Modelling of Impact Caused by Flood after Water Flow Optimization at Volga-Kama River Basin

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***Abstract*—In this paper two different water flood scenarios at Volga-Kama river in Russia are presented. First scenario is based on the existing water management approach that has been implemented in the period from 23 August 2013 until 22 August 2014. The second scenario is based on the original management approach aimed at mitigation of flood impact to the populated areas. The flood propagation has been modelled in HEC-RAS software, while post-processing and impact analysis were performed in QGIS 3.0. The results show that proposed original management approach allows to decrease the impact caused by inundation at Volga-Kama river basin by two times compared to the one implemented by the operator management approach. This result is achieved due to mitigation of the flood in highly populated areas and allowing additional water discharge among water management facilities in the areas with low population.**

***Index Terms*— Inundation, flood, risk, dam management**

I. INTRODUCTION

IN the past decades issues related to floods mitigation become even more important. Floods occur more often and their magnitude becomes even higher. This results in severe damages incurred to the population, buildings and harvest. Whereas the systems for water level monitoring and weather forecasting have improved steadily and still continues to improve, the management of a river system that would consider many aspects at once, such as power production, flood safety, water irrigation, navigation, safety of the ecosystems and others has experienced less progress. Consideration of many criteria requires more resources and up to now was not successfully implemented.

In [1, 2] an original approach for optimization of a tandem water reservoir system management was presented. This approach included into consideration three major criteria.

The first one was aiming at maintaining the normal headwater level in the reservoir to avoid the bowl overflowing (and, as a consequence, collapse of the dam) and shallowing, which could lead to the disruption of the household and agricultural supply operation, local biocenosis, etc. It can be achieved by minimizing the difference between the expected and available water levels in the reservoir.

The second one was to generate the greatest income from power production, so the value of the expected profit was used for the normalization purpose.

And the third one was to minimize floods, which was solved by limiting the discharged flow from the reservoir.

In order to compare the proposed management approach with the existing one a flood risk assessment has to be performed. According to [3] risk assessment comprises of three distinct steps:

--the identification of hazards likely to produce hazardous events,

--estimation of the risks of such events and their contingent consequences,

--the social evaluation or weighting of the risk so derived.

The social evaluation of the risk is major research by itself and will not be discussed in this paper, while the first two steps are highly important for comparison of two river system management approaches.

The identification of the hazards for a river system can be performed by modelling water inundation and identification floodable areas. This is done mainly by flood mapping [4].

GIS-based mapping of floods and other natural hazards is actively used in the scientific environment [5, 6, 7]. A good case study of such mapping using a self-developed software is presented in [8]. They use FloodCalc urban tool to model flood and evaluate the risk at most populated areas of Leipzig. Another example from Bangladesh using NOAA-AVHRR satellite images is provided in [9]. Likewise, satellite digital elevation model (DEM) was used in [10] when modelling flood plain delineation of a South Nation River system in Canada. A hydrologic Engineering Center's River Analysis System (HEC-RAS) has been successfully validated and used.

After having the flood plain mapped the flood risk may be evaluated as a combination of the recurrence probability of a damaging flood event and a number of potential negative consequences in a given area [11].

Estimation of the contingent consequences of floods can also be performed in various ways.

In [12] a methodology has been developed for assessment of flood risk arising from fluvial and coastal sources that explicitly considers defense failures represented through

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Fig. 1. Location of Volga-Kama river basin

fragility curves. This method evaluates risk of separate flooded cell as a product of a conditional event probability of exceeding any particular flood depth by economic consequence for this flooded cell. The total risk of the flood area is the sum of the risk of the associated with each impact cell. Additionally, the approach considers a probability of flood defense systems failure. However, this approach does not consider the severity of flood, which could be measured by the depth of the flood above surface level.

For this purpose stage-damage-functions are used for different building types and considered as internationally accepted standard approach for flood damage estimation [13]. But they are very hardly applicable when considered vast landside, e.g. when risk assessment is performed at the national level [14]. Furthermore, such functions introduce high uncertainties [15].

An extensive research that would consider most of the above-mentioned drawbacks is presented in [16]. In this paper a new damage estimation approach was presented that is based on the developed by the authors GIS tool. In the software tool a possibility to apply different damage functions was implemented. These are: Linear Polygon Function, Square Root Function, and Point based Power Function. These three options allow performing different level of damage estimation depth. One of the simplest ones is square root function, where damage is defined as follows:

$$D = b \times \sqrt{h}$$

with b – constant that stands for damage for h = 1 m, h – water depth.

In our paper the flood consequences have been estimated as a product of water level above surface and population density. Linear dependency of damage to water height was chosen to more properly compare the flood impact on population. This is the most simple and obvious approach that would allow us to assess the severity of flood and compare different cases between each other. On the other hand, if needed, it can be relatively easily enhanced by adding relative costs of the territories and other indicators of flooded area tangibles and intangibles.

II. METHODOLOGY AND MODELLING

A. *Description of Volga-Kama River Basin*

Volga-Kama river basin (Fig. 1) includes two rivers: Volga and Kama that are located in central Russia and flow into Caspian Sea. Volga River is the longest river in Europe with a catchment area of 1 350 000 km^2.

The modelled area includes a major part of Volga river including Nizhny Novgorod Hydroelectric Station (HES) located near Nizhny Novgorod city, Cheboksary HES located near Cheboksary city, Zhiguli HES located near Tolyatti and Samara cities, Saratov HES located near Saratov city and up to Volga HES located near Volgograd city.

Kama river is the longest left tributary of Volga river with total catchment area of 507 000 km^2. The modelled area includes Votkinsk HES located near Votkinsk town, and Nizhnekamsk HES located near Naberezhnye Chelny city. Kama flows into Volga river between Kazan and Ulyanovsk cities.

