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CREATION OF CADASTRAL MAPS OF FLOODING BASED ON NUMERICAL MODELING

*A. Yu. Klikunova*¹, klikunova@volsu.ru,
*A. V. Khoperskov*¹, khoperskov@volsu.ru,
*E. O. Agafonnikova*¹, agafonnikova@volsu.ru,
*A. S. Kuz'mich*¹, anna.kuzmich@volsu.ru,
*T. A. Dyakonova*¹, dyakonova@volsu.ru,
*S. S. Khrapov*¹, khrapov@volsu.ru,
*I. M. Gusev*², 3276391@gmail.com

¹Volgograd State University, Volgograd, Russian Federation,

²Lomonosov Moscow State University, Moscow, Russian Federation

We consider the possibilities of numerical hydrodynamic modeling for the construction of cadastral maps of dangerous flood zones on the example of the Volgograd region. The numerical model is based on shallow water equations and Combined Smooth Particle Hydrodynamics – Total Variation Diminishing (CSPH-TVD) method for integrating hyperbolic differential equations. To create a digital elevation model (DEM), we use an iterative approach, assimilating all available spatial data, including remote sensing data, topographic measurements and observations of flooding in different years. The agreement of the observed data with the numerical simulation results can significantly improve the quality of the DEM. Digital elevation models are based on elevation matrices in increments of 3 to 10 meters, depending on the topography of the study area. The result of our work is a set of maps with flood boundaries for different probabilities of catastrophic events. For each such flood, we calculate the river hydrograph and its integral characteristics.

Keywords: shallow water model; computational experiments; flooding; cadastral map.

Introduction

The numerical model of shallow water allows us to solve various applied and engineering problems related to the dynamics of surface water for a specific area, taking into account a large number of physical factors [1–3]. Let us highlight the problems of the impact of the sea on the coastal environment [4–6] and in particular floods in the coastal zone by storm surge [7–9]. An important area of applied research is the modeling of river systems to determine the effects of seasonal flooding, runoff and rain flows, and the dynamics of river sediments [8, 10, 11].

The transition from the complete three-dimensional system of hydrodynamic equations to the shallow water equations (regularized equations [3]) implies the study of only sufficiently long-wave motions in the absence of dispersion effects. However, even bore-waves and hydraulic jumps are sometimes described quite well by the shallow water model, as noted in [12]. Comparisons of shallow water models with results of 3D flow modeling in [13] and the real experiments of [14] indicate a fairly acceptable agreement.

The shallow water model and its multi-layered modifications make it possible to describe not only various hydrological phenomena on land, but also underlie the predictions of meteorological and climatic processes in the atmosphere-ocean system [15] and propagation dynamics of various pollutants in water bodies and in the atmosphere [16]. Numerical models are increasingly used for technical assessments at the design stage of hydraulic structures [5, 17], for cadastral works [18], for assessing the environmental outcomes of various negative processes, emergency events and accidents [3, 9].

The description of dispersion effects requires more complex models than the shallow water equations, for example, the modified Boussinesq equation [19], which allows modeling nonlinear soliton waves. Various methods are used to simulate the vertical structure of water dynamics, for example, spectral methods [20]. The 3D approach based on the Smoothed Particle Hydrodynamics method allows you to calculate the collapse of nonlinear waves on water when multiple-valued solutions occur.

Terrain is a crucial factor for hydrological applications, therefore the creation of a high-quality digital elevation model (DEM) requires the use of a variety of geoinformation methods and data, including remote sensing of the Earth, processing satellite images, geodetic survey [11]. The most difficult is the modeling of river systems, water reservoirs with complex and extensive floodplain valleys, river deltas in the case of strong floods [9].

The problems of creating cadastral maps for various purposes are at the center of the global digitalization of all spheres of society and industry [21, 22]. We see the rapid development of 3D-map technology for the cadastre [23–25], for example, 3D underground cadastral data model [18]. Thematic digital terrain models with additional semantic information can be attributed to this kind of 3D cadastres.

