Modeling the hydrophysical soil properties as a part of self-regulated flood dams projection in gis-environment for sustainable urban development

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Abstract. The problem of flood protection measures are considered in the paper. The regulation of river flow by the system of Self-Regulated Flood Dams (SRFD) is analyzed. The method of SRFD modeling in GIS environment is proposed. The question of the ecological aspect of the SRFD management is considered based on the hydrophysical properties of the soil. The improved Mualem-Van Genuchted method is proposed for the evaluation of the possible SRFD location influence on the soil of flooded territory – the temporary reservoirs. The importance and utility of the proposed complex method is stated.

1. Introduction

Emergencies caused by the rare recurrence floods could lead to considerable damage to people’s lives and properties [1]. The situation becomes more complicated due to climate changes, which increase the frequency and intensity of these floods [2-3].

One of most dangerous type of flood phenomena is flash flood. These events are caused by a rain storm over a water basin. As a result, a catastrophic rise of water levels and flows in catchment streams are observed. There are many publications, which are devoted to preparing of appropriate flood-protection measures [4-7].

Timely warnings of the emergency services and public alert about the possible threat of flooding is a condition for the preservation of life and health of people, as well as to minimize the economic damage in hazardous areas. According to the forecasts, the trend towards an increase in the number of large-scale natural disasters hydrological nature in the foreseeable future will remain, which is confirmed by
the catastrophic floods have occurred in recent years. Therefore, we can conclude that the prediction and modeling of floods is one of the main tasks of hydrological modeling [8, 9].

It is important to note that the assessment of possible flooding boundaries and water level rising at preset times distinguishes the problem of forecasting flood monitoring tasks. At the same time, GIS modeling allows to evaluate the possible boundaries of floodwater areas under one or other potential levels of its recovery [10].

In present study as the measures for mitigation of flash floods, the regulation of river flow by the system of Self-Regulated Flood Dams (SRFD) are analyzed concerning of Far East region of Russia. SRFD are distributed on the river network, saving the water volume from flash floods in temporary detention reservoirs, created by themselves. The selection of the location of the Self-Regulated Flood Dams on the specific river network is the main and multicriteria task. It consist of the economical, ecological, social and technological criteria [10].

All the modeling measures are held in the GIS environment. Usage of the modern complicated GIS complexes allows building an extended model, which will include different aspects. These data could be updated online with the information from the hydrological and meteorological posts [5].

These models could also include the information about the entire transport infrastructure of the observed region. Transport network is highly important during the emergencies, when the population evacuation measures are required. The emergency services should have all the online information about the current and future condition of these infrastructures during the flash flood events, so as the prediction of its condition. This is why the usage of the GIS complexes is so urgent in nowadays [13].

In addition, the specifics of the SRFD working mode should be taken into account. SRFD location means that the certain terrain area will be covered with water for a certain time, according to the amount of the precipitations volume during the flood events. Such terrain may be belong to the valuable agricultural land, so it is necessary to calculate the hydrophysical properties of the soil, which compose these areas.

2. Materials And Methods

2.1 GIS modeling of the Self-Regulated Flood Dams
SRFD is considered as a structural measure for the flash floods impact minimization. It represents itself as a special kind of dam with an aperture. In normal condition, this aperture does not resist to flows. For this reason, SRFD has minimal impact on the environment. SRFD is used primarily for solving hydrological problems by changing the shape of the catastrophic flood hydrograph, which become smoother. If SRFD is distributed on branches of mainstream of river basin, then resulting hydrograph in a basin control section will have a smooth shape without peaks, which are characteristics of catastrophic floods. Therefore, flood risks for population and sustainable urban development will decrease [9].

The flood area modeling into the specific river basin consists of several steps:

- Modeling in the ArcGIS program with HEC-GeoRAS module which necessary to work with the landscape and to create the river network and the cross-sections;
- Direct work in the HEC-RAS program, which necessary to edit the river cross-sections and its objects and to determine the hydrological properties of flow;
- Creation of the demanded model, so as static, as a dynamic (by setting the hydrographs in specific cross-section).

