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V.I. Elfimov, H. Khakzad
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AN ALTERNATIVE APPROACH TO ASSESSING FEASIBILITY OF FLUSHING SEDIMENT FROM RESERVOIRS

Effective parameters on feasibility of sediment flushing through reservoirs include hydrological, hydraulic, and topographic properties of the reservoirs. In this study, the performances of the Decision tree forest (DTF) and Group method of data handling (GMDH) for assessing feasibility of flushing sediment from reservoirs, were investigated. In this way, Decision tree Forest, that combines multiple Decision tree, used to evaluate the relative importance of factors affecting flushing sediment. At the second step, GMDH deployed to predict the feasibility of flushing sediment from reservoirs. Results indicate that these models, as an efficient novel approach with an acceptable range of error, can be used successfully for assessing feasibility of flushing sediment from reservoirs.

Key words: flushing, sediments, reservoirs, Decision tree forest, Group method.

1. *Introduction*

Sediment deposition in reservoirs causes loss of capacity, increased flood risks, degradation of water quality, boosted difficulty in reservoir operation, maintenance and consequent increased in their associated cost. Besides, this sediment storage can hold significant implications for ecosystem downstream of large river systems. Substantial sedimentation problems experienced within many national and international reservoirs, making sediment management in reservoirs a widespread problem.

The substantial environmental and economic costs of restoring storage capacity by building a new dam are prompting a shift in the paradigm toward managing existing projects as renewable resources. Potential alternatives can be sub-divided into four general concepts as follows:

1) Watershed rehabilitation; 2) Sediment routing and bypass; 3) Sediment removal and flushing; 4) Compensate for Sediment Accumulation in Reservoir.

Consideration of technical feasibility, environmental concerns and economic factor should be used in combination with alternatives to extend the useful life of reservoirs. The cost and applicability of each strategy will vary from one site to another and study of sites, will appreciate the complexity of sediment problems and the way they can be controlled.

Reducing a sediment yield with a watershed management program based on environmental concerns is the best alternative for decreasing the rate of reservoir sedimentation. However, erosion control only cannot achieve the sediment balance required to stabilize reservoir storage capacity and achieve sustainable use.

Sediment routing partially preserves the natural sediment-transport characteristics of the river, whereas flushing usually changes these characteristics dramatically. A major disadvantage of sediment routing is that a significant amount of water released sediment transport during flood events to transport sediments. Sediment routing is most applicable to hydrologically small reservoirs where the water discharged by large sediment-transporting floods exceeds reservoir capacity, making water available for sediment release without infringing on beneficial uses. The bypass of flood flow and sediment from entering the reservoir requires certain topographic and flow conditions, and this method is unsuitable for removing sediment.

Flushing is one of the most economical methods, which allows recovering the lost storage without incurring the cost of dredging. Hydraulic flushing can be an effective mechanism for removing sediments, emptying the reservoir through low-level outlets, and allowing natural, flows to scour out deposits. However, many reservoirs cannot be removed from service for flushing and in many cases flushing cannot maintain the original reservoir volume. Flushing also releases large volumes of sediment downstream creating potentially serious problems, including interference with water intakes, increased sediment loading on downstream reservoirs, and negative impacts on fisheries, the environment, and recreational uses.

Every Reservoir of the world cannot be flushed successfully due to the number of parameters affecting it, like flatter bed slope, wider section, greater height of the dam and availability of water for flushing (Muhammad A.C. and Habib U.R., 2012) [1]. In the present study, which was carried out at 14 reservoirs, based on hydraulic parameters, a model was suggested to predict feasibility of flushing sediment from reservoirs. This paper is prepared as follows: Section 2 describes the worldwide experience of sediment flushing through reservoirs and data set. Section 3 describes Decision tree forest (DTF) and Group method of data handling (GMDH). Section 4 gives the description of results and statistical error analysis and Section 5 covers the summary and conclusions.

2. Material

2.1. Worldwide Experience of Sediment Flushing Through Reservoirs

Flushing is the scouring out of deposited sediment from reservoirs through the use of low level outlets in a dam to lower the water levels, and so to increase the flow velocities in the reservoir. The first time a flushing is done, a channel will form in the deposited material, and the next times this channel will be maintained by the flushing flows (Morris and Fan, 1997) [2].

