is the basic piece of information (boundary condition), which is time dependent. It is possible to describe this time sequence by time series of the average daily, monthly or annual flow. The basis of each flow series is the time course of discharge Q, which is derived from measurements of the water stage in the Hydrometric gauging station. To obtain the actual measured discharge Q, the pieces of information from measurements of water stage of the sampling water stage h_p are necessary as well as stage - discharge rating curve, interspersed with long-term repeatedly measured (Q,h) points. The discharge Q is subtracted from the water stage and stage - discharge rating curve.

Sampling water stages h_p are obtained by means of repeated reading from the measuring device installed in the hydrometric gauging station (pressure transducer, bubble water level sensor), the values of coordinates (Q,h) of points of stage - discharge rating curve of hydrometric gauging station are also deduced from the measurement. If these values are obtained by the measurement, it is necessary to take into account that they are loaded by random errors, which arise during the measurements. According to valid current European or rather Czech Directives and Standards WECC 19/90 (1990), TPM 0051 – 93 (1993), ČSN EN ISO 748 (2001) there has been the standard defining the errors emerged during the measurement as the uncertainty of measurement for many years.

Suppose that during the whole process of measurement of the water level arises a number of errors. These errors can be random or systematic. Random errors are reflected into the statistical processing of repeatedly measured values and the uncertainties measurement type A are determined from them. The uncertainty type B is determined indirectly. It means that the measurements uncertainty is determined in another way than the repeated measuring. Basically It is possible to take into account that the uncertainty of type B are made with systematic errors. In this case It Generally, measurement uncertainties define the area of possible occurrence of values around the mean of measured magnitudes. Uncertainties type A are the standard deviations of a selective mean; they are called the standard uncertainties u_A. Standard uncertainties u_A can be geometrically added together with the standard uncertainties u_B into the combined uncertainty u_C. If we multiply the combined uncertainty by coefficient k, we obtain the expanded uncertainties U. All of it can be carried out assuming that the probability distribution of observed values around the mean μ is a normal distribution. Then the interval $\langle \mu - U ; \mu + U \rangle$ defines the area, in which the observed value with measured error effect can occur with the probability of 95% for $k = 2$ and probability of 99,75% for $k = 3$ Palečář et al. (2001).

Taking into account the uncertainty emerging from the determination of values of sampling water stages h_p and (Q,h) points of stage - discharge rating curve, it is vital to consider these uncertainties further within the derivation of discharge values, or rather members of flow series. If we determine these uncertainties, it will be possible to make another step in the solution, which is their inclusion in related calculations of the reservoir storage volume.

2. Methods

For the determination of uncertainty of mean monthly discharges on devices described sizes of standard uncertainties type B u_B were used, which the producer indicates in the product specification. The measured values of sampling water stages h_p with the time step of one hour and coordinates of (Q,h) points of stage - discharge rating curve were considered as means $\mu(h_p)$. The standard uncertainty $u_{B,z}$ was considered like standard deviation $\sigma(h_p)$. Uncertainty measurement was introduced into the solution using Monte Carlo Method. These assumptions allow to look at measured values like randomly determined values from the interval of possible realization, which was always given as the normal distribution $N(\mu(h_p), \sigma(h_p))$. The result of the repeated generation was random processing of sampling water stages Rh_p around $\mu(hp)$ and random (RQ,Rh) point positions of stage - discharge rating curve around empirical stage - discharge curve $\mu(Q,h)$. The principle of the generation of random point positions of stage - discharge rating curve is indicated in the Fig. 1.

