Two-dimensional flow movement in the area of protective regulatory structures

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Abstract. The article discusses the results of numerical studies of the flow movement with a sharp change in the parameters of the channel. Basically, the results of the study using the system of two-dimensional equations of hydrodynamics-Saint-Venant are analyzed. The divergent form of two-dimensional equations describing the movement of a water stream at a site of regulation of a channel by protective and regulatory dams is given. The influence of the length step on the results of numerical experiments is investigated numerically. Graphs of the time variation of the longitudinal velocity component behind the sudden double expansion of the channel are compiled. The flow was unsteady all the time and had the character of stationary pulsations, and the finer the grid, the richer the spectrum of these pulsations. It was noted that in numerical calculations, the time step in the calculations was always much less than the minimum pulsation period, therefore, these pulsations were not associated with difference oscillations that can arise when approximating by central differences. It is concluded that, according to the authors from the following and the present work, they collectively show that the pulsations on different grids differ significantly, the average values of the velocities are close, and thereby the solution for the average values is well converged, this shows that the pulsations are a property source equations of Saint-Venant. The applicability of the numerical model, consisting of two-dimensional shallow water equations, the vector equation of momentum conservation and the scalar equation of mass conservation, in description the flow with the presence of circulation zones, which is typical when water flows are constrained by protective-regulatory structures. In this case, the solution pulsates around a certain average value, and the average length of the circulation zone behind the sudden expansion of the open flow is in good agreement with the laboratory experiments of G.L. Mazhibits.

Key words: structures, hydrodynamics, riverbed, numerical model, protective and regulatory structures.

1 Introduction

In many watercourses of the region, a sharp change in the hydrological regime of rivers leads to a change in the nature of the interaction between the channel and the water flow. As a result of this, many difficulties arise in the operation of hydrotechnical and hydropower facilities. An example is the problem of damless water intake, deigish, the deterioration of the throughput of rivers and canals, and many others. To solve this problem in engineering practice, protective regulatory structures are often built that greatly change the plan for the flow of water in the zone of their influence. As a result of this change in the hydrodynamic characteristics of the flow, it leads to undesirable channel processes. Since the present work is devoted to determining the nature of the flow in the zone of protective and
regulatory structures, its relevance is beyond doubt. In view of the foregoing, the authors of this work selected a section of the river channel where protective and regulatory structures were built.

In practice, protective and regulatory structures of various designs are widely used to protect coasts and regulate river channels. The research, design and construction of coastal protective structures on Flood Plain Rivers have been dealt with by many researchers [1, 2]. An analysis of the literature and generalization of the results of field observations and the operation of protective and regulatory structures [3-6] show that one of the most effective ways to protect the banks and create favorable conditions for turning the wandering section of the river into a normally meandering channel is transverse dams, which belong to the class of protective and regulatory structures built from local soil. In addition, in this case there is the possibility of development and floodplain lands.

The tightness of the channel by protective and regulatory structures greatly violates the everyday flow regime. In the upper pool, a backwater area forms, while at a certain distance from the site of constraint, the water level reaches a maximum, then there is a planned and vertical compression of the stream and at a certain distance below the site of pressure, the maximum compression of the stream is observed, in the future, the water level gradually rises to household horizons. In this regard, the interaction between the flow and the structure can be divided into three characteristic areas: the backwater region (from the limited sensor to the end of the backwater), the compression region (from the limited sensor to the compressed section), the spreading region (from the compressed section to the end of the spa), from the point of view of hydraulic design, it is important for operators to obtain information about the hydrodynamic characteristics in the above areas, the dynamics of the channel morphometry, the nature of the interaction of the channel and flow. It should be noted that the study of these preparations by laboratory experiments is expensive and time consuming. Therefore, in modern practice in hydraulic engineering, methods of numerical research are increasingly being used. In addition to researchers of experimenters, representatives of computational hydraulics were involved in the study of the movement of water flow in the regulation zone by various structures. Computational hydraulics schools used the method of numerical research [9-15]. It should be noted that due to the multifactorial nature of the interaction of the water flow with the soil through which the channel passes, the problem of describing the movement of water into the river or channel has not been completed. Based on the foregoing, the purpose of the study the identification of the applicability condition for systems of two-dimensional equations of unsteady motion of a water stream during the formation of a transverse circulation in it is established [16-19].

2 Materials and methods

Analysis of the results of numerical studies of sharply changing flow movements with changes in the planned channel dimensions, numerical studies of the flow in the river channel at the site of its regulation by protective and adjustment structures located at different angles is accepted as the research method of this work.

3 Result and discussion

A detailed comparison of the results of numerical and laboratory modeling of the flow in open channels with a sharp increase in the width of the channel, characteristic of the movement of the water flow behind the blind dams, was carried out by V.M. Lyatkher and A.N. Militeev [2-4]. The results of the numerical experiments of the aforementioned researchers that are of fundamental importance in comparison with the data of laboratory experiments by B.A. Fidman are presented in figure 1[7].