The oldest known practice of flushing was referred to by D'Rohan (1911), who described the method practiced in Spain in the 16th century, where bottom-outlet gates known as the Spanish gates or undersluices were used [3]. For the last 6 decades, the study reveals that there are about 50 reservoirs which are flushed. Among the 50 flushed reservoirs 42 reservoirs are desilted by flushing mode, 3 reservoirs by flushing along with routing, 2 reservoirs by flushing along with density current venting, 2 reservoirs by flushing along with routing and density current venting, 1 reservoir by density current venting aided by flushing (White W.R., edt. 2000) [4]. A number of attempts at sediment flushing have been reported in the literature, but only some have proved successful. Every Reservoir of the world cannot be flushed successfully due to the number of parameters affecting it like flatter bed slope, wider section, greater height of the dam and availability of water for flushing. Flushing experiences of successfully and unsuccessfully flushed reservoir are given in Tab. 1—2, respectively (White W.R., edt. 2000) [4].

Tab. 1. Successfully flushed reservoirs

No.	Reservoir	Country	Capacity (Mm^3)	Flushing Experience
1	Baira	India	2.4	Used diversion tunnel, clearing 0.38 Mm^3 in 40 hours, interruption to generation, annual flushing thereafter
2	Gebidem	Switzerland	9.0	Reservoir emptied for 2—4 days per year and about 3 Mm^3 water was used, virtually no sediment accumulation, because of gorge-type and annual flushing
3	Gumend	Austria	0.93	Flushing undertaken intermittently between 1946—1960 and annual flushing thereafter
4	Hengshan	China	13.3	3.19 Mm^3 deposition between 1966—1973. Emptied and flushed for 37 days in 1974, removing 0.8 Mm3 of deposits; 52 days flushing in 1979 removed 1.03 Mm^3 deposits
5	Palagnedra	Switzerland	5.5	1978 flood caused 1.08 Mm^3deposition, flushing between November 1978 to March 1979 removed 2.4 Mm^3 deposits, virtually full capacity of reservoir can be maintained in the long term
6	Santo Domingo	Venezuela	3	Only one flushing operation in May 1978, after 4 years of operation and flushed 50—60 % of deposition in 3 days. Concluded that flushing should be annual

Tab. 2. Unsuccessfully flushed reservoirs

No.	Reservoir	Country	Capacity (Mm^3)	Flushing Experience
1	Guanting	China	2270	Only one flushing operation in 1954, removing 10 % of annual flow, partly venting by density current
2	Guernsey	USA	91	Attempted in four years 1959—1962, but not considered effective, as recovered less than 0.2 % of the original capacity of reservoir
3	Heisonglin	China	8.6	From 1962, density current venting and flood season sluicing reduced trap efficiency to about 15 %; lateral erosion technique successfully implemented from 1980, recovering some lost storage; long term capacity expected to be 30—35 % of original
4	Ichari	India	11.6	No bottom outlet built for flushing and reservoir flushed annually by fully opening spillway gates
5	Ouchi-Kurgan	Former USSR	56.4	Sluiced for 3—4 months annually since 1963

End of Tab. 2.

No.	Reservoir	Country	Capacity (Mm^3)	Flushing Experience
6	Sanmenxia	China	9640	Rehabilitation from 1966 included construction of larger low level outlets; flushed for 4 months annually; six development stages are described in literature
7	Sufid-Rud	Iran	1760	Flushing (about 4 months/year) commenced in 1980; after 7 years 26 % of lost storage had been recovered; from 1992 flood plain erosion enhanced using diversion channels; expected that long term capacity could be up to 90 % of original reservoir capacity
8	Shuicaozi	China	9.6	Implemented experimentally from 1965; but limited by high elevation of spillway and short duration annually to about one third of inflow

2.2. Existing Flushing Criteria

Criteria for determining whether flushing at a particular reservoir will be successful are required. There are two key requirements for effective flushing; first, the sediment quantities transported through the low level outlets during flushing are sufficient to enable a long term balance between the sediment inflow and the sediment flushed, and second the volume of deposits remaining in the reservoir after a sediment balance has been achieved is sufficiently small to enable a specified storage requirement to be met. These criteria depend on the hydraulic efficiency of flushing. By applying these criteria, the reservoirs, at which flushing might be viable, can be identified. The hydraulic efficiency of flushing can be defined in several ways. Some definitions are shown in tab. 3.