The river network and bank lines are paved based on remote sensing data, so as the floodplains. Further, the cross-sections are created. Hydrological Engineering Center (HEC) is using the paved cross-sections during the calculation of flood zones and their characteristics. They could be set as automatically with specific interval and width, so as manually. After that, the program analysing the data taking into account the distance and the terrain elevation, and creating the file for export to the HEC-RAS (figure 1).
In the next step, the imported data processing occurs using the HEC-RAS software package. Hydrological conditions also should be set. After creation of the separate project within the HEC-RAS, modeling starts with Geometric Data tab. Here each cross-sections could be edited to reduce the number of points on which they are based, or the anti-aliasing alignment could be produced, if working with the original riverbed is not possible due to software limitations. Such restrictions arise from the possible occurrence of «false channels» effects. If the large differences in the elevations are presented, the program can identify them as separate riverbeds, which lead to the calculation error. In addition, the Manning coefficient (Eq.1) is set in the Geometric Data tab, so as the changes in the river network characteristics. Any hydrological facilities at a certain point could additionally be set. Adjustments of the cross-sections and the set of synthetic roughness coefficient could be made (figure 2)

\[ v = k, H^{2/3}, \sqrt{T}. \]  

Further, the work carried out using the SteadyFlow Data tab, or the UnsteadyFlow Data tab, depending on the desired model type. Finally, the chosen tab analyzes the given data and the flood zone of the specific area of river basin could be received. The data can be exported in ArcGIS for visual map creation, in order to build a complicated visual online database (figure 3). After that, we could fill the database with the other information, such as transport network, important facility objects etc.
2.2 Hydrophysical properties of the soil, water retention capacity

There is a need for soil properties modelling for various engineering purposes, the importance of them during this research is mentioned in the previous chapter. Water-retention capacity (WRC) of soil is described by a functional dependence of volumetric water content (m³·m⁻³) on capillary pressure (capillary-sorption potential) of moisture (m H₂O) [14].

The soil hydraulic conductivity function (HCF) describes the ability of liquid water to pass through the soil as a porous media. The HCF is formulated as a dependence of water velocity k (m s⁻¹) on the volumetric water content θ (m³·m⁻³) or capillary pressure (capillary-sorption potential) of moisture ψ (m H₂O) in soil. Under conditions of the water-saturated soil, the velocity of water downflow effected by gravity is characterized by the filtration coefficient kᵈ (m s⁻¹). During soil drying, the influence of gravity is gradually replaced by the capillary sorption forces that retain water in the soil. The soil water holding ability is usually described by the function of the integral water capacity θ(ψ), which is called the water-retention capacity (WRC). The velocity of soil water transfer k at lower values of θ and ψ (in the so-called unsaturated zone, or vadose zone) is considerably lower than kᵈ because of the interaction between water and solid soil phase [15-18].

There are various examples of the WRC description within the physical concepts for different ranges of ψ, including its description as an exponential model [19]. However, so far, a comprehensive physically reasonable mathematical description of the WRC and HCF as a generalized system of functions for the combined range of capillary and film soil water has not been offered [14]. Thus, in mathematical descriptions of dependencies θ(ψ), k (ψ), and k (θ), some empirical functions are often used. However, these functions can only be recognized as approximations to the WRC and HCF and are used for interpolating data of direct measurements [20, 21]. The implementation of such measurements is a laborious process. Therefore, the development of methods for estimating the values of WRC and HCF on the basis of indirect evidences and available data is an urgent problem in soil hydrophysics.

The Mualem–Van Genuchten method allows calculating the values of HCF using θ(ψ) and kᵈ without direct measurements of k (ψ) and k (θ).

3. Results And Discussions

The modeling of the specific part of river network was made, with the choice of the SFRD location. Appropriate models was built according to the abovementioned method.