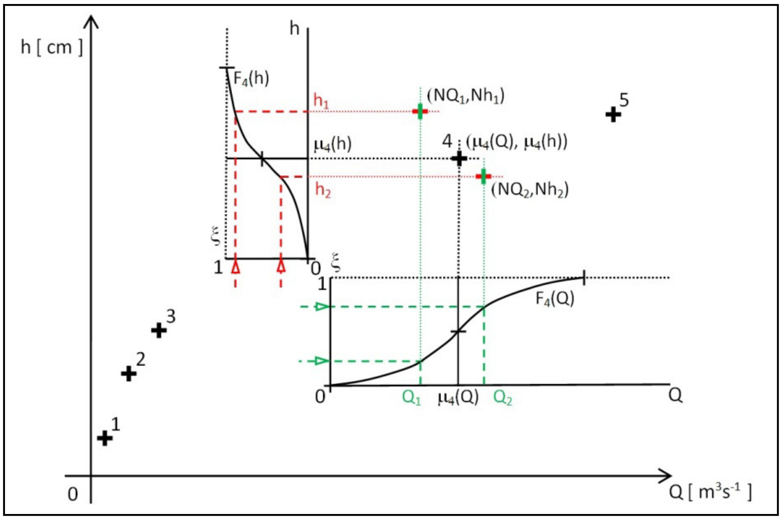

Fig. 1. Scheme of Generation of Random Position (RQ_j,Rh_j) Points of the Empirical Stage - discharge Rating Curve around Measured Points $\mu_i(Q,h)$ using Monte Carlo Method.

The assessment of random values of immediate hourly discharges was as follows. Every set of randomly generated (RQ,Rh) points of stage - discharge curve was fitted by the regression curve by means of software HYDROM by Starý (1995). To each regression curve random series of sampling hourly water stages was assigned, from which random series of hourly flows was deducted. By the repeated procedure for the selected number of repetitions random sets of immediate hourly discharges were compiled. Then the immediate hourly discharge values were transferred to the mean daily discharge values Q_d and to the values of mean monthly discharges Q_m. The result was random sequences of average monthly discharge series, which have been further statistically evaluated into the chronological statistical characteristics. The mean in each month was considered as the result of average monthly discharge. The standard deviation in each month $\sigma(Q_m)$ was considered as the standard uncertainty of average monthly discharge u_{Qm}.

Analogically it was possible to generate random sequences of real discharge series repeatedly if the average monthly discharge values Q_m and standard uncertainty values u_{Qm} were known, using Monte Carlo method. From each generated random real discharge series the reservoir storage capacity was determined based on the basic reservoir equation (1).

$$V_n = V_0 + \sum_{i=1}^{n} \left(Q_{m,i} - O_{m,i}\left(V_i\right)\right) \cdot \Delta t_i \tag{1}$$

where:

V_0 … is the initial filling of reservoir (full reservoir),

$O_{m,i}$ … is average monthly inflow to reservoir,

$Q_{m,i}(Vi)$ … is controlled average monthly outflow from reservoir and is substituting as improved outflow O_p, if reservoir doesn´t full, otherwise $O_{m,i} = Q_{m,i}$,

V_i … is finished filling of reservoir at the end of each time step Δt_i,

V_n … is finished filling of reservoir at the end of the solved period,

n … is the order of solved time step.

By repeated calculation a set of random storage volumes was created, which was statistically evaluated. Then each randomly generated real discharge series was used as input data for repeatedly generating of artificial discharge series of average monthly discharges.

For generating of artificial discharge series from sequences of real discharge series AR and ARMA models were chosen. AR and ARMA models were described by Hirsch (1979), which subsequently programmed by Pilař (1988). Repeatedly generated random sequences of artificial discharge series were used again to calculate supply function of the isolated reservoir. The result was a set of calculations of storage volumes that was evaluated by using appropriate statistical methods.

3. Application

The application was carried out on the profile Borovnice on the Svratka River, in which hydrometric gauging station is situated. The location is situated in the Vysočina Region. Data for hydrometric gauging station were provided by the Czech Hydrometeorological Institute, Subdivision Brno. In the profile there is the annual mean discharge $Q_a = 1.53\ m^3\ s^{-1}$.

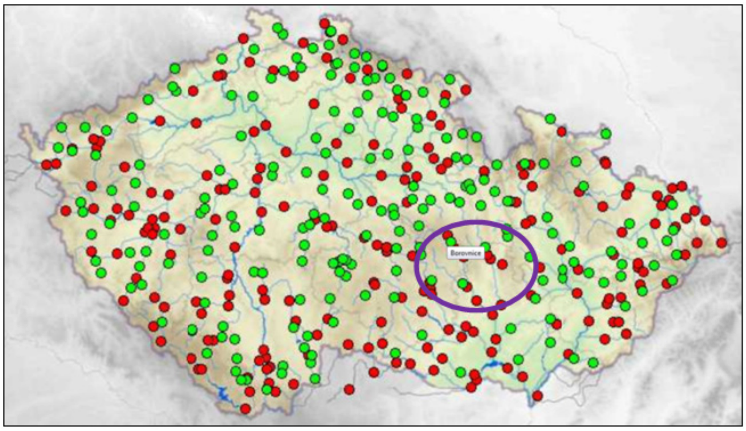

Fig. 2. Hydrometric Gauging Station Svratka / Borovnice.