In this paper, we concerned the sediment balance and the ratio between useful storage capacity that can be maintained in reservoir and a substantial proportion of the original capacity, as criteria to predict the feasibility of flushing sediment from reservoirs. For this purpose, the main criteria such as the sediment balance ratio (SBR), the long term capacity Ratio (LTCR), the draw down ratio (DDR), flushing width ratio (FWR), reservoir top width ratio (TWR), capacity inflow ratio (C/I) and sediment potential (SP) are used. These criteria are defined as the following (Atkinson 1996) [8]:

$$\text{SBR} = \frac{\text{sediment mass flushed annually}}{\text{sediment mass depositing annually}}; \quad (1)$$

$$\text{LTCR} = \frac{\text{sustainable capacity}}{\text{original capacity}}; \quad (2)$$

$$\text{DDR} = 1 - \frac{\text{flow depth for the flushing wather level}}{\text{flow depth for the normal impounding level}}; \quad (3)$$

$$\text{FWR} = \frac{\text{predicted flushing width}}{\text{representative bottom width reservoir}}; \quad (4)$$

$$\text{TWR} = \frac{\text{top width of scoured valley}}{\text{actual top width}}; \quad (5)$$

$$\text{C/I} = \frac{\text{original storage capacity}}{\text{mean annual water inflow volume}}; \quad (6)$$

$$\text{SP} = \frac{\text{mean annual sediment inflow}}{\text{original storage capacity}}. \quad (7)$$

Tab. 3. Different definitions of flushing efficiency

Efficiency expression	Author
$E = V_o / V_d$	Qian (1982) [5]
$E = L_o / L_i$	Ackers and Thompson (1987) [6]
$E = (V_2 - V_1) / V_o$	Mahmood (1987) [7]
$E = (V_2 - V_1) / V_{ori}$	Mahmood (1987) [7]
$E = Tr / (1 - Tf)$	Mahmood (1987) [7]
$E = L_o / L_d$	Atkinson (1996) [8]
$E = (V_{so} - V_{si}) / V_o$	Lai and Shen (1996) [9]
$E = (V_o C_o - V_i C_i) / (\rho V_o)$	Morris and Fan (1997) [2]

Note: C_i is total sediment concentration of inflow [kg m^{-3}]
C_o is total sediment concentration of outflow [kg m^{-3}]
E is flushing efficiency
L_d is annual quantity of sediment deposited [kg]
L_i is annual quantity of sediment inflow [kg]
L_o is annual quantity of sediment flushed out [kg]
T_f is fraction of year used for flushing
T_r is fraction of year that the river's sediment load will take to refill $V_2 - V_1$
V_d is volume of deposit flushed out [m^3]
V_i is inflowing water volume [m^3]
V_o is outflowing water volume [m^3]
V_{ori} is original live capacity of the reservoir [m^3]
V_{so} is outflowing sediment volume during flushing [m^3]
S_{si} is inflowing sediment volume during flushing [m^3]
V_1 is storage capacity of reservoir before flushing [m^3]
V_2 is storage capacity of reservoir after flushing [m^3]
ρ is bulk density of deposit [kg m^{-3}]

3. Method

3.1. Decision tree forest

A Decision tree forest (DTF) can be used to evaluate the sensitivity of parameters or parameter combinations. A DTF is an ensemble of single decision trees (SDTs), predictions of which are combined to make the overall prediction for the forest (Fig. 1). In DTF, a large number of independent trees are grown in parallel, and they do not interact until after all of them have been built (Kunwar, 2013) [10]. Bootstrap resampling method (Efron, 1979) [11] and aggregating are the basis of bagging, which is incorporated in DTF.

