EcoGIS-Simulation Software for riverbed sediments modeling

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Abstract. The paper describes the EcoGIS-Simulation software and hardware complex for numerical hydrological modeling of river systems. The computing core makes it possible to carry out a non-stationary self-consistent calculation of the dynamics of surface and groundwater, as well as the transfer of entrained and suspended sediments. The main attention is paid to the organization of geoinformation support for such calculations at the stages of preparation of initial data, processing of results and their visualization. EcoGIS-Simulation software is designed to simulate non-stationary self-consistent dynamics of surface and groundwater together with the transport of entrained and suspended sediments. The strong dependence of the nature of sediment transport on the particle size in the conditions of the Medveditsa River in the vicinity of the city of Mikhailovka (Volgograd Region, Russia) is shown.

1 Introduction

Mathematical modeling of the consequences of the implementation of various kinds of hydraulic engineering projects (dams, canals, pumping stations, sluices, water protection structures, etc.) is a necessary element of technical expertise at the design stage [1-3]. Geoinformation systems are the most convenient tool for accumulating data on the state of river systems for subsequent analysis of trends in their changes. The aim of the work is to develop the integration of hydrodynamic modeling with geoinformation technologies. The paper describes software modules for geoinformation support of the EcoGIS-Simulation hardware and software complex designed to simulate the hydrological regime of a given territory. A mathematical model of suspended sediment dynamics is described and some results of hydrodynamic modeling are presented.

2 Materials and methods

The general structure of the EcoGIS-Simulation software is shown in Figure 1. We will allocate three blocks in accordance with the three stages of modeling the hydrological regime for the selected area. The first stage provides with the assignment of spatial distributions of all characteristics necessary for the most complete description of the

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properties of the territory that are required for hydrodynamic modeling. We will call this whole set of parameters the Digital Hydrological Landscape Model (DHLM), developing the ideas of the hydrological landscape concept [4]. The second block allows you to calculate the dynamics of flooding. The third block is designed to process and visualize the results. The first and third blocks are the geoinformation infrastructure for the computing core.

The module “Hydrograph” sets the hydrograph for each riverbed at the entrance to the computational domain. The hydrograph according to observations is usually known in increments of one day. For modeling tasks, it is possible to recalculate \( Q(t) \) with interpolation for an arbitrary given time step. In general, you can specify any arbitrary function \( Q(t) \) in tabular form.

The central module is the “Digital Elevation model (DEM)” (Digital elevation model, DEM), which sets the altitude characteristics for the computational grid and with which other altitude matrices are associated that determine groundwater and other landscape characteristics.

The module “Channel structure” contains a vector map of the riverbed system with the ability to edit them. This functionality is of particular importance for floodplain areas with a branched channel structure. The main stages of the algorithm used to build a digital terrain model are described in [5]. For river systems, the creation of a DEM includes the construction of a vector map of all riverbeds, followed by the introduction of appropriate altitude data in the DEM.

The DMHL block provides the formation of input and initial data for starting the block “Computing core”. The simulation begins with the generation of a computational grid on the DEM or with the loading of an existing grid. The basic one is a rectangular grid with square cells of the size \( \Delta x = \Delta y \) within a few meters, so for Cartesian coordinates we choose \( \Delta x = i \Delta x, x_j = j \Delta y \). The choice of \( \Delta x \) is determined by the resolution of the DEM. There are small areas that require high modeling accuracy. If there is a high-quality DEM in the vicinity of riverbeds or other critical zones, it is possible to generate a triangulation grid for a section of the computing area. Such zones include settlements, terrain features and landscapes such as gullies, dry riverbeds, islands, dense vegetation, quarries, ravines, etc.

The block "Spatial data processing and visualization" is designed to build a given set of thematic maps using a DEM substrate, or for additional mathematical data processing. The module “Depth distribution and velocity field” in addition to the function also constructs a vector function \( u(x, y, t) \) in the form of a given system of current lines or velocity vectors. Figure 2 shows the example of modeling severe flooding (for water
availability of 1%) of the Buzuluk River in the vicinity of the town of Novoanninsky and the village of Berezovka 1st. The resolution of the computational grid is 5 m, and the size of the area in the figure is 10.58 km. The red triangle in the center of the drawing indicates the mouth of the Perevozinka River (during the inter-war period), which flows along the western border of the city.

**Fig. 2.** Fields of streamlines and velocities (insets) near Novoanninsky City according to the results of hydrodynamic modeling.

### 3 Results and Discussion

**Suspended sediments mathematical modeling**

The effect of water flow on the riverbed determines the morphodynamics and hydromorphology of riverbeds [6-8]. Mathematical modeling of riverbed processes based on self-consistent accounting of water dynamics [1, 9] and sediment transport is an effective tool both for the analysis of channel deformations [10-14], and to provide environmental expertise in the design of hydraulic structures, sand extraction and other anthropogenic impacts. The dynamics of suspended sediments is described by the transport equation [10]:

\[
\frac{\partial \alpha H}{\partial t} + \nabla \cdot (\alpha H \mathbf{u}) = \nabla \cdot (D \nabla \alpha) + q_\alpha - q_{bx}
\]  

(1)

Where \( \alpha = \rho_s / \rho_g \rho_s \) – the density of suspended sediments averaged over the depth of the flow \( H \) (turbidity), \( q_\alpha \) – the rate of inflow of suspended sediments, \( D \) – the total diffusion coefficient of suspended sediments in the horizontal plane (taking into account the dispersion) [15]. The rate of gravitational sedimentation of suspended sediments is determined by the following expression:

\[
q_{bx} = \phi_a \omega \alpha
\]  

(2)
Where \( \omega \) – hydraulic size of sediment particles, \( \phi_\alpha \) – the ratio of the bottom and average depth sediment concentration [15, 16].