The annual series of sampling water stages with time step of one hour from 2009 and coordinates (Q,h) of points of the stage - discharge curve were available for the estimation of mean monthly discharge uncertainties. These points were made by the evaluation of hydrometric measurements. Standard uncertainties Type B of input values were determined by the following values. The uncertainty measurement of water stages has been specified for the float measuring device LU 503 G of size $u_{B,\,hp} = \pm\ 0.133\%$ of reading values. The size of uncertainty was obtained from the technical documentation for this device. The uncertainty of reading on the vertical line at hydrometering has a value of $u_{b,h} = \pm\ 0.166$ cm from the measured values. The uncertainty of discharge rate obtained by evaluating of hydrometric measurements corresponded to the value of $u_{b,Q} = \pm\ 2.0\%$ ($U_Q = \pm\ 6.0\%$). The value was obtained by means of generalization of calculations using the HYDROS software by Starý (1991). For Monte Carlo method the number of repetitions NR = 300 was chosen.

Partial results of the uncertainty calculation average monthly discharges are illustrated in the set of three graphs, in which there is a graphical representation of the stage - discharge rating curve in hydrometric gauging station Borovnice, where in the graph a) is shown the progress of the measured values of empirical measurement of points of stage - discharge curve including their fitting by the theoretical curve. The theoretical curve was constructed by combining two regression functions, polynomial-power functions. Graph b) shows positions of randomly generated (Q,h) points by Monte Carlo method for the repetition NR = 300. Positions of generated points lie around the area of measured values, which are listed in the graph a). Graph c) shows the fitted stage - discharge rating curves corresponding to random sets of (RQ,Rh) points for NR = 300.

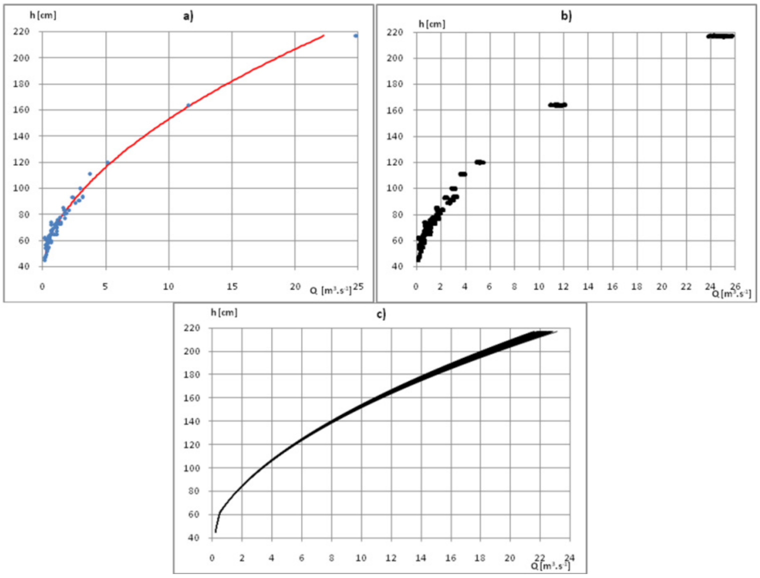

Fig. 3. Stage - discharge Curve Created from Real Measured Values and Group of Stage - discharge Curves when Reflecting Uncertainties of (Q,h) Points in Profile Svratka/Borovnice.

Table 1 shows the results of magnitude of the uncertainty average monthly discharges, which were derived by the described procedure from random sequences of hourly water stages and randomly assigned stage - discharge rating curves.

Table 1. Statistical Characteristics of the Average Monthly Discharges Qm Burdened by Measurement Uncertainty.