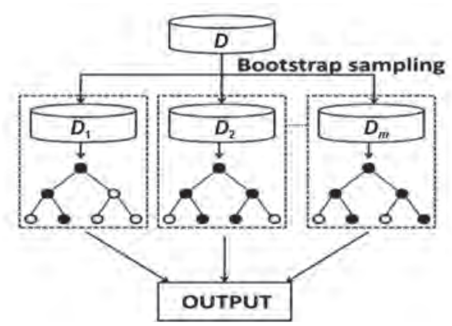

Fig. 1. Conceptual diagram DTF

Different training sub-sets are drawn at random with replacement from the training data set. Separate models are produced and used to predict the entire data from aforesaid sub-sets. Then various estimated models are aggregated by using the means for regression problems or majority voting for classification problems. Theoretically in bagging, first a bootstrapped sample is constructed as (Erdal and Karakurt, 2013) [12]:

$$D_i^* = \left(Y_i^*,\ X_i^*\right), \tag{8}$$

where D_i^* is a bootstrapped sample according to the empirical distribution of the pairs $D_i = \left(X_i,\ Y_i\right)$, where ($i$ = 1, 2, ..., n). Secondly, the bootstrapped predictor is estimated by the plug-in principle.

$$C_n^*(x) = h_n\left(D_1^*,\ \ldots,\ D_n^*\right)(x), \tag{9}$$

where $C_n(x) = h_n\left(D_1,\ \ldots,\ D_n\right)(x)$ and h_n is the nth hypothesis Finally, the bagged predictor is:

$$C_{nB}(x) = E^*\left[D_n^*(x)\right]. \tag{10}$$

Bagging can reduce variance when combined with the base learner generation with a good performance (Wang et al., 2011) [13]. The DTFs gaining strength from bagging technique use the out of bag data rows for model validation. This provides an independent test set without requiring a separate data set or holding back rows from the tree construction. The stochastic element in DTF algorithm makes it highly resistant to over-fitting.

Statistical measures such as the Coefficient of variation (CV), the Normalized mean square error (NMSE), the Correlation between actual and predicted, Root Mean Squared Error (RMSE) and Mean Squared Error (MSE) were employed for qualitative evaluation of the models.

3.2. Group method of data handling (GMDH)

GMDH is a learning machine based on the principle of heuristic self-organizing, proposed by Ivakhnenko in the 1960s. It is an evolutionary computation technique, which has a series of operations such as seeding, rearing, crossbreeding, and selection and rejection of seeds corresponding to determination of the input variables, structure and parameters of model, and selection of model by principle of termination (Ivahnenko AG. 1971) [14]. In fact, the GMDH network is a very flexible algorithm, and it can be hybridized by using evolutionary and iterative algorithms such as genetic algorithm (GA), genetic programming (GP), particle swarm optimization (PSO), and back propagations. The previous researches established that hybridizations were successful in finding solutions of the problems in different fields of engineering. By means of GMDH algorithm, a model can be represented as a set of neurons, in which different pairs of them in each layer are connected through quadratic polynomial and thus produce new neurons in the next layer. Such representation can be used in modeling to map inputs to outputs. The formal definition of system identification problem is to find a function $\hat{f}$ that can be approximately used instead of actual function f, in order to predict the output $\hat{y}$ for a given input vector $X = \left(x_1,\ x_2,\ \ldots,\ x_n\right)$ as close as possible to its actual output y. Therefore, given n observation of multi input single-output data pairs so that:

$$y_i = f\left(x_{i1}, x_{i2}, x_{i3}, \ldots, x_{in}\right) \ \left(i = 1, 2, \ \ldots, M\right). \tag{11}$$

It is now possible to train a GMDH network to predict the output values $\hat{y}_i$ for any given input vector $X = \left(x_{i1}, x_{i2}, \ldots, x_{in}\right)$ that is

$$\hat{y}_i = \hat{f}\left(x_{i1}, x_{i2}, x_{i3}, \ldots, x_{in}\right) \ \left(i = 1, 2, \ \ldots, M\right). \tag{12}$$

In order to solve this problem, GMDH builds the general relationship between output and input variables in the form of mathematical description, which is also called reference. The problem is now to determine a GMDH network so that the square of difference between the actual output and the predicted one is minimized, that is:

$$\sum_{i=1}^{M}\left[\hat{f}\left(x_{i1}, x_{i2}, x_{i3}, \ldots, x_{in}\right) - y_i\right]^2 \rightarrow \min. \tag{13}$$

