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Using computer modelling for regulation of sediment transport under hydraulic structures on a large river

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Abstract Mathematical models based on shallow water equations and equations of bed deformations are proposed for use in designing hydraulic structures and channel straightening for large rivers in northeast Siberia (Russia). The objective of the simulation was to evaluate short time changes of channels under man-made and natural impact. The methods of hydrodynamic models application for studying of river relief change are described, and examples of simulations are demonstrated.

Key words channel deformations; computer model; equation of deformation; equations of unstratified shallow water; hydraulic structures

INTRODUCTION

The economic problems are related to questions of the planning and construction of small hydraulic structures such as water intakes, river harbours, underwater pipelines, bridges, spring water levies, bank protection dams, etc. Most projects are purposed for the regulation of water flow and sediment transport, along rather short river sections. In some cases it is required to induce the sedimentation near hydraulic constructions, for instance to protect the coast from erosion. However, in other cases the sedimentation is an undesirable factor, e.g. when it is necessary to stabilize the balance of alluvium around water intakes. Navigable rivers need to control configuration and variation of bed forms, even without any hydraulic constructions.

Forty years ago the preference was given to large flow regulation structures, the design of which was associated with widely practiced physical modelling. Application of physical models for designing of small hydraulic engineering constructions is unfairly expensive. Usually empirical methods are applied for calculation of construction parameters. The operation of such structures revealed the imperfection of the design technology, which was based on very rough calculations and methods of the similarity. As a consequence, the errors in designing resulted in quick destruction and failures in operation of small hydraulic structures. For design of different variants of the engineering constructions and artificial influence on the river, it is possible to use the computer models, which should be based on equations of unstratified shallow water and equation of deformation.

Simulations made by such models determine trends of channel deformations and allow the consideration of the required number of alternatives for the arrangement of hydraulic structures with regard to their interaction with the river channel under natural and hypothetical conditions. The technological sequence worked out by the authors was tested for large rivers in the northeast of Russia and offered the solution of a number of problems related to the national economy.

COMPUTER MODELLING IN FLUVIAL HYDRAULIC PRACTICE

Before starting computer model development the following information on the subject is required:

(a) to carry out the analysis of natural controls of river channel development, including endogenic (geological structure and tectonics) and eczogenic (climatic conditions, runoff, etc.) factors;
(b) to execute channel analysis;
(c) to determine initial (morphologic data) and boundary (hydrologic data) conditions;
(d) to decide about the location and configuration of hydraulic structures in the course of design, the provision of permanent control of their technical condition, and the elaboration of alternatives of repair recommendations based on the results of the channel deformation study.

At the following stage it is required to collect the data for modelling. In the present work the river bathymetry data was collected by hydrographic survey of the study reach. Improvement of ultrasonic methods of sounding has led to the development of up-to-date echo sounders, side-scan sonars, seismoacoustic profilographs (Zaitsev & Egorov, 1999). The spatial location of measured point was defined using navigation satellites of NAVSTAR (USA) and GLONASS (Russia) systems. The survey procedure underwent continuous improvement and was gradually put into practice. Standard and specialized software was used to plot graphs and layouts of channels on the basis of the observation results.

The flood plain topography data was obtained by vectorization of detailed topography maps. High-altitude marks of a ground and a water table were determined by means of geodesy systems and satellite positioning. Numeric data arrays were used for developing a digital model of channel configuration. The network nodes for the modelling area were automatically generated on a regular and non-regular grid by special software (Zajtsev *et al.*, 2003). As a result a numerical model of a relief was obtained.

The computer model consists of system of equations describing the stimulated phenomenon, numeric scheme of their discretization, computer program, and information on a particular object. The model should adequately reveal the flow structure at the studied site. The use of computer models in further calculations is based on solving a system of equations (Saint-Venant equations) and an elementary equation, which are used to calculate bed deformations (Grishanin, 1979; Lyatkher & Militeev, 1981). For rivers the 2-D system of equations is usually applied:

$$\frac{\partial q_i}{\partial t} + \frac{\partial q_j U_i}{\partial x_j} + gh\frac{\partial \zeta}{\partial x_i} = \tau_{n_i} + \tau_{w_i} \qquad (1)$$

$$\frac{\partial \zeta}{\partial t} + \frac{\partial q_i}{\partial x_i} = q_{ïð} \qquad (2)$$

$$(1-p)\frac{\partial z}{\partial t} + \frac{\partial U_1 sh}{\partial x_1} + \frac{\partial U_2 sh}{\partial x_2} = 0 \qquad (3)$$

(use for all the equations the indices *i* and *j*).