	January	February	March	April	May	June	July	August	September	October	November	December
$\mu(Q_m)$ [m³/s]	1.6	1.407	6.087	3.087	0.737	1.178	2.082	0.813	0.426	1.136	1.254	2.218
$u_{Qm} = \sigma(Q_m)$ [m³/s]	0.0107	0.0066	0.0563	0.0204	0.0048	0.004	0.011	0.0035	0.0018	0.0054	0.0058	0.0122
u_{Qm} [%]	0.669	0.469	0.925	0.661	0.651	0.340	0.528	0.431	0.423	0.475	0.463	0.550

Using the above mentioned results, the rate of standard uncertainties of average monthly discharges u_Q was estimated. The determined uncertainties from the Table 1. were used for each month from 30-year real discharge series, which was the basis for the calculation of the storage capacity of the fictive reservoir. The solved storage capacity is determined depending on the improved outflow O_p and its hydrological reliability P, which is equal to P = 100%. Generating of real and synthetic discharge series of average monthly discharges including the calculation of reservoir storage capacity was made by UNCE-V software by Marton and Starý (2012). For generating of artificial discharge series were used generators of type LTAR (log - transformed, Autoregresive Model) and LTMA (log - transformed, Moving Average Model). The length of the generated artificial discharge series was determined to 10,000 years.

The following tables show the size of the reservoir storage capacity V_z for the changing improved outflow O_p value and its corresponding absolute and relative size of the standard uncertainties u_{Vz} and expanded uncertainties U_{Vz}. When expanded uncertainty is calculated for coefficient k = 3. The coefficient α is defined as follows $\alpha=O_p/Q_a$. Where O_p is improved outflow from reservoir and Q_a is long-range average discharge.

The results of the calculation of uncertainties of reservoir storage capacity performed by using random sequences of real discharge series were processed in Table 2.

Table 2. Uncertainties of Reservoir Storage Capacity, Calculation in the Random Sequences of Real Discharge Series.

α	0.2	0.3	0.4	0.5	0.6	0.7
O_p [$m^3 s^{-1}$]	0.306	0.459	0.612	0.765	0.918	1.071
$\mu(V_z)$ [m^3]	1 068 219	2 806 661	5 165 432	7 579 770	9 994 109	15 803 573
$u_{Vz}=\sigma(V_z)$ [m^3]	4 207	7 050	10 123	10 122	10 122	44 120
U_{Vz} [m^3]	12 621	21 150	30 368	30 366	30 366	132 360
$u_{Vz}=\sigma(V_z)$ [%]	0.394	0.251	0.196	0.134	0.101	0.279
U_{Vz} [%]	1.181	0.754	0.588	0.401	0.304	0.838

The results of the calculation of uncertainties of reservoir storage capacity performed by using random sequences of artificial discharge series generated by LTAR generator were processed in Table. 3.

Table 3. Uncertainties of Reservoir Storage Capacity, Calculation in the Random Sequences of Artificial Discharge Series - LTAR Generator.

α	0.2	0.3	0.4	0.5	0.6	0.7
O_p [$m^3 s^{-1}$]	0.306	0.459	0.612	0.765	0.918	1.071
$\mu(V_z)$ [m^3]	1 904 002	5 150 868	8 497 199	15 720 905	32 631 340	59 591 484
$u_{Vz}=\sigma(V_z)$ [m^3]	10 069	11 522	13 268	56 030	181 391	181 391
U_{Vz} [m^3]	30 206	34 567	39 805	168 090	544 173	544 172
$u_{Vz}=\sigma(V_z)$ [%]	0.529	0.224	0.156	0.356	0.556	0.304
U_{Vz} [%]	1.586	0.671	0.468	1.069	1.668	0.913

The results of the calculation of uncertainties of reservoir storage capacity performed by using random sequences of artificial discharge series generated by LTMA generator were processed in Table 4.

Table 3. Uncertainties of Reservoir Storage Capacity, Calculation in the Random Sequences of Artificial Discharge Series - LTMA Generator.

α	0.2	0.3	0.4	0.5	0.6	0.7
O_p [$m^3 s^{-1}$]	0.306	0.459	0.612	0.765	0.918	1.071
$\mu(V_z)$ [m^3]	2 565 124	6 186 623	12 630 862	23 997 166	37 998 040	71 329 584
$u_{Vz}=\sigma(V_z)$ [m^3]	9 237	9 241	64 044	72 420	134 711	281 753
U_{Vz} [m^3]	27 711	27 723	192 133	217 261	404 134	845 259
$u_{Vz}=\sigma(V_z)$ [%]	0.360	0.149	0.507	0.302	0.355	0.395
U_{Vz} [%]	1.080	0.448	1.521	0.905	1.064	1.185

4. Summary and Conclusion

The theoretical description of the generation of random sequences of sampling hourly water stages and position (Q,h) points of stage - discharge rating curve, including their integration into the real discharge series and related reservoir storage capacity calculations were described into details in article Marton et al. (2011) and in the Doctoral Thesis (Marton, 2011).