General connection between inputs and output variables can be expressed by a complicated discrete form of the Volterra function a series in the form of:

$$y = a_0 + \sum_{i=1}^{n} a_i x_i + \sum_{i=1}^{n}\sum_{j=1}^{n} a_{ij} x_i x_j + \sum_{i=1}^{n}\sum_{j=1}^{n}\sum_{k=1}^{n} a_{ijk} x_i x_j x_k \tag{14}$$

which is known as the Kolmogorov — Gabor polynomial (Farlow SJ etd. 1984) [15]. The polynomial order of PDs is the same in each layer of the network. In this scenario, the order of the polynomial of each neuron (PN) is maintained the same across the entire network. For example, let's assume that the polynomials of the PNs located at the first layer are those of the second order (quadratic):

$$\hat{y} = G\left(x_i, x_j\right) = a_0 + a_1 x_i + a_2 x_j + a_3 x_i x_j + a_4 x_i^2 + a_5 x_j^2. \tag{15}$$

Here, all polynomials of the neurons of each layer of the network are the same, and the design of the network is based on the same procedure. The second-order polynomial is fundamental structure of the GMDH network that has been proposed by Ivakhnenko. Generally, different types of polynomial such as bilinear, quadratic, triquadratic, and third order are used to design self-organized systems. The use of tri-quadratic and third-order polynomial can generate more complicated network in comparison with quadratic polynomial. Bilinear polynomial produces lower complicated structure in comparison with quadratic polynomial. Quadratic polynomial has six weighting coefficients that generated good results in engineering problems. Based on the previous investigations, selection of polynomials could depend on minimum error of objective function and complexity of polynomial type. In this study, quadratic polynomial was utilized for modeling of scour depth around different types of bridge pier. The weighting coefficients in Eq. (14) were calculated using regression techniques so that the difference between actual output, y, and the calculated one, $\hat{y}$, for each pair of x_i; x_j as input variables was minimized. In this way, the weighting coefficients of quadratic function G_i were obtained to optimally fit the output in the whole set of input-output data pair, that is:

$$E = \frac{\sum_{i=1}^{M}\left(y_i - G_i()\right)^2}{M} \rightarrow \min. \tag{16}$$

4. Results and discussions

In this study, we made a thorough study on the feasibility of flushing sediment from reservoirs. We used Equation 1 to 7 and tested them on flushing at several reservoirs around the world. To find the model to predict whether flushing can be considered a feasible alternative for sediment management, based on equations

1 to 7, firstly, SBR, LTCR, DDR, FWR, TWR, C/I and SP, for 14 reservoirs (tab. 1—2) have been calculated. By using these criteria, long-term balance between the sediment inflow and the sediment flushed, the volume of sediment remaining in the reservoir compared with the storage requirement, the cost of flushing compared with the benefits, the degree of water-level drawdown and its effect on sediment balance, the width of the channel formed, and steepness of the side slopes; a determination can be made whether flushing is feasible or not (Atkinson, 1996) [8]. Table 4 shows the values of these criteria at several reservoirs.

Tab. 4. The values of criteria in several reservoirs

Reservoir Name	Country	Initial Capacity (Mm^3)	SBR Value	LTCR Value	DDR Value	FWR Value	TWR Value	C/I	SP	Estimated Long Term Capacity
Baira	India	9.6	7	0.85	0.68	3.4	1.6	0.005	0.032	0.85
Gebidem	Switzerland	9	7	0.99	0.93	6.7	1.5	0.022	0.055	1
Gmund	Austria	0.93	21	0.98	0.89	5.2	1.3	0.0046	0.21	0.86
Hengshan	China	13.3	3	0.77	0.77	0.1	7.1	0.841	0.088	0.75
Palagnedra	Switzerland	5.5	33	1	1	1.4	1	0.018	0.014	1
Santo Domingo	Venezuela	3	11	1	1	1.4	1.8	0.007	0.066	0.97
Guanting	China	2.27	0.2	0.2	0.81	0.04	0.5	0.037	0.026	0.1
Guernsey	USA	91	1	0.26	0.44	1.4	0.26	0.043	0.018	0.03
Heisonglin	China	8.6	0.7	0.3	0.77	0.06	0.8	0.61	0.081	0.28
Ichari	India	11.6	7	0.36	0.31	9.9	1.4	0.0035	0.49	0.35
Ouchi-Kurgan	USSR	56	7	0.1	0.14	2	0.3	0.037	0.23	0.14
Sanmenxia	China	9.64	3.4	0.39	0.75	0.26	0.9	0.22	0.166	0.31
Sefid- Rud	Iran	1.76	4	0.13	0.96	0.3	0.1	0.352	0.028	0.26
Shuicaozi	China	9.6	4.6	0.39	0.37	1	2.1	0.018	0.065	0.28

Secondly, by the decision tree forest (DTF) method, relative importance of variable on estimated long term capacity has been assessed. Tab. 5 and fig. 2 show that long term capacity ratio (LTCR) and reservoir top width ratio (TWR) are most important on estimated long term capacity in 14 reservoirs.