Where i = 1,2; j = *1*, are postscripts for Cartesian coordinates x_1, x_2; *t*-time; $\vec{q} = (q_1, q_2)$, vector of unit discharges of water (m^2 s^{-1}); *h*, depth; $\vec{U} = (U_1, U_2)$ –

vector of averaged velocity; g, gravity acceleration; ζ, elevation of water table; $\vec{\tau}_n = (\tau_{n_1}, \tau_{n_1})$, $\vec{\tau}_w = (\tau_{w_1}, \tau_{w_1})$, shear stress accordingly at the bottom and on a free surface of water (wind tension); z, elevation of bottom; p, porosity of sediment; S, equilibrium sediment concentration.

Shear stress at the bottom and on a free surface can be expressed as:

$$\bar{\tau}_n = -\lambda_n |\bar{U}| \bar{U}, \qquad \lambda_n = g n_n^2 h^{-1/3} \tag{4}$$

$$\bar{\tau}_w = -\lambda_w |\bar{W}| \bar{W}, \qquad \lambda_w = 2.8 \cdot 10^{-7} \tag{5}$$

where $\bar{W}$ is the vector of wind velocity; λ_n, λ_w are the hydraulic resistance factors respectively at the bottom and on a free surface of water; n is Manning's roughness factor.

For calculation of sediment discharge the most acceptable Bagnold's formulae could be simplified for practical application:

$$S = 0.42 \frac{U^2}{gh} \left(0.24 + 0.01 \frac{U}{\omega} \right) \tag{6}$$

Where ω is fall velocity of bottom sediment particles. Equation (6) demonstrates that sediment concentration and yield depended on flow velocity and can strongly vary in non-uniform and non-stationary flows. At present, more complicated models, which take into account the degree of flow saturation with sediments and the noncolinearity of the sediment flux and averaged flow direction, are also used in calculations (Belikov & Volchenkov, 1985; Militeev & Bazarov, 1999). However, the sediment mass conservation equation gives quite reasonable results in solving most practical problems, particularly if wide channels of large rivers are considered.

Effective numerical procedures for solving shallow-water equations (Militeev *et al.*, 1983; Militeev, 1999; Belikov *et al.*, 2001), which have been developed throughout recent years, permit the calculation of bed deformations over a short time period (years or less). Systems of equations are numerically solved using different methods on rectangular and triangular grids. The channel bed configuration at the initial moment is taken as the initial condition for calculation. Boundary conditions are specified in the form of water discharges or levels at liquid borders; the condition characterizing the absence of flow is specified as solid borders (river banks, man-made structures); the sediment discharge is specified at inlet borders. As a consequence, the flow velocity field, the field of water surface levels, water discharges through specified cross sections, and the "new" bed configuration can be determined.

COMPUTER MODELS OF LARGE RIVER REACHES

One-dimensional model describes a process on long sections of narrow flows. Catastrophic deformations of bottom relief of the large rivers are not observed in nature. Such deformations are probably possible after the break of dams of large reservoirs. Usually one-dimensional (1-D) models are used for calculation of the water table. We have applied 2-D and 1-D models to flooding calculation for Lensk—the town on the Lena River where the great ice jam occurred in 2001. Calculations have shown that the water level sharply rises (up to 6.5 m) when ice movement stops. The factor of roughness under ice cover increased from 0.024 to 0.045. When the ice dam reached a height of 4 m, 40 km upstream, the water level only rose by 0.2 m (Fig. 1).