A new stage is the transition to Spatio-Temporal Cadastral Database, which receives results from of the Simulation Application [22], and we develop this approach in this work. We create cadastral maps of hazardous flood zones for various levels of water supply for floodplain sections of the rivers in the Volgograd region based on the results of GIS (Geographical Information Systems) and hydrodynamic simulations.

1. Basic Equations and Numerical Model

1.1. Saint-Venant Equations

The equations of shallow water in differential form are written as [1, 7, 8, 10, 11, 26, 27]:

$$\frac{\partial H}{\partial t} + \frac{\partial(Hu_x)}{\partial x} + \frac{\partial(Hu_y)}{\partial y} = q^{(s)} - q^{(inf)} - q^{(ev)}, \quad (1)$$

$$\frac{\partial(H\mathbf{u})}{\partial t} + \nabla(H\mathbf{u} \otimes \mathbf{u}) = -gH\nabla(H + b) + H(\mathbf{f}^{fric} + \mathbf{f}^{Cor}), \quad (2)$$

where $H(x, y, t)$ is water depth, $\mathbf{u}(x, y, t) = \{u_x, u_y\}$ is water velocity vector, $q^{(s)}(x, y, t)$ is water source due to precipitation, outflow of water from a groundwater system and inflow through hydraulic structures, $q^{(inf)}(x, y, t)$ is function of drain due to infiltration into the ground, $q^{(ev)}$ is water loss rate due to evaporation, $\nabla = \{\partial/\partial x, \partial/\partial y\}$ is the nabla operator, g is the acceleration of gravity on the Earth's surface, $b(x, y)$ is the bottom function.

The components of the Coriolis force are:

$$f_x^{Cor} = -2\Omega_E \sin(\Theta) u_y, \quad f_y^{Cor} = 2\Omega_E \sin(\Theta) u_x, \quad (3)$$

where $\Omega_E = 7.3 \cdot 10^{-5} \text{ sec}^{-1}$ is the Earth's rotation frequency, Θ is the latitude of the point (x, y) . The bottom friction force \mathbf{f}^{fric} acting on the fluid for the standard quadratic friction model is

$$\mathbf{f}^{fric} = -\mathbf{u} \frac{\Lambda}{2} \sqrt{u_x^2 + u_y^2}, \quad (4)$$

where $\Lambda = 2gn_M^2/H^{4/3}$ is the hydraulic friction coefficient, n_M is Manning bottom roughness coefficient. In the general case, the roughness coefficient n_M depends on a variety of physical factors such as the roughness of the canal bottom, large-scale irregularity of the bottom structure, meandering, various obstacles, water and coastal vegetation, water turbulence, sediment transport [28, 29]. Thus, the parameter n_M depends on the coordinates and is a phenomenological quantity, which is determined by the set of spatial characteristics.

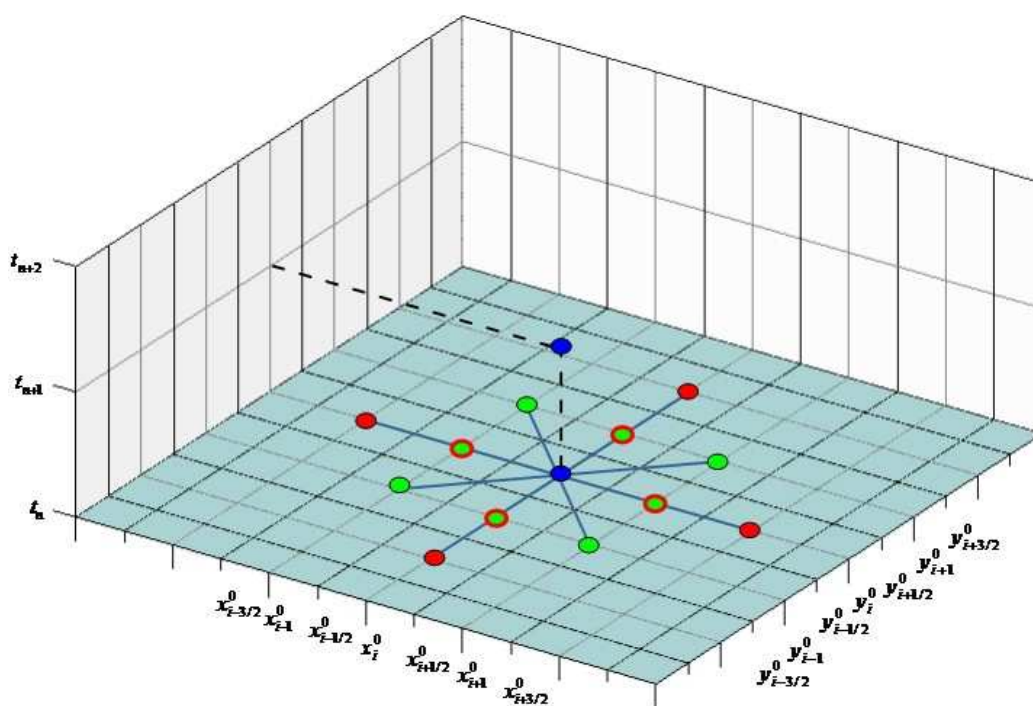


Fig. 1. CSPH-TVD numerical scheme

1.2. Numerical Algorithms

We use the Combined Smooth Particle Hydrodynamics – Total Variation Diminishing (CSPH-TVD) method for numerical integration of the equations' system (1)–(2), which is described in detail in [2, 26]. This scheme includes two main stages – the Lagrange stage of calculations, based on the ideas of the method of smoothed particles, and the Eulerian stage, where finite-difference approximations are applied on a fixed numerical grid ($x_{i+1} = x_i + \Delta x$, $y_{j+1} = y_j + \Delta x$) and satisfy the principle of not increasing the total variation of the numerical solution (TVD-principle). The characteristic variables are used for TVD reconstruction [30].

This numerical scheme is conservative and well balanced [26]. The need to create complex algorithms is due to irregular changes in the bottom function $b(x, y)$ on various

scales, including $L/H \sim 1$ ($L = b/|\nabla b|$ is the characteristic inhomogeneity scale of bottom), when we have moving wet-dry fronts on the flooding stage or the drying up of the terrain. The important advantage of our algorithm is that it provides the through calculation of the internal nonstationary boundaries between liquid and dry (shorelines) environments for any complex DEM.

Figure 1.1 shows the computational pattern for the CSPH-TVD method in the case of transition from the time layer n to the time layer $(n + 1)$. Green color indicates nodes that are considered at the Lagrangian stage, and red nodes are used at the Eulerian stage. Moreover, green nodes with a red contour are involved in each of the stages. At the Eulerian stage, the integral characteristics are specified, taking into account the mass and momentum fluxes across the cell boundaries at time $t^{n+1/2} = t^n + \tau_n/2$. To calculate fluxes, the modified TVD approach and the approximate solution of the Riemann problem for each cell boundary are used. The use of piecewise linear reconstruction provides the second order of accuracy in space.

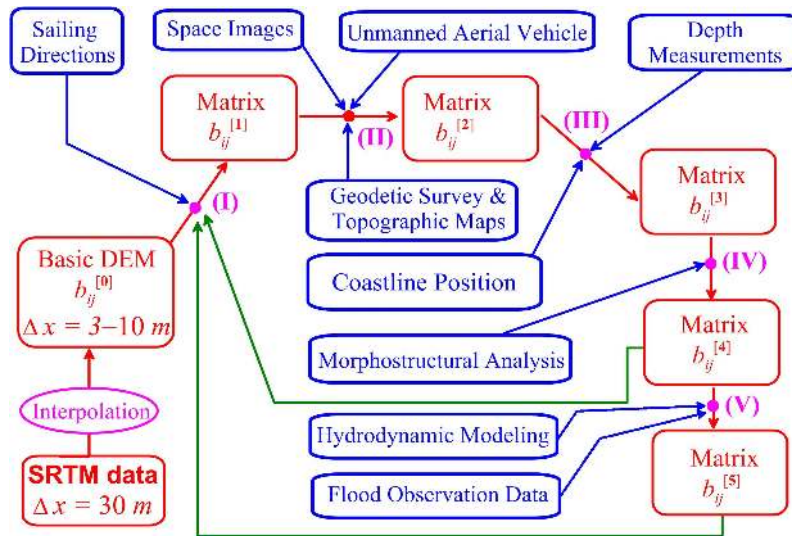


Fig. 2. Iterative procedure for creating a digital elevation model

For the study of seasonal floodplain floods, flash floods, tsunami waves ashore, the situation is complicated by the emergence of subcritical and supercritical flows in addition to the above mentioned problem of moving wet-dry interfaces. An analysis of the use of various methods of setting boundary conditions shows the advantage of a waterfall type condition in the presence of strong heterogeneity of topography [31]. Our computational experiments demonstrate that the waterfall on the boundaries of the computational domain and the heterogeneity of the relief in the vicinity of the boundary provide the formation of the critical flow area with a hydraulic jump, which significantly weakens the effect of the waterfall on the flow structure upstream [31], and the practice of applying this approach showcases its effectiveness [11, 17, 26, 27].

We use the "EcoGIS" software package for numerical simulation of shallow water dynamics [26], in particular, the parallel version for NVIDIA GPUs [32].

1.3. Digital Elevation Model (DEM)

The function $b(x, y)$ in the equation (2) is the digital elevation model. We use an iterative process to construct the DEM by assimilating all available spatial data (Figure 2). Our initial basic DEM is the Shuttle Radar Topography Mission data (SRTM3 SRTMGL1 release), which form the $b_{ij}^{[0]}$ matrix after interpolating for a small step Δx , usually within 3 – 10 meters.

A key role in improving the quality of the digital topographic model belongs to a comparative analysis of the results of numerical simulations based on shallow-water equations with observational data on the nature of flooding in city or village and its surroundings.

2. Numerical Simulation of the Dynamics of Settlements Flooding in the River Valleys of the Volgograd Region

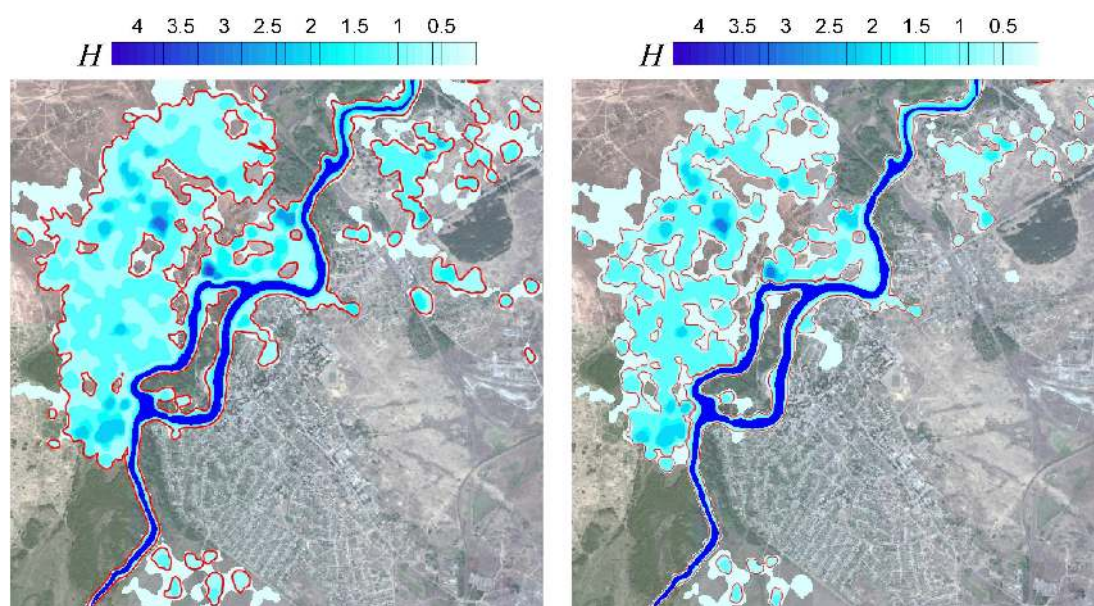


Fig. 3. Flooded areas near the Ilovlya city for various levels of river water supply (β). Left panel — Distribution of water depth ($H(x, y)$) with a water supply of $\beta = 1$ percent. The red line corresponds to the boundary with a depth of 0.5 m. Right panel — same as left panel for $\beta = 3$ percent.

2.1. Stages of Work for Each Locality

The total number of cities and villages that may be at risk of flooding exceeds 200 settlements. We describe the common procedure for constructing cadastral maps of floodplain territories according to the degree of danger.

Stage I. Preparation of initial data for modeling the dynamics and forecast of flooding of the selected area.

- 1) Construction of the matrix of heights of the simulated part of the terrain based on remote sensing data, topographic maps, geodetic and hydrographic measurements.
- 2) Creation of matrices of qualities (roughness and infiltration coefficients) for the computational domain on the basis of cartographic data, satellite images and field observation data.

Stage II. Simulation of flooding areas.

- 1) Preparation of initial states and calculation parameters for various variants of the hydrological regime on the floodplain and meteorological conditions.
- 2) Carrying out calculations for the computational domains in the range of 100 – 2000 km² with a duration of 3 – 10 days.

Stage III. Processing simulation results.

- 1) Mapping of flooding (distributions of water depths and vectorial velocity field) at different points in time for various options of the hydrological and meteorological regimes (2D and 3D maps, GIF-animation of the dynamics of flooding).
- 2) Determining the boundaries of the flood zone.
- 3) Constructing dependence of the flooded area on time.
- 4) The coordination of theoretical dependences of water depth and water velocity on time at control points with observational data.

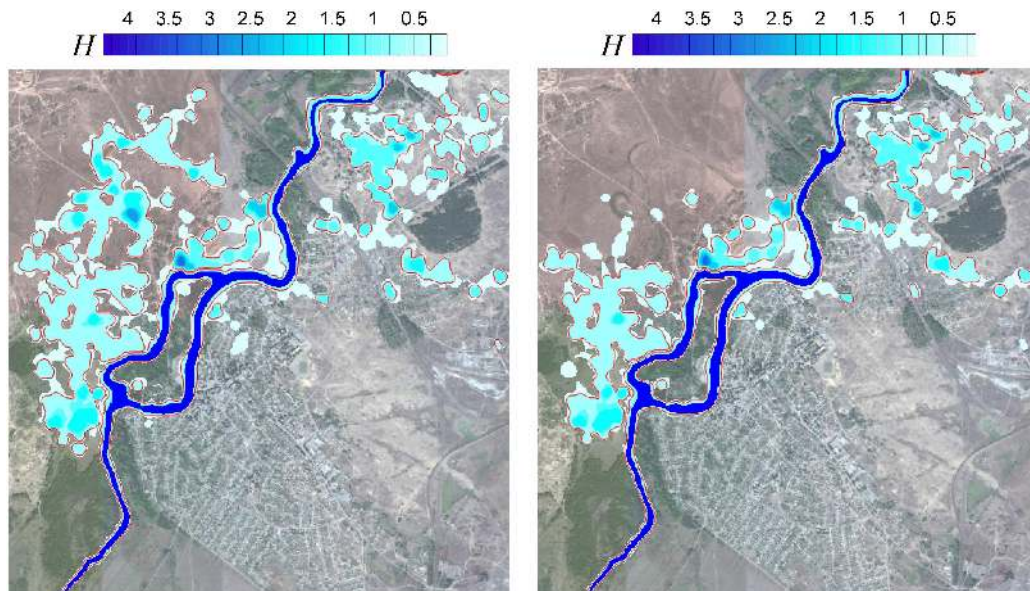


Fig. 4. As in Figure 3 for $\beta = 5$ percent (left panel), for $\beta = 10$ percent (right panel).

2.2. Simulation Results

We use the iterative method of self-consistent refinement of the DEM and numerical hydrodynamic modeling to determine the boundaries of flooded areas in the vicinity of settlements, depending on the level of water in the river. As an example, let us consider in detail the calculations of flood zones in the vicinity of settlements on the Ilovlya River and its inflows (Fig. 3).

The most important characteristic of flood zones is the probability of a flood of a given magnitude of β , which is convenient to determine as a percentage. For example,

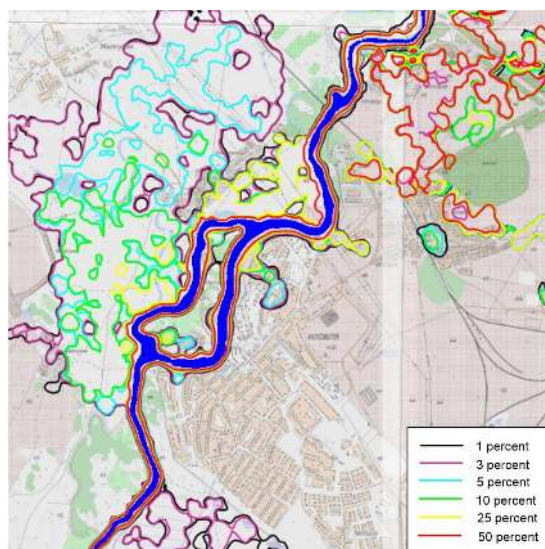


Fig. 5. The boundaries of the flood zones for different β . Solid lines correspond to the boundaries of flooding with $H = 0.1$ m.

$\beta = 1$ percent means that such a flood occurs 1 time per 100 years on average, while $\beta = 10$ percent corresponds to one event for 10 years, etc. This traditional method has a disadvantage, since all catastrophic events occur unevenly, and β is a statistical quantity.

Figures 3 and 4 show the results of flooding the vicinity of the Ilovlya City in the Ilovlya River valley for different probabilities of β . The main flooded area covers the right bank of the Ilovlya River with a low population. However, suburbs may be affected by flooding. The final result of the study for Ilovlya City is shown in Figure 5, where the cadastral map shows the boundaries of hazardous areas for different probabilities of such an event.

The important characteristic of the hydrological regime of a river is its hydrograph $Q(t)$ (rate of flow or discharge), which is an integral value (See $q^{(s)}$ in (1)):

$$Q_r(t) = \int_{L_n} (\mathbf{u} \cdot \mathbf{n}) H dl, \quad (5)$$

where L_n is the line along the cross section of the watercourse, \mathbf{n} is normal to L_n . We are forced to input additional inflow of water not through the cross-section of the river (Q_{nr}) to explain the observed picture of flooding, which is due to the peculiarities of the specific topography. The contribution of Q_{nr} to the total discharge $Q = Q_r + Q_{nr}$ can be significant for some areas.

Each computational experiment is characterized by a $Q(t)$ hydrograph, which we vary to match the simulation results with the observations. Table 1 contains the results of calculations of the flooding area of S_f and the discharge Q depending on the flood probability.

Conclusion

Our project is aimed at developing an approach for building maps of flooding in river valleys. The main result is the boundaries of hazardous areas, depending on water

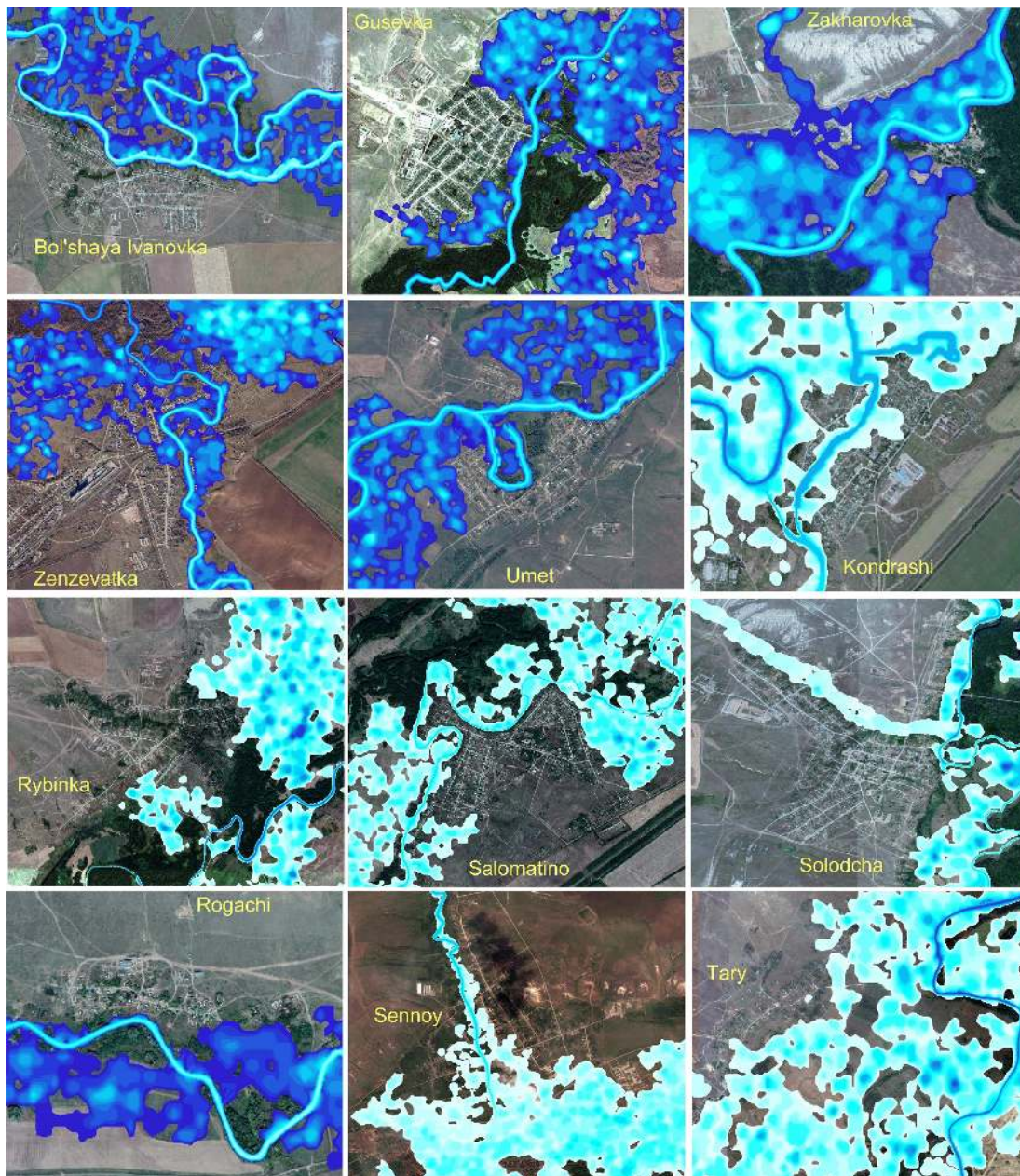


Fig. 6. The boundaries of the flood zones for different villages in the Volgograd Region in the case $\beta = 1$ percent.

Table 1

Integral characteristics of catastrophic flooding
for the vicinity of the Ilovlya City

β (percent)	50	25	10	5	3	1
Q ($\text{m}^3\text{sec}^{-1}$)	62.3	123	214	311	366	492
S_f (km^3)	2.04	3.00	4.34	5.62	7.34	8.66

availability, as well as estimates of the flow discharge in the conditions of unsteady catastrophic flooding. The methods of computational experiment demonstrate their

efficiency and indispensability for the most diverse engineering applications in hydrology, which is due to the considerable extent to the great potential of shallow water models.

An interdisciplinary approach based on the synthesis of hydrodynamic simulations, GIS modeling, assimilation of observed data can be a powerful tool for design work. The critical point is the digital elevation model, the accuracy of which determines the quality of the entire study.

It is remarkable that the refinement of the DEM occurs iteratively when we compare the results of numerical simulation with the available observational data, which are very selective and sparse. Small-scale DEMs are highly volatile due to natural and anthropogenic processes, so updating digital topography is a big problem for engineering applications.

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Anna Yu. Klikunova, Student, Department of Information Systems and Computer Simulation, Volgograd State University (Volgograd, Russian Federation), klikunova@volsu.ru.

Alexander V. Khoperskov, DSc (Math), Professor, Head of the Department of Information Systems and Computer Simulation, Volgograd State University (Volgograd, Russian Federation), khoperskov@volsu.ru.

Ekaterina O. Agafonnikova, Department of Information Systems and Computer Simulation, Volgograd State University (Volgograd, Russian Federation), agafonnikova@volsu.ru

Anna S. Kuz'mich, Student, Department of Information Systems and Computer Simulation, Volgograd State University (Volgograd, Russian Federation), anna.kuzmich@volsu.ru.

Tatyana A. Dyakonova, PhD (Techn), Department of Information Systems and Computer Simulation, Volgograd State University (Volgograd, Russian Federation), dyakonova@volsu.ru.

Sergey S. Khrapov, PhD (Math), Associate Professor, Department of Information Systems and Computer Simulation, Volgograd State University (Volgograd, Russian Federation), khrapov@volsu.ru.

Ilya M. Gusev, Postgraduate Student, Lomonosov Moscow State University (Moscow, Russian Federation), 3276391@gmail.com.

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ПОСТРОЕНИЕ КАДАСТРОВЫХ КАРТ ЗАТОПЛЕНИЙ НА ОСНОВЕ ЧИСЛЕННОГО МОДЕЛИРОВАНИЯ

*А. Ю. Кликунова, А. В. Хоперсков, Е. О. Агафонникова, А. С. Кузьмич,
Т. А. Дьяконова, С. С. Храпов, И. М. Гусев*

Мы рассматриваем возможности численного гидродинамического моделирования для построения кадастровых карт опасных зон затопления на примере Волгоградского региона. Численная модель основывается на уравнениях мелкой воды и методе интегрирования Combined Smooth Particle Hydrodynamics – Total Variation Diminishing (CSPH-TVD). Для построения цифровой модели рельефа местности (ЦМР) мы используем итерационный подход, ассимилируя все доступные пространственные данные, включая данные дистанционного зондирования, топографические измерения и наблюдения о затоплениях в различные годы. Согласование данных наблюдений и результатов численного моделирования позволяет улучшить качество ЦМР. В основе цифровых моделей рельефа лежат матрицы высот с шагом от 3 до 10 метров в зависимости от топографии местности. Результатом является набор карт с границами затоплений для различных вероятностей наступления катастрофического события. Для каждого такого паводка мы определяем гидрограф реки и его интегральные характеристики.

Ключевые слова: модель мелкой воды; вычислительные эксперименты; затопление; кадастровая карта.

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Кликунова Анна Юрьевна, студент, кафедра информационных систем и компьютерного моделирования, Волгоградский государственный университет (г. Волгоград, Российская Федерация), klukonova@volsu.ru.

Хоперсков Александр Валентинович, доктор физико-математических наук, профессор, заведующий кафедрой информационных систем и компьютерного моделирования, Волгоградский государственный университет (г. Волгоград, Российская Федерация), khoperskov@volsu.ru.

Агафонникова Екатерина Олеговна, старший преподаватель, кафедра информационных систем и компьютерного моделирования, Волгоградский государственный университет (г. Волгоград, Российская Федерация), agafonnikova@volsu.ru.

Кузьмич Анна Сергеевна, студент, кафедра информационных систем и компьютерного моделирования, Волгоградский государственный университет (г. Волгоград, Российская Федерация), anna.kizmich@volsu.ru.

Дьяконова Татьяна Андреевна, кандидат технических наук, старший преподаватель, кафедра информационных систем и компьютерного моделирования, Волгоградский государственный университет (г. Волгоград, Российская Федерация), dyakonova@volsu.ru.

Храпов Сергей Сергеевич, кандидат физико-математических наук, доцент, кафедра информационных систем и компьютерного моделирования, Волгоградский государственный университет (г. Волгоград, Российская Федерация), khrapov@volsu.ru.

Гусев Илья Михайлович, аспирант, Московский государственный университет им. М.В. Ломоносова (г. Москва, Российская Федерация), 3276391@gmail.com.

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