Tab. 5. Relative importance of variables on estimated long term capacity

Variable	Importance
LTCR	100
TWR	59.771
SBR	44.715
DDR	30.997
C/I	27.337
FWR	19.991
SP	13.305

Note: Coefficient of variation (CV) = 0.407810
Correlation between actual and predicted = 0.861061
Normalized mean square error (NMSE) = 0.348612
RMSE (Root Mean Squared Error) = 0.2091484
MSE (Mean Squared Error) = 0.043743

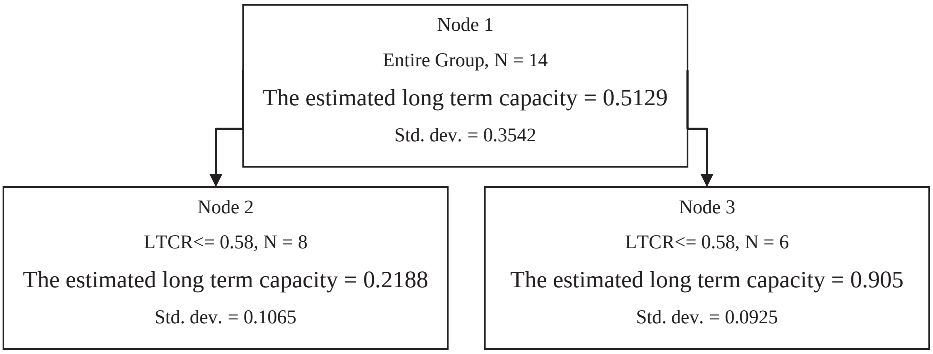

Fig. 2. Result of single decision tree to predict the estimated long term capacity
Note: Coefficient of variation (CV) = 0.196400
Correlation between actual and predicted = 0.95872
Normalized mean square error (NMSE) = 0.080855
RMSE (Root mean squared error) = 0.1007251
MSE (Mean Squared Error) = 0.0101455

And finally, the steps discussed above are used to design GMDH model to predict the feasibility of flushing sediment from reservoirs. Based on the tab. 5, the parameters of interest in this model, which affects the estimated long term capacity are LTCR, TWR, SBR, DDR, C/I. Equation 17 and Fig. 3 show the results of this method to predict the estimated long term capacity.

$$\text{The estimated long term capacity} = \text{LTCR} \times 0.9369 + \text{SBR} \times \times \text{TWR} \times -0.002104 + \text{SBR} \times \text{DDR} \times 0.002983 + \text{SBR} \times \text{C/I} \times \times 0.06031 + \text{DDR} \times \text{C/I} \times -0.09653. \tag{17}$$

MAE 0.07449, RMSE 0.07449, Correlation between actual and predicted = = 0.9774.