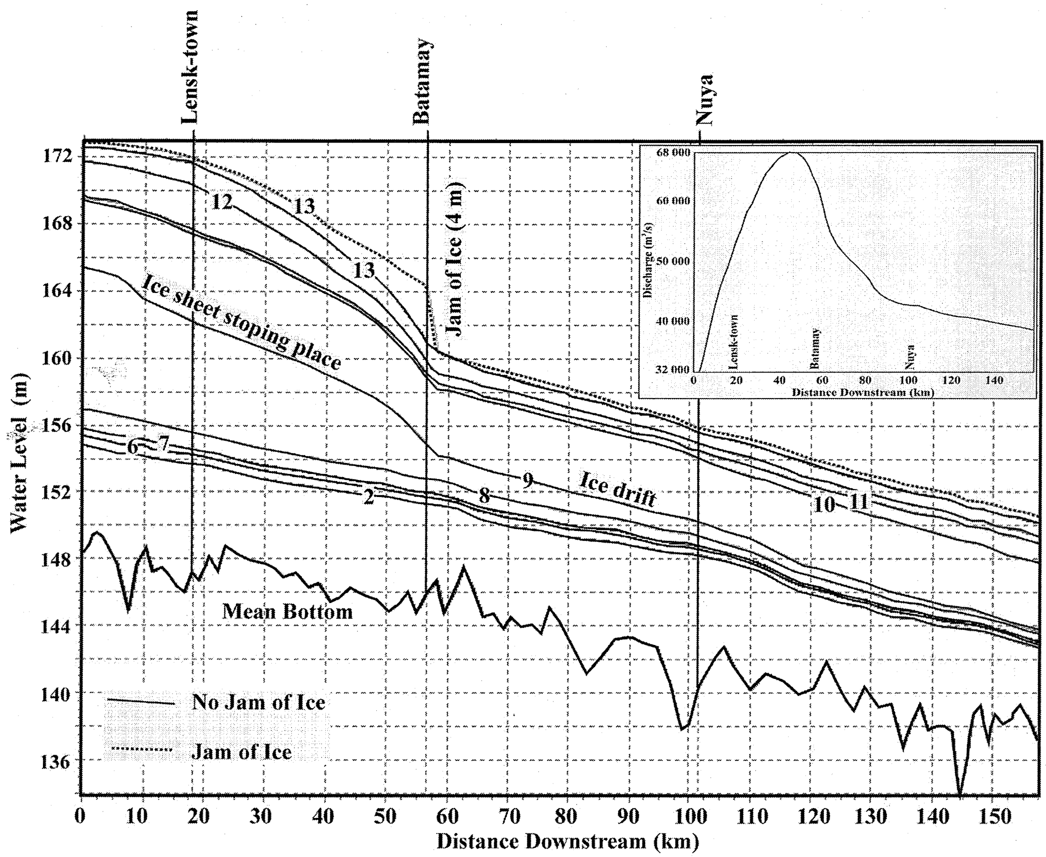

Fig. 1 Simulation of water surface profile upstream of the ice jam at the middle reaches of the Lena River.

Two-dimensional equations of shallow water are accepted for modelling in the particular case of large rivers. The computer 2-D models are used to decide more difficult problems, in the cases of: (a) low water and bankfull flows in singlethread channels; (b) anabranched rivers, (c) confluence of a river with its tributary; and (d) overflowing a flood plain.

(a) Simulation was executed for elaboration of the bank protection strategy in the area of the town of Vilyuisk at the Vilui River. The length of the modelled river section was 15 km, and the mean river width was about 1 km. During the low-flow period, the main stream moves away from the right bank, where a large sand shoal is being formed within the town area; this shoal pushes the stream away at low water. During the flood period, the coastal shoal becomes submerged and the midstream rushes to the right to the terrace, where the town is located. The urban area has been flooded for many days. For >150 years the flow washed out a strip of 150 m wide. Many dwelling houses and buildings in the historical centre of the town were ruined.

In recent years, the bank erosion has become more intensive as a result of the formation of a gentle meander near the town. The concave bank of the meander attracts the stream during the flood period. Moreover, the abovementioned sand shoal gradually shifts downstream and its terrace-protecting effect decreases. During low-flow periods, water discharges are insignificant (about 1000 $m^3 s^{-1}$). However, during flood periods, the water discharge increases up to 10 000 $m^3 s^{-1}$ and more. At this time, water level rises up to 12 m and flow velocity reaches 2 $m s^{-1}$. The river bed is mainly composed by sand of particle size 0.28 mm. Slopes of the terrace where the town is located are constituted by homogeneous sands of mean particle size 0.22 mm. Therefore, bank erosion and bed deformations are considerable here. At the depth of about 4 m from the low-flow level, the riverbed is underlain by bedrock; that contributes to intensive horizontal channel deformations. In addition the large tributary (the Tyung River) enters the Vilyui River from the left bank side 8 km upstream of the town. The tributary noticeably influences the flow kinematic structure. The runoff volume of the Tyung River, during the open channel period, makes 10–40% of the Vilyui runoff volume. The hydrographs of the Vilui and the Tyng Rivers are often asynchronous.