In earlier works, it was noted that when numerically simulating flows in such channels using the full hydrodynamic equations of motion of the water flow in a two-dimensional formulation, taking into account convective terms, a whirlpool zone appears behind the step, observed both in physical experiments and in natural conditions; if we use simplified equations with discarded convective terms, then the flow spreads right behind the ledge, without forming a whirlpool. In addition, this is confirmed by the results of numerical experiments by M. Abbott presented in figure 2 [8]. In this work, the impossibility of realizing the hydraulic phenomena described by the Saint-Venant equations
without taking into account the friction between the jets in terms of the stationary whirlpool zone corresponding to the Kartvelishvili theorem [9] was not noted.

Figure 1. a) Comparison of the results of physical (solid line) and numerical experiments to study the flow with a sharp change in channel width. Averaged whirlpool length in the scheme of sudden expansion of the channel as a function of parameter $\lambda b/h$; 1, 2 – air pressure model $b_2/b_1=2$; 3 – hydraulic model, $b_2/b_1=1.33$; 4 – hydraulic model, $b_2/b_1=2$; 5 – calculation; b) Diagram of averaged speeds with a sudden expansion of a calm flow [7]: 1 – calculation on a frequent grid, 2 – calculation on a rare grid 3 – experiments by B.A. Fidman; c) The standard ripple of the longitudinal component of the velocity during the sudden expansion of a calm flow [7]; 1 – experiments by B.A. Fidman; 2 – calculation.
Figure 2. Numerical solution of the problem of the sudden expansion of the flow using the two-dimensional Saint-Venant equations with and without convective terms [8].

According to G.V. Stefanovich[10], who compared a large number of results of numerical and laboratory experiments of various authors (including the results of her own experiments), at sufficiently large depths of the flow, the relationship between the relative length of the whirlpool \(l/b\) and parameter \(\lambda b/h\) violated even at very small values of the Froude number. G.V. Stefanovich explains this violation by the need to take into account in this case the turbulent viscosity forces in the mathematical model. We note, however, another factor that can affect the length of the vortex: the presence of pulsations in the inlet section (inlet turbulence). In numerical experiments V.M. Lyatcher and A.N. Militeev there were no hydrodynamic quantities in the input section of pulsations. According to the research results, at shallow water depths at the inlet prismatic section of the channel, the input pulsations decay, and at large depths of the flow they do not decay.

In figure 3 and 4 the results of numerical and physical experiments are presented, in which water flows in areas with a sharp change in the channel width, which were carried out during the design of real objects, were studied.

Figure 3. The plan of currents in the area of the river. Kama in the Lower Kama reservoir [15]:
1 – the boundary of the fragment of the reservoir on the model; 2 – estimated border;
3 – velocity vectors measured on the model (experiments of A.D. Khalturin and V.T. Silkin);
4 – calculated velocity vectors [16].
The average slope of the bottom is $i = 0.001$. Roughness coefficient $n = 0.013$:
1 – dams; 2 – calculated diagram of the velocity module; 3 – observed on the diagram.

In the experiments presented in figure 4, the flow of water in a fragment of the Lower Kama Reservoir in the zone with a complex topography of the bottom was studied. The studies were carried out both by numerical methods and on the air pressure model. A good agreement was obtained between the results according to which the values of the water velocity and the parameters of the whirlpool zones coincided. In the experiment presented in figure 5 studied the flow of water at a bridge over the river [11, 12]. The studies were carried out both numerically and on a hydraulic model. The longitudinal velocity diagrams obtained by both methods are close to each other.

A detailed study of the applicability of the planning equations of Saint-Venant for sharply unsteady flows in areas of significant changes in the shape of the channel was carried out in [13]. A channel of rectangular section without a slope of the bottom with a sharp five-fold expansion in plan was considered. A quick-opening shutter was installed in the extension section. Before the shutter opened in a narrow section of the channel, the depth exceeded the depth in a wide section. When the shutter opened, a breakthrough wave arose; during its propagation in the region, hydrodynamic flow parameters were measured.

In figures 6-8 the fields of depth isolines obtained in a numerical experiment and photographs of the water surface obtained in a numerical experiment, and also plotted graphs of changes in the calculated depth in a wide part of the channel on the axis of symmetry of the flow. For comparison, the plots during the experiment measured depth values at several points.

The results of numerical experiments using models: A.N. Militeev and B.L. Historian, well agreed with the physical experiments of G.L. Mazhibits[14]. Significant deviations observed in the period immediately following the arrival of the wave, G.L. Mazhibits refers exclusively to the influence of the curvature of the jets and the deviation caused by them from the hydrostatic pressure [1]. We note, however, another possible reason for this deviation: the influence of the shutter opening process.

After a relatively short time interval after the arrival of the depth wave, the results obtained in physical and numerical experiments turn out to be close to each other with an accuracy of 5-10%. Judging by comparing the calculated fields of the isolines of the free surface of the water and the photographs of a physical experiment, the qualitative picture of the phenomenon, including the location of inverted burs turning into oblique hydraulic jumps, is almost the same. The greatest difference at all time instants of the point closest to the site (figures 6-8), located at a distance of 1 m from the channel extension site, is apparently explained by the deviation of pressure in this zone from the hydrostatic one.
Figure 5. Comparison of the results of physical (solid line) and numerical (dashed) experiments on the propagation of a spout wave along a channel with a fivefold expansion [16] (numerical experiment was performed according to the program of A.N. Militeev).