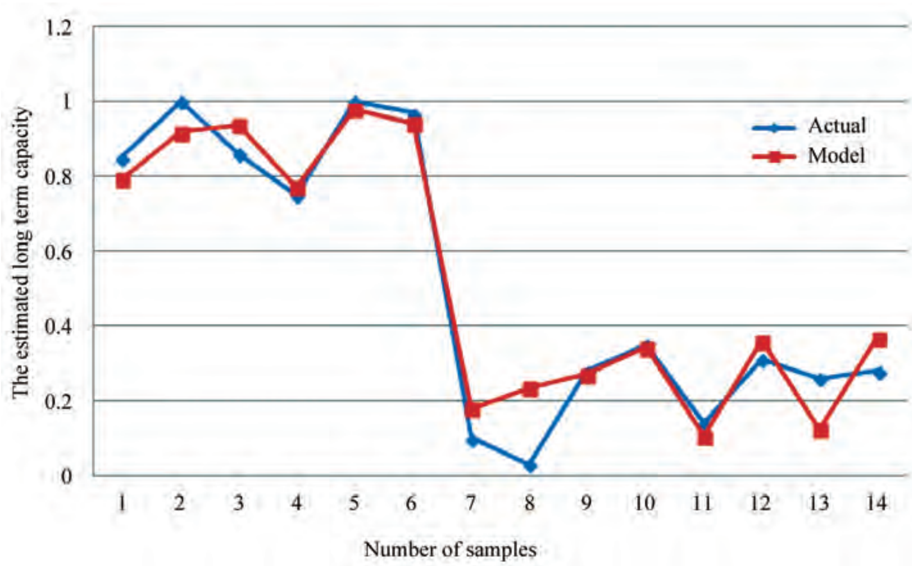

Fig. 3. Results of GMDH considering the LTCR, TWR, SBR, C/I and DDR values in 14 reservoirs

Fig. 3 shows that the data fit tightly around the GMDH values and the model provide precise prediction capability. Regression analysis performed on actual and GMDH values resulted in a strong positive correlation with a R^2 around of 0.97. In addition, in contrast traditional methods such as Atkinson method (1996), this model could assessment long term capacity in reservoirs.

5. Conclusions

In this study, Decision tree forest (DTF) and Group method of data handling (GMDH), were used successfully for prediction of the feasibility of flushing sediment from reservoirs based on the sediment balance ratio (SBR), the long term capacity Ratio (LTCR), the draw down ratio (DDR), flushing width ratio (FWR), reservoir top width ratio (TWR), capacity inflow ratio (C/I) and sediment potential (SP). In this way, it has been shown that DTF and GMDH, provide effective means to model and predict the estimated long term capacity according to different reservoirs. By means of DTF model, some important facts in the estimated long term capacity have been obtained and proposed basing on GMDH model. Further, in contrast to traditional methods to predict the feasibility of flushing sediment, DTF and GMDH model could assess relative importance of variables and provide a reliable estimate to predict it.

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About the authors: **Elfimov Valeriy Ivanovich** — Candidate of Technical Sciences, Associate Professor, Department of Hydraulics and Hydraulic Engineering Structures, **Peoples Friendship University of Russia (PFUR)**, 6 Miklukho-Maklaya str., Moscow, 117198, Russian Federation; +7 (495) 9520831; elfimov370@rambler;

Khakzad Hamid — postgraduate student, Department of Hydraulics and Hydraulic Engineering Structures, **Peoples Friendship University of Russia (PFUR)**, 6 Miklukho-Maklaya str., Moscow, 117198, Russian Federation; +7 (495) 9520831; khakzad.hamid@mail.ru.

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В.И. Елфимов, Х. Хакзад

АЛЬТЕРНАТИВНЫЙ ПОДХОД К ОЦЕНКЕ РАБОТОСПОСОБНОСТИ ПРОМЫВКИ ВОДОЕМОВ ОТ ОСАДОЧНЫХ ОТЛОЖЕНИЙ

Параметры эффективности процесса промывки водоемов включают гидрологические, гидравлические и топографические качества водоемов. Исследованы древовидная схема решений и групповой метод обработки данных для оценки работоспособности очистки водоемов от осадков. Древовидная схема решений соединяет в себе разветвленную схему решений, используемых для оценки относительной важности факторов, влияющих на процесс очищения. На следующей ступени задействуется групповой метод для прогноза эффективности очищения резервуаров от осадков. Результаты исследования показывают, что эти модели как эффективный новый подход с допустимым количеством неточностей могут быть успешно использованы для оценки очищения водоемов от осадочных отложений.

Ключевые слова: промывка, осадочные отложения, водоемы, древовидная схема решений, групповой метод.

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Об авторах: **Елфимов Валерий Иванович** — кандидат технических наук, доцент кафедры гидравлики и гидротехнических сооружений, **Российский университет дружбы народов (ФГБОУ ВПО «РУДН»)**, 117198, г. Москва, ул. Миклухо-Маклая, д. 6, 8 (495) 952-08-31, elfimov370@rambler;

Хакзад Хамид — аспирант кафедры гидравлики и гидротехнических сооружений, **Российский университет дружбы народов (ФГБОУ ВПО «РУДН»)**, 117198, Москва, ул. Миклухо-Маклая, д. 6, 8 (495) 952-08-31, khakzad.hamid@mail.ru.

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