Simulation of hydrological regimes of a river with a specified roughness coefficient

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Abstract. The result of simulating the hydrological regimes of the river in the Mike11 software and predicted the flush of water to the reservoir dam due to a theoretical study of existing methods for calculating the roughness coefficient on a river section, verification of the coefficient using mathematical modeling of the river outflow, clarifying the method of calculating the roughness coefficient are presented in the paper. It is shown that water level in the river has positively associated connection to the roughness coefficient. The highest water level in the lower reaches of the river will be achieved in the case of calculating the roughness coefficient using the Manning formula.

1. Introduction

Problem of forecasting and simulating natural and man-made disasters is one of the most important and relevant nowadays. In particular, the risk of emergency situations associated with the flooding of territories remains very high, the number of victims and the economic damage caused by floods continue to increase [1]. At the same time, it is no longer possible to achieve high quality and speed of work on simulating the prediction of natural processes and phenomena without automation aids, as well as the associated emergency situations. Geo-information systems ideally cover this requirement [2].

The following methods are possible for simulating a breakthrough wave: physical experiment, laboratory experiment, numerical computer simulation. Numerical simulation of breakthrough waves can be divided into one-dimensional, two-dimensional and three-dimensional modeling. So one-dimensional modeling does not give accurate results and does not allow to derive two-dimensional results, but it is the fastest. One-dimensional modeling is carried out, for example, in the software product MIKE11 [3]. Two-dimensional and three-dimensional modeling in existing software systems, such as, for example, MIKE21, Flow Vision, requires high-class specialists and high-performance computers [4].

Estimation of the quality and accuracy of simulation the progress of a breakthrough wave along a river course is a complicated issue. Using any of the methods, only approximate data about the flooded areas resulting from the passage of a breakthrough wave is obtained. The accuracy of the obtained results is difficult to estimate. One of these reasons is the difference in the methods of models calibration [5]. To calibrate such models, we use the selection of roughness coefficients, which allows us to bring the model closer to actual conditions.
2. The Roughness coefficient of the rivers and canals

In the canals of the large cross section channels, a large number of factors that cause changes in the values of roughness coefficient $n$ and hydraulic friction coefficients can be identified.

The factors affecting the value of the roughness coefficient of the earthen canals of the channels will be listed.

1) Surface roughness [6] — characterized by the shape and size of the grains of the material composing the channel along the wetted perimeter and exerting a braking effect on the flow. This factor is often regarded as the only one when choosing a roughness coefficient, but in reality it is one of many important factors.

2) Vegetation — can be considered as a kind of roughness surfaces [7], which at the same time reduces the channel capacity and inhibits movement.

Based on experimental and field studies [8], a formula for determining the roughness of an overgrown canal without weed was proposed:

$$n = n_0 \sqrt{1 + \frac{R^3}{2g \sigma_n^2} \left[ C_D \bar{d} \left( N + \sigma_n \sqrt{2 \ln \frac{V_0}{P_N}} \right) \right]^2},$$

where

- $n_0$ — roughness coefficient without vegetation;
- $R$ — hydraulic flow radius;
- $\bar{d}$ — average plant diameter;
- $C_D$ — vegetation drag coefficient;
- $\sigma_n$ — mean square deviation of plant density;
- $N$ — average plant density per 1 m$^2$;
- $P_N$ — vegetation Gauss distribution.

1) Channel heterogeneity — consists in the heterogeneity of the shape of the wetted perimeter and changes in the shape of the channel cross-section (size and shape) along its length. Depending on the heterogeneity of the channel, the roughness coefficient may increase to 0.0005 or more.

2) Channel alignment — a smooth curvature with a large radius of curvature gives a low value of $n$, while a sharp curvature increases the value of $n$. Based on the tests in trays, it was established [9] that the value of $n$ is increased by 0.0001 for every 200 curvature per 100 meters of the channel length.