In the paper there is outlined the procedure of incorporation of measurement uncertainties of sampling water stages and position (Q,h) points of stage - discharge rating curve into the series of average monthly discharges. Nowadays, this piece of information is not specified in the common practice and even the intervals in which the uncertainty of the average monthly discharges can move is not known. The article shows how these uncertainties can be grasped and incorporated into follow-up water management calculations. Not only into the reservoir storage capacity calculation determined from real discharge series, but also their incorporation into the generating of artificial discharge series. These ones serve as an extended hydrological foundation in the design or assessment of the reservoir storage capacity with a high demand on its hydrological reliability. The results presented in the paper show that uncertainties of monthly discharges in the hydrometric gauging station Svratka/Borovnice are variable month by month and move in an interval of standard uncertainty u_{Qm} from ±0,34% to ±0,925%, extended uncertainty from U_{Qm} = ±1.02% to U_{Qm} = ±2,775%. The value of average standard uncertainty u_{Qm} determined from monthly values over the year u_{Qm} = ± 0.549%, which corresponds to the expanded uncertainty U_{Qm} = ± 1.647%.

The UNCE-V software allows to integrate the uncertainty into the calculations either as absolute values by standard deviations $\sigma(Q_m)$, or as relative values by the coefficient of variation $C_v(Q_m)$. Software is able to integrate the uncertainties also as a constant value for the whole period of solutions, or as variable values for each month. In our case measurement uncertainties were integrated into the real and artificial discharge series of average monthly discharges variably, separately for each month. It means that each month corresponded one value of the relative uncertainty referred to in Table 1.

Uncertainties of reservoir storage capacity determined from real and artificial discharge series have been changing with increasing improved outflow O_p. In terms of absolute values of the uncertainty it is possible to see the increase of uncertainty with the corresponding increase of improved outflow O_p and reservoir storage capacity V_z. Even if there are some cases that occur in the results when the values of absolute uncertainty of reservoir storage capacity do not change with the increasing value of improved outflow O_p. This phenomenon is caused by the method of the reservoir storage capacity calculation, which results from basic equation of reservoir in the summative form. It can be generally stated that the average relative standard and relative extended uncertainty of the reservoir storage capacity varies on the values u_{Vz} = ±0.263% and U_{Vz} = ±0.789 % at the storage capacity determined from real discharge series. The standard uncertainty in the reservoir storage capacity determined from artificial discharge series for generator LTAR was u_{Vz} = ± 0.483% and the expanded uncertainty was U_{Vz} = ± 1.449% for the generator LTMA was standard uncertainty u_{Vz} = ± 0.391% and the expanded uncertainty was U_{Vz} = ± 1.174%.

The above-mentioned results should be accepted. The question is how to present the results of uncertainties of the reservoir storage capacity or rather what way of the implementation of uncertainties is generally acceptable.

From the results it is obvious that the impact of uncertainties of members of real and artificial discharge series on the values of reservoir storage capacity is not insignificant. So how the individual input series are implemented into the solution by Monte Carlo method not only by means of one value, but the range of randomly generated input series, also the calculated storage volume is described by the range of storage volumes whose range of scatter is significant. Currently, the used hydrological reliability of solutions (assurance of improved outflow from the reservoir) in the Czech standards is recommended to consider the values from 95% to 99.5% (according to the importance of the water user for the society). It is obvious that the outlined procedure will strongly deform actually achieved hydrological reliability of the solution. The above-mentioned problem could be avoided by the fact that from the spectrum of storage capacities only the highest storage capacity will be considered which corresponds to the uncertainty U_{Vz} that will be considered as value $\mu(V_z) + U_{Vz}$. Obviously, more accurate solution is an introduction of uncertainties of the primary inputs directly into the solution with using the different types of water management solution storage reservoir function when considering the hydrological reliability less than 100% and dealing with it by outlined working process.

The described method of the uncertainty incorporation into the determination of values of the average monthly discharges as well as its follow-up implementation into the related calculations of the reservoir storage capacity is universal. It can be used at various hydrometric gauging station and different types of measuring instruments which measuring of water stages and discharges is realized with. Currently, the mentioned procedure of deriving the uncertainty of average monthly discharge is based on the use of more algorithms and the calculation is time consuming. The authors try to automatize the whole process of the calculation more so that the calculations could be more effective and applicable to other hydrometric gauging station with varying water bearing and the length measurement.

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