B. *River Flood Modelling*

River flood modelling was performed in HEC-RAS software. As it was shown in the introduction this tool has been many times tested and validated and successfully used by other research groups.

In order to set the heights of land surface a Shuttle Radar Topography Mission (SRTM) data was used that provides digital elevation model (DEM) with spatial resolution of 30 meters [17]. Bathymetry of Volga and Kama rivers were taken from the rivers' bathymetry atlases and [18].

For the given region of Volga-Kama basin in 1D modelling of HEC-RAS rivers center lines, bank lines, flow paths lines and cross sections were entered. A zoomed view of the Volga – Kama junction with the above-mentioned lines is shown on Fig. 2. An example of the river cross section is shown on Fig. 3. And the lateral straightened Volga profile below the junction with Volga HES, Saratov HES and Zhiguli HES (downstream to upstream) is shown on Fig. 4.

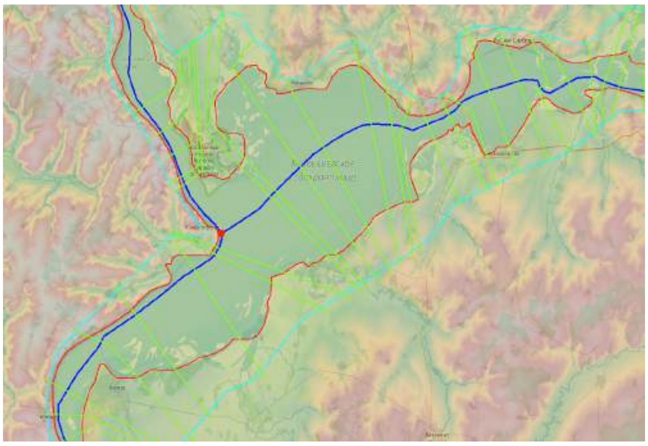

Fig. 2. Volga-Kama junction with center lines, bank lines, flow path lines and cross sections.

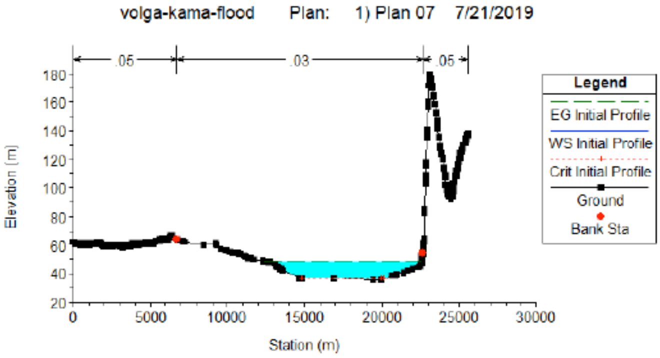

Fig. 3. An example of the cross section plot at Volga river

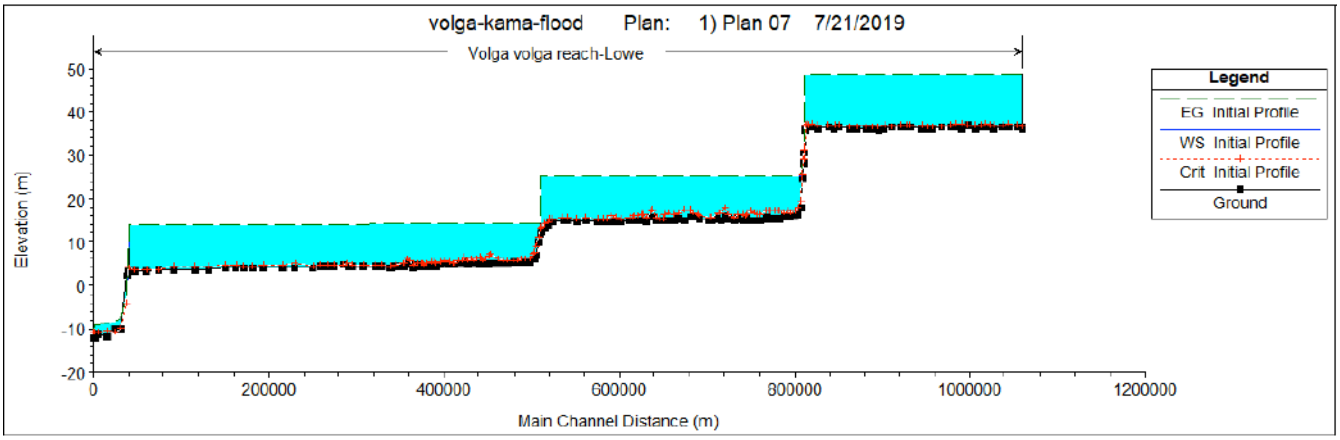

Fig. 4. Lateral straightened profile of Volga river below the junction with Kama river

The initial conditions, such as water level, discharges, precipitation and other were set according to the service provided by RusHydro – Russian hydroelectricity company that is managing all the power plants along the studied river system [19]. Same source was used for setting the current water discharge over all HESs of the river system in the time period was taken from 23 August 2013 to the 22 August 2014. This data was used to model river flow in the Scenario 1.

For the Scenario 2 were used same initial conditions, but current water discharge over all HESs were taken from a model described in [1, 2].

Minor reaches were not considered as the main task was just to compare two approaches of river management.

The water flow modelling resulting in water surface elevation are shown on Fig. 5. There is no comparison provided between the two scenarios at this stage because at such scale there may not be seen any difference. However, it may be clearly observed that water surface elevation drops down from ca 67 m to ca -11 m along whole river basin profile with significant water level change at the hydroelectric stations.