It was suggested that a series of relatively short wing dykes should be constructed. Their number and length were also determined using mathematical modelling. Fragments of the velocity field around dykes in the course of modelling are presented in Fig. 2. For example, the construction of two short dykes (about 100 m long) did not provide the complete protection of the bank against erosion, both in the period of increased low flow (Fig. 2(a)) and during the flood period (Fig. 2(b)). The construction of four dykes causes the reduction of flow velocities along the bank to the nonscouring values. Dykes are of different length and directed at the angle of about 85° to the flow direction. In the periods of increased low flow (Fig. 2(c)) and flood (Fig. 2(d)), bank protection should prevent bank erosion. The calculations for different combinations of the tributary and main river discharges as well as for real hydrographs of low-flow, high-flow and medium-flow years resulted in obtaining of the "new" bed configuration. The conclusions made are supported by the results of the followed observations.

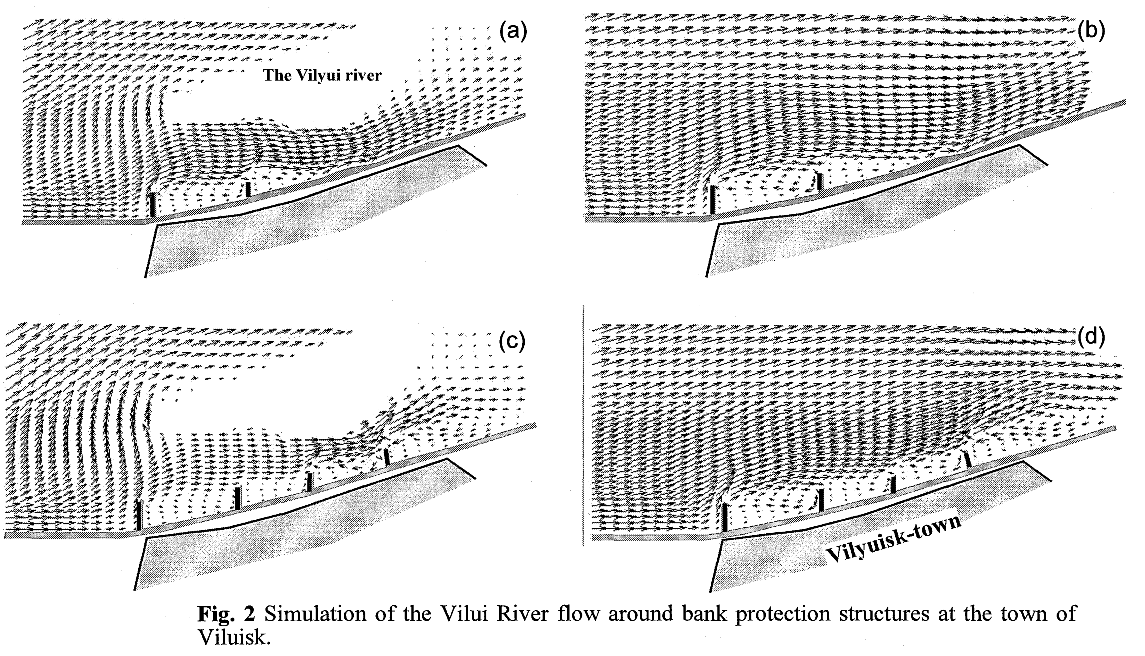

Fig. 2 Simulation of the Vilui River flow around bank protection structures at the town of Viluisk.

(b) The first mathematical model of the Lena River was successfully used in 1989 when it was applied for the project of flood plain and old channel aggradation for the construction of dwelling houses in a new district of the city of Yakutsk. The aggraded areas are located at the bank of the secondary branch Gorodskaya Protoka, anabranched from the main channel at approximately 10 km upstream of the city and deriving 4–7% of the Lena runoff. The ground for the aggradated area was taken from the branch bottom. The volume of annually withdrawn sand made up several million tons and in some years this volume exceeded the total yield of bed load of the entire river. The sand extraction caused an increase of water discharge in the branch and decrease of water level that should result in activization of the branch. It was necessary to evaluate consequences of large-scale sand withdrawals and the amount of sand that could be withdrawn from the channel of Gorodskaya Protoka without any adverse effects. Mathematical models were also used to work out recommendations for designing bank protection structures; these models made it possible to understand the mechanism of flow interaction with hydraulic structures and to choose the model parameters. The example of calculation of bottom relief transformation is demonstrated in Fig. 3.