Width: narrow part – 1 m, wide part – 5 m.
Initial depth: in the narrow part $H_0 = 0.6$ m, in the wide part $h_0 = 0.03$ m.
Figure 6. Comparison of the results of physical and numerical experiments on the propagation of a spout wave along a channel with a five-fold extension [16] (a numerical experiment was performed according to the program of BL Historian). Time 2 seconds after the shutter opens. Width: narrow part – 1 m, wide part – 5 m. Initial depth: in the narrow part $H_0 = 0.6$ m, in the wide part $h_0 = 0.03$ m, $n = 0.012$.

Figure 7. Comparison of the results of physical and numerical experiments on the propagation of a spout wave along a channel with a five-fold extension [16] (a numerical experiment was carried out according to the program of BL Historian). Time 4 seconds after the shutter opens. Width: narrow part – 1 m, wide part – 5 m. Initial depth: in the narrow part $H_0 = 0.6$ m, in the wide part $h_0 = 0.03$ m, $n = 0.012$. 
The flow was unsteady all the time and had the character of a property of the original Saint-Venant equations. Therefore, these values of the velocities are close, the solution for the average values also converges well, it is proved that the pulsations are a property of the original Saint-Venant equations.

In the authors’ studies, the divergent form of the system of hydrodynamic equations of Saint-Venant was taken as the basis of the mathematical model:

\[
\frac{\partial Q}{\partial t} + \frac{\partial QU_i}{\partial x_i} + \frac{\partial }{\partial t} \frac{gh^2}{2} = -gh \frac{\partial Z_h}{\partial x_i} - 0.5\lambda U_j |U_j|; \quad \frac{\partial Z_h}{\partial t} + \frac{\partial Q_i}{\partial x_i} = 0. \tag{1}
\]

Using the developed model, numerical studies of the movement of water flow in the area of influence of protective and regulatory structures were carried out. The research results are shown in the following figures (figures 9-11).

**Figure 8.** Comparison of the results of physical and numerical experiments on the propagation of a spout wave along a channel with a five-fold extension [16] (a numerical experiment was performed according to the program of BL Historian).

Time 8 s after the shutter opens. Width: narrow part – 1 m, wide part – 5 m.

Initial depth: in the narrow part \( h_0 = 0.6 \) m, in the wide part \( h_0 = 0.03 \) m, \( n = 0.012 \).

Fallen in figure 8, a point located at a distance of 8 m from the channel extension apparently, should not be taken into account, since the marked increase in the level is associated with the reflection of the wave from the channel wall, which was not specified in the numerical model.

The authors of this work and D.R. Bazarov [17] investigated the influence of the length step on the results of numerical experiments. Based on the results of numerical studies, graphs of the time variation of the longitudinal velocity component behind the sudden twofold channel expansion are presented. These graphs and the above presented results clearly demonstrated the behavior of the water velocity in the area below the sudden expansion. The flow was unsteady all the time and had the character of stationary pulsations, and the finer the grid, the richer the spectrum of these pulsations. The time step in the calculations has always been much less than the minimum pulsation period; therefore, these pulsations are not associated with difference oscillations that can arise when approximating by central differences. Since the flow is strongly elongated along the longitudinal direction, a large ratio of steps was chosen for the main series of calculations. According to the authors of the aforementioned studies and this article, together they show that the pulsations on different grids differ significantly, the average values of the velocities are close, the solution for the average values also converges well, it is proved that the pulsations are a property of the original Saint-Venant equations.
Figure 9. The flow pattern in the channel regulation zone, protective and regulatory structures located asymmetrically along the stream [the results of numerical studies of the authors].

Figure 10. The flow pattern in the regulation zone of the channel, protective and regulatory structures located oblique to the stream [the results of numerical studies of the authors].
The results of numerical studies allow us to obtain information on the dynamics of the planned components of the average speed, water level, and flow condition, flow depth in the zone of influence of protective and regulatory structures. The information obtained allows us to develop measures for the layout of protective and regulatory structures, ensuring guaranteed water intake in the head structures without dam water intakes [18-20].

4 Conclusions
Thus, the analysis of the above studies allows the authors to make a conclusion about the applicability of the numerical model made up of two-dimensional shallow water equations - the vector equation of momentum conservation and the scalar equation of mass conservation, in describing the flow with the presence of circulation zones, which is typical when water flows are constrained by blind dams. In this case, the solution pulsates around a certain average value, and the average length of the circulation zone behind the sudden expansion of the open flow is in good agreement with the laboratory experiments of G.L. Mazhibits. The results of numerical studies allow us to obtain information on the dynamics of the planned components of the average speed, water level, flow condition, flow depth in the zone of influence of protective and regulatory structures. The information obtained allows us to develop measures for the layout of protective and regulatory structures, ensuring guaranteed water intake in the head structures without dam water intakes.

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