The hydraulic size of the sediment particles \( \omega \) is determined by the Wexler formula [15-17]:

\[
\omega = \frac{(s - 1)gd_{50}^2}{v_0\left(1 + \sqrt{1 + \frac{2}{45}Re_d^2}\right)} \left(1 - \frac{3}{4} \cdot \frac{1 + 1,75 \cdot 10^{-12}Re_d^5}{\left(1 + \frac{24}{Re_d^2}\right)^2 - \frac{44}{Re_d} + 1,75 \cdot 10^{-12}Re_d^5}\right)^{-1/2},
\]

Where \( v_0 \) – the coefficient of kinematic viscosity of water, depending on its temperature (see [15]), \( Re_d = \frac{d_{50}}{v_0}\sqrt{(s - 1)gd_{50}} \).

We suggest considering the example of the joint use of the module “Water Dynamics” and “Suspended sediments” for a strongly meandered section of the Medveditsa River in the vicinity of Mikhailovka. The calculated area is set to the size of 37\( \times \)26 km. The granulometric composition of the soil is critically important, which can be integrally characterized by the median particle size \( d_{50} \). To analyze the deformation rate of the riverbed, calculations have been carried out at various values of \( d_{50} = 0.0003 – 0.01 \) m.

We use a real hydrograph of 2022 and calculate the differences of the DEM before the flood and after its completion. Figure 3 shows the results of sediment redistribution for three values of \( d_{50} \), which shows a small modeling area where the length of the river is only 5 km and \( \Delta x = 10 \) m. The red color shows the areas of positive deformations of the bottom (\( \Delta b > 0 \)), and the blue color shows the areas of negative deformations (\( \Delta b < 0 \)). The insets show sections of the riverbed big scale, demonstrating the complex nature of changes in the DEM.

The critical values of the median size, at which changes in the riverbed practically do not occur, are approximately 2-3 mm, which corresponds to the skeleton of the soil. At very small values of \( d_{50} \), local deformations of the earth’s surface during a month of flooding can reach 3 meters. The average amplitudes of these changes depend non-linearly on \( d_{50} \), and the nature of this dependence is determined by the coefficient of tortuosity of the channel.

4 Conclusion

We present a new version of the EcoGIS-Simulation software package designed to simulate the hydrological regime of a given territory, taking into account the dynamics of surface and groundwater, as well as sediment transport. The most important part of EcoGIS-Simulation is a specialized geoinformation system to support working with spatial data.

Let us distinguish two functional GIS blocks, one of which (block I in Figure 1) is responsible for preparing all the components of the digital model of the hydrological landscape that are necessary for hydrodynamic modeling. The proposed approach to constructing a DMHL is based on specifying a set of discrete tensor functions that determine the characteristics that affect the hydrological regime of the territory. These include, first of all, the DEM, the Manning coefficient, the depth of the waterproof layer, the density and porosity of the soil, infiltration parameters, the distribution function of the particle size of sediment, meteorological parameters, landscape characteristics (vegetation, buildings, infrastructure structures), the distribution of water sources and effluents with specified hydrographs, locations and operating modes of hydraulic structures, etc.
Where:  
- hydraulic size of sediment particles,  
- the ratio of the bottom and average depth sediment concentration [15, 16].

The hydraulic size of the sediment particles is determined by the Wexler formula [15-17]:

\[
\text{Hydraulic Size} = \frac{k}{\nu}
\]

Where:  
- the coefficient of kinematic viscosity of water, depending on its temperature (see [15]),

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Fig. 3. Distribution of bottom level differences at different values of median particle size: a) \( d_{50} = 0.0001 \text{ m} \); b) \( d_{50} = 0.0003 \text{ m} \); c) \( d_{50} = 0.0009 \text{ m} \). A section of the Medveditsa River 10 km long is shown.

The second functional block is designed for processing and visualization of spatial and temporal data obtained as a result of computer modeling (block III in Figure 1) and allows you to build three-dimensional surfaces that are part of the DMHL and visualize the simulation results: display water levels, current lines, velocity fields, two-dimensional sections of the distributions of sediment (bottom) parameters, calculate the flows of water and solid matter through specified sections, the volume of water sediment and the area of flooding within a certain area.

The EcoGIS-Simulation system allows you to simulate the dynamics of riverbeds in conditions of unsteady flow, when sediment transport can change the structure of the riverbed in a short period of seasonal flooding. Using the example of the Medveditsa River, the process of local redistribution of sediments at large values of the tortuosity coefficient, which enhances the meandering of the riverbed, has been studied.
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