(c) A computer model of a multibranch river section at the confluence of the Lena and the Aldan rivers was developed in 1999. The model was based on the bathymetrical map plotted in compliance with the results of field surveys carried out in 1996. The size of the object covered >600 km^2. The model was verified using a series of measured water discharges. The most complicated stage of the model development was related to editing the data on the channel configuration, because the data array was of a huge dimension. As a consequence, the detailed

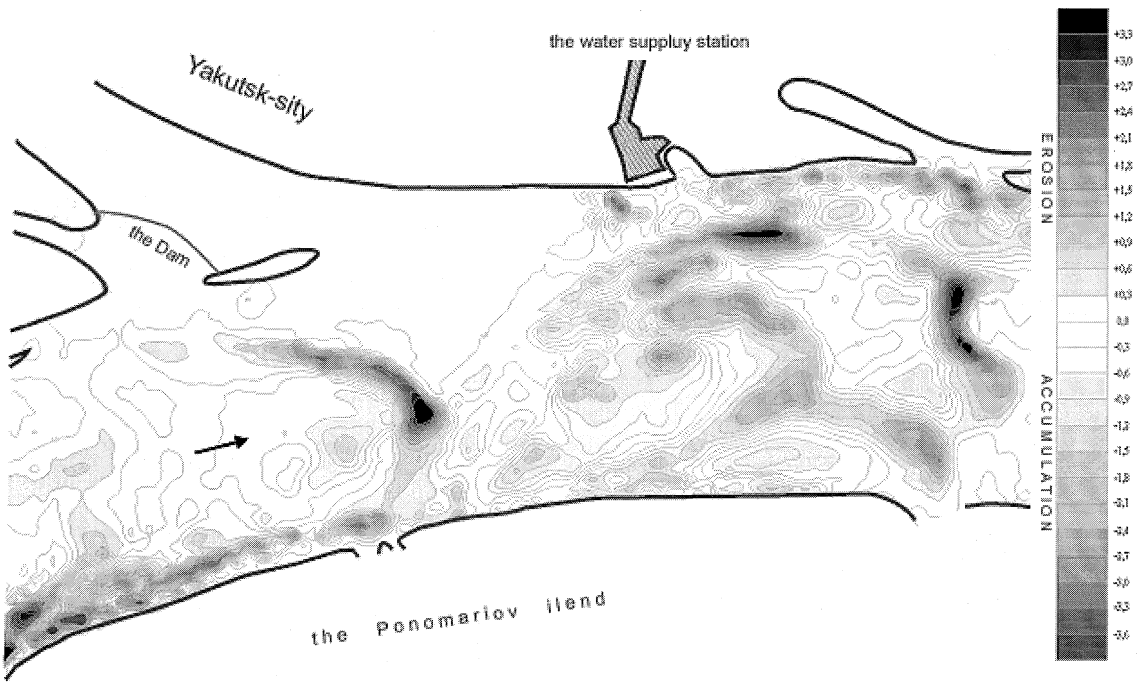

Fig. 3 Simulation of bed relief transformation of the Lena River at the City of Yakutsk during one hydrological year (fragment).

information on the bed configuration made it possible to plot a specific irregular triangular grid with the number of elements exceeding 20 000. The grid condensing was made at places of detailed calculation of deformations and around numerous small islands. Computer modelling permitted the solution of one of the most widespread and important problems—the distribution of water discharges among branches and arms at different water levels. Modelling of channel deformations made it possible to reveal the area of erosional and accumulative flow activity amidst the river section. Any significant deformations were not recorded in the Aldan River channel composed of pebbles (unlike the Lena River channel where sands dominate). Forecast of channel deformations were made.

(d) The flood plain at a period of the flooding had a serious influence upon the river channel process. Therefore the relief of the riverbed and flood plains should be included in composition of the models. There are many settlements along the section of the Lena River near Yakutsk where many problems connected with fluvial processes occur. So the computer model of the river section of 40 km length was constructed in 2002. The relief of the channel and valley bottom was described by 500 000 points. For this section of the river the flow kinematics and channel deformations were calculated. A fragment of calculation of the river bottom deformation is shown in Fig. 4.