3) Siltation and erosion — silting can turn a very homogeneous channel into a relatively homogeneous and reduce $n$, while erosion, on the contrary, can increase $n$.

4) Hindrance — the existence of ridge agglomerate, bridge abutments and other hindrances causes an increase of $n$.

5) Dimensions and shape of the channel — the hydraulic radius increase may increase or decrease $n$, depending on the channel’s condition.

6) Water level and flow rate — in most channels, an increase in water level and flow rate cause a decrease of $n$.

For channels without canals lining n coefficients vary in a relatively small range of 0.02–0.04.

The table of coefficients $n$ is famous in the USA — compiled [10], it is a generalization of data available in the United States of various authors. For channels in the soil, a very large range of $n$ is given, in particular, 0.016–0.14. This is explained by the fact that $n$ values are given for channels that are not supported under normal operating conditions, for example, when both grass and bushes are not cleared.

A major contribution to the establishment of norms of resistance to movement made [11]. He proposed a table of coefficients $n$, which became the most popular in the USSR; later the he published new tables of roughness coefficients for rivers, calling them a classification of rivers by resistance. Fundamentally correct point of view of N.N. Pavlovsky [12] about the inconsistency of the indicator $y$ in the formula for the Chezy coefficients [13] is reflected in this tables and this is a distinctive and
important feature of the tables. Values of the indicator $y$, varying from 0.16 to 0.50 are given in tables [11]. The international standard [14] contains a table of coefficients $n$, varying from 0.019 to 0.20.

The question of individual assessment of factors affecting hydraulic resistance is not removed. For example, [15] a dependency was proposed:

$$n = \sqrt{n_0^2 + n_1^2 + n_2^2 + n_3^2 + n_4^2}$$

where

- $n_0$ – coefficient of roughness of the channel with a uniform surface of natural material;
- $n_1$ – coefficient taking into account the heterogeneity of the surface;
- $n_2$ – coefficient taking into account the change in the length of the shape and size of the section;
- $n_3$ – coefficient taking into account the influence of local resistance;
- $n_4$ – coefficient taking into account the influence of vegetation;

The question of the turbidity effect on the magnitude of hydraulic resistance and roughness has been discussed for a relatively long time. There is a decrease in the roughness coefficient with increasing turbidity.

Special hydrobiological studies [8] were established that the presence of hard coatings (concrete linings) contributes to a more intensive development of weed (phytobenthos), due to a decrease in the self-cleaning ability of the canal. In addition, the weed growth is influenced by the following factors: water transparency, flow rate, channels cleaning, the presence of biogenic substances in water and soils.

The problem of hydraulic resistance of lined canals is closely related to the reliability of linings, their durability. Monographs [16] are devoted to the operational reliability of hydraulic structures, and, consequently, channels. The state of linings surfaces change depending on its working conditions. Cracks, which increase the roughness coefficient, may appear.

In [8], there is a significant variability of the roughness coefficient of the lined canals, which, in his opinion, is associated with disorder of joints, destruction, siltation under the influence of vegetation and weed lead to a significant loss of energy. These changes in hydraulic efficiency really turn them into unlined canals, as mentioned above, with characteristic processes of siltation and overgrowing.

To establish the minimum flow rate that does not cause the siltation of concrete canals, the formula [8] was proposed by the author:

$$V_{\text{max}} = V_{\text{no_silt}} \left[ 1 + 0.141 \sqrt{\frac{0.707 \lambda_T}{\ln P}} \right]$$

where

- $V_{\text{no_silt}}$ – water speed with does not causes the siltation;
- $T$ – channel operation time;
- $P$ – siltation probability of the channel.

Thus, the analysis of many dependencies to determine the values of $n$ and $\lambda$ showed that, despite large number of methods, there are areas in which the changes in roughness are still studied not so deeply. A large number of dependencies for determining $n$ non-uniform around the perimeter are given by authors, but in practice the values of $n$ may vary along the length of the channels.

3. Simulation of hydrological regimes of the river in MIKE11 software

The stretch of the Eshkakon River is considered in the paper [17]. The canal of the river is located 123 km along the right bank of the Podkumokriver. The length of the river is 344 km. At this site in the area of the dam, it is necessary to increase the efficiency of surface water treatment sent for water supply to the Kislovodsk city.
In case of unsteady water movement along a river channel or along a channel, the flow characteristics in any section change over time, and at each timepoint they are not the same along the length of the section. Unsteady movement is observed in the regulation of water flow rate in hydraulic project, and in unregulated rivers — during the passage of a flood or flood wave. Unsteady motion is a general case of motion in rivers and channels, and steady-state (uniform and non-uniform) is its particular case. The task of calculating the unsteady motion is to determine two characteristics describing the state of a one-dimensional flow (flow and depth) as a function of length and time. Other characteristics, such as flow rates, can be determined from the flow and depth values.

In this paper, the model will describe the situation of the flow augmentation of variable flow rate, fed from above. In the lower site of the river stretch is described the confluence of the channel into a large reservoir (reservoir), where the fluctuations of the water level during the estimated time (1.04.2017–25.04.2017) are minor.

In the Mike 11 software [18], the Eshkakon River stretch (figure 1), cross sections (figure 2) were simulated based on: the outlines of the boundaries of the river bed, the topography of the river bed and floodplains, hydrometric data for boundary conditions, and data on water consumption (figure 3) as initial data.

The hydraulic radius was calculated by the formula

\[ R = \frac{F}{P} = 24.18 \text{ m} \]

where

\[ F \] — square of effective cross-section, \( F = 1584.28 \text{ m}^2 \);

\[ P \] — wetted perimeter, \( P = 65.52 \text{ m} \).

Figure 1. River stretch.
One of the main parameters is the coefficient of roughness, which is laid in the model in MIKE11. This coefficient can be calculated in different ways, for example by the Manning's Formula [19]

\[ C = \frac{1}{n^\frac{1}{6}} \frac{1}{R^6} = \frac{1}{0.021^{\frac{1}{6}}} 24.18^{\frac{1}{6}} = 81.90; \]
Pavlovsky formula [12]

\[ C = \frac{1}{n} R^{y} = \frac{1}{0.021} 24.18^{0.08} = 61.44 \]

\[ y = 2.5\sqrt{n} - 0.13 - 0.75\sqrt{R} \left( \sqrt{n} - 0.10 \right) = 0.08; \]

Agroskin formula [20]

\[ C = \frac{1}{n} + 17.72\log R = \frac{1}{0.021} + 17.72\log 24.18 = 72.13 \]

4. Results and discussion

Based on the roughness coefficient calculations, the river stretch was modeled in the MIKE11 software. Mannings formula was taken as the basic one. The change in water level in the canal profile with the calculated roughness coefficient at the extreme sections of the selected river stretch is schematically shown on figure 4. It is obvious that along the course of the river, the difference in water level can reach 1.5 meters: at the initial river stretch, the water level was 7.8 m, and at the final river stretch — 6.4 m.

Figure 4. Water flow in the canal profile with a calculated roughness coefficient.

Figure 5. Water flow with a calculated roughness coefficient.
The change in the water level in a river with distance along its course in the canal is more clearly shown in figure 5. A sharp decrease in the current water level closer to the canal is the results of a significant increase in the roughness coefficient in this river stretch.

5. Conclusions
Thus, in this paper, the Eshkakon River stretch was simulated, the boundary and initial conditions that characterize the distribution of the flood wave during flood in April were set. The results obtained in the process of simulation are correlated with the hydrograph, in which the level of water in different sites was determined during field observations, and the initial discharge of water was recorded. Based on the foregoing, it can be concluded that the created model of the river stretch is correct.

It is shown that the water level in the river is directly proportional to the roughness coefficient. The highest water level in the lower reaches of the river will be achieved in the case of calculating the roughness coefficient using the Manning formula.

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