The time period of specific water level standing could be received during the dynamic modeling, according to the specific hydrograph and flood dam configuration. These data allow solving the problem taking into account the ecological criteria. Having the time period of water level standing and the agricultural data in the supposed location of the SRFD, the influence of the possible SRFD, its configuration restrictions could be determined. The received data are shown on the figure 4-6. The figure
4 shows the flood hydrograph itself, so as the smoothed ones, depending on the width of a SRFD operation hole. Figure 5 shows the dependence of the water level in the Upper stream from the hole width of the SRFD. Figure 6 shows the dependence of the water surface width from the hole width of the SRFD.

Figure 4. Flood hydrograph.

Figure 5. Water level - hole width dependence.

Figure 6. Water surface width – hole width dependence.
The justification of the such engineering solutions requires the detailed study of the hydrological conditions of the construction site. These conditions include the hydrophysical properties of the soil [22].

This means that it is required to select and analyze the samples of soils in the laboratory, which requires both temporary and material costs. Given that such surveys are very time consuming, it becomes obvious to develop methods for indirect assessment of indicators characterizing the hydrophysical properties of soils. The Mualem-Van Genuchten method is among these methods [23].

Its advantages allow to evaluate the hydraulic conductivity of the soil according to the data of the water-retention capacity of soils and filtration coefficient. The authors have own their development, which significantly develops this method and allows the more accurate assessment of hydrophysical parameters [24]. It is necessary to study and evaluate the percolation of moisture through the soils of temporary reservoirs parameters. In such terms our improved Mualem-Van Genuchten metod could be successfully applied. The example of application of this method are already exists in previous articles [25]

Figure 7. Water-retention capacity and ratio of hydraulic conductivity to filtration coefficient on the example of Beit Netofa Clay.

The verification of the improved Mualem–Van Genuchten method for the BNC soil is visualized in the figure presenting the results of interpolating the measured WRC data. The circle points of the figure related to the water-retention capacity, square points – to the hydraulic conductivity.

As seen from the figure, a comparable accuracy of interpolating the measured data $\theta(\psi)$ is achieved with the use of WRC and approximation (curves 1–3). However, the matching of the result of the $k(\psi)/k_s$ estimation with the experimental data is significantly better with the use of HCF and approximation proposed by the authors of this paper (curves 5 and 6) than with the use of HCF (curve 4). The proposed improved method was tested on the Beit Netofa Clay data, the original method shows very low accuracy for this type of soil. The curves, obtained by the authors (2,3,5,6) are closer to the experimental points, than the Van Genuchten curves (1,4).

This method could be applied for the evaluation of the possible SRFD location influence on the soil of flooded territory – the temporary reservoirs. Such territories frequently could be the valuable agricultural lands. In addition, it is possible to explore the potential aftermaths of the water standing in the area with the transport and other infrastructure.

4. Conclusion
The regulation of river flow by the system of detention reservoirs for flood diversion with non-operational dams for flash flood mitigation was analysed. The method proposed adapts the principles
supporting structural measures as diverting water away from urban area to making room for water and save natural landscapes. The complicated online database could be made based on the results of the modeling. The proposed WRC model was applied to the GIS modeling as the part of the hydrophysical properties of the soil research. The results of these calculations are used to study the hydrological conditions of the area in the design of irrigation and drainage systems [26-28], underground constructions [29-32] and artificial foundation based on weak, for the bank protection tasks, drainage problems, marine works, hydropower protection, urban ecological and economical challenges; it helps to find the effective engineering solution based on knowledge of the hydrophysical properties of soils. The modeling as a complex of works, both in GIS environment and by the improved Mualem-Van Genuchten method is representing a multicriteria system, which allows to work with various information and translate it into the complicated database with the landscape data, river networks, possible SRFD and their impact on the basin. This block allows to build a model of the flash floods, from the past, current in the online mode and to predict the future floods with the adjusted parameters. The appliance of the the improved Mualem-Van Genuchted method allows researching the situation with the soils of the study area [33-36]. Proposed models are very important for the appropriate management of the infrastructure (transport, energetic, ecological objects etc.) during the emergencies, especially – flash floods.

Acknowledgements

The research was supported by Russian Foundation for Basic Research (#16-04-01473-a).

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