The three-dimensional hydrodynamic model considers streams with small sediment load, allowing not to take it into account in equations of water movement. Influence of deposits is only reflected by the change of bottom elevation that causes change of stream parameters. This assumption causes the pressure to be close to hydrostatic. Movement of liquid is described by 3-D equations of shallow water. This model could be applied for the following conditions: (a) vertical acceleration in liquid is much less than gravity acceleration, therefore distribution of pressure on a vertical can be assumed as hydrostatic; (b) change of tangents of pressure in the plan is much less than in a vertical direction.

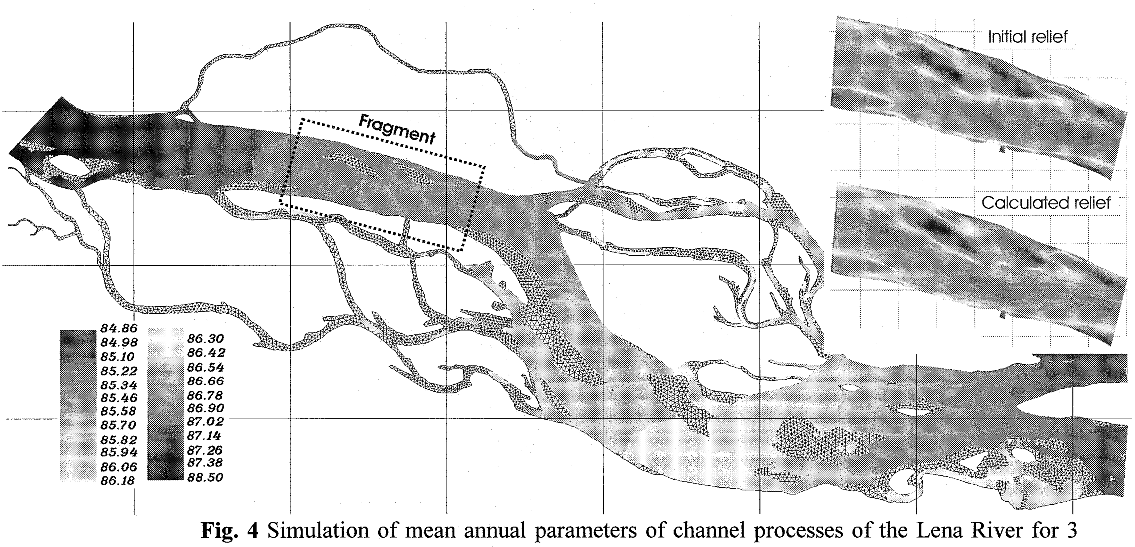

Fig. 4 Simulation of mean annual parameters of channel processes of the Lena River for 3 years.

Transport of deposits occurs both in a suspension, and in the benthonic layers. The discharge of suspended deposits of various fractions can be presented as:

$$\overline{q}_{s\,m} = \int_{Z_d}^{Z_s} \vec{U} c_m \mathrm{d}z \tag{7}$$

where c_m is the volumetric concentration of fraction m of deposits. Wilson's formula was used for bed load:

$$\vec{q}_b = \alpha_b \frac{1}{g} \sqrt{|\vec{\tau}_b|} \vec{\tau}_b \tag{8}$$

The 3-D model simulates moving of a sandy bars that allows to solve problems connected with parameters of hydraulic engineering constructions (Fig. 5).

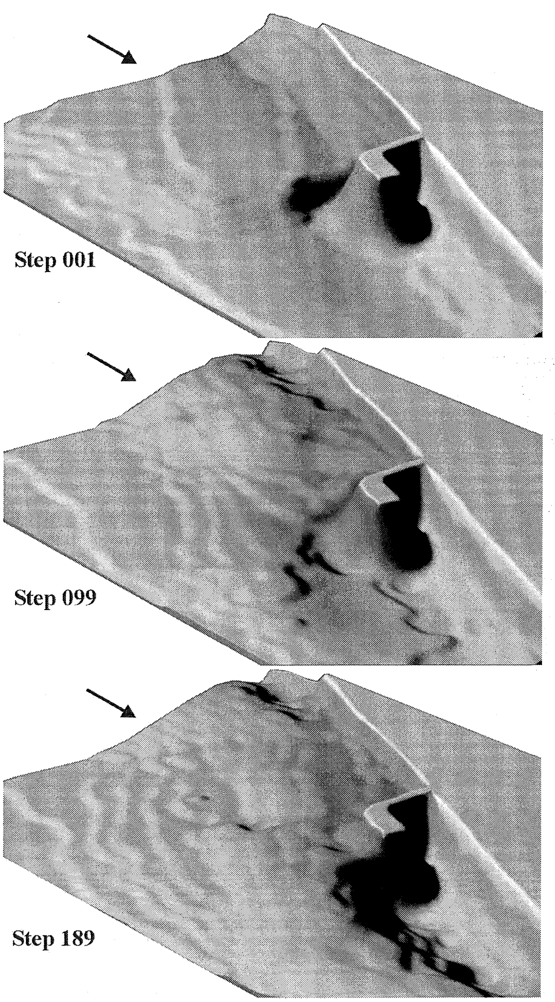

Fig. 5 Simulation of sandy bar movement near water intake.

CONCLUSIONS

Computer modelling allows study ofthe regime of natural channel deformations and impact of hydraulic structures on the flow. The objectives of computer modelling are as follows:

(a) analysis of the river flow structure and bed deformations under natural conditions at different water discharges;
(b) calculation of the parameters of water flow and sediments in a stream with hydraulic structures to choose the optimum arrangement of these structures.

The maximum available information on channel configuration is used to construct a mathematical model of fluviomorphological processes. Initial parametric characteristics are achieved by collecting a database for the object under study. Main and secondary factors of channel formation, as well as methods of organizing further observations over fluviomorphological processes, are determined after introducing the model into practice and analyses of results. The application of channel deformation equation in the computer model allows the definition of zones of accumulation and erosion. The use of real or hypothetical hydrographs makes it possible to forecast channel development and record the rates of its natural transformation with regard to the maximum possible number of the most essential factors.

REFERENCES

Belikov, V. V. & Volchenkov, G. Ya. (1985) *Gidravlika dorozhnykh vodopropusknykh sooruzhenii* (Hydraulics of Road Water Conduits). SPI, Saratov, Russia (in Russian).

Belikov, V. V., Zaitsev, A. A. & Militeev, A. N. (2001) Numerical modeling of flow kinematics in a segment of inerodable channel. *Vodn. Resur.* **6**, 640–648.

Grishanin, K. V.(1979) *Dinamika ruslovykh potokov* (Channel Flow Dynamics). Gidrometiozdat, Leningrad, Russia (in Russian).

Lyatkher, V. M. & Militeev, A. N. (1981) Hydraulic investigation by digital methods (Hydraulic studies in energy and water facilities) *Vodn. Resur.* **3**, 36–41 (in Russian).

Militeev, A. N. (1983). Gidravlicheskie issledovaniya v energetike i vodnom khozyaistve (Hydraulic study in energy and water industries). In: *Collection of Works of Hydroprogekt Hydraulic Studies in Power Engineering and Water Management* (ed. by A. M. Prudovskii), 67–80. Energiya, Moscow, Russia (in Russian).

Militeev, A. N. & Bazarov, D. R. (1999) Gidravlicheskie issledovaniya chislennuimy metodamy (Hydraulic studies by numerical methods). *Vodn. Resur.* **l**, 22–29 (in Russian).

Militeev, A. N., Petrov, P. G. & Belikov, V. V. (1989) Paket prikladnih programm dliy rascheta techeniy gidkosty v otkruituih potokah (package of the applied programs for calculation of the current to liquids in opened flowpackage of the applied programs for calculation of the current to liquids in opened flow). In: *Dinamikai termika rek, ozer, vodokhranilishch i okrainnykh morei.* Moscow, IVPAN SSSR **2**, 85–87 (in Russian).

Zaitsev, A. A. & Egorov, V. F. (1999) Primenenie programmno-apparatnogo compleksa I sputnikovogo coordinirovaniay pri provedenii iziskanii na vodnuih putiah (Using the software-instrument complex and satellite positioning for investigation the prospecting on water ways). In: *Sovremennoe sostoyanievodnykh putei i problemy ruslovykh protsessov* (ed. by R. S. Chalov), 113–124. Mosk. Gos. University, Moscow, Russia (in Russian).

Zajtsev A. A., Il'jasov A. K., Savel'ev R. A., Belikov V. V. & Militeev, A. N. (2003) Compiuternuie modeli ruslovuih processov (Computer models of channel processes). Problems of channel processes. *Trudy Academii vodohozaistvennyh problems* **9**, 89–105 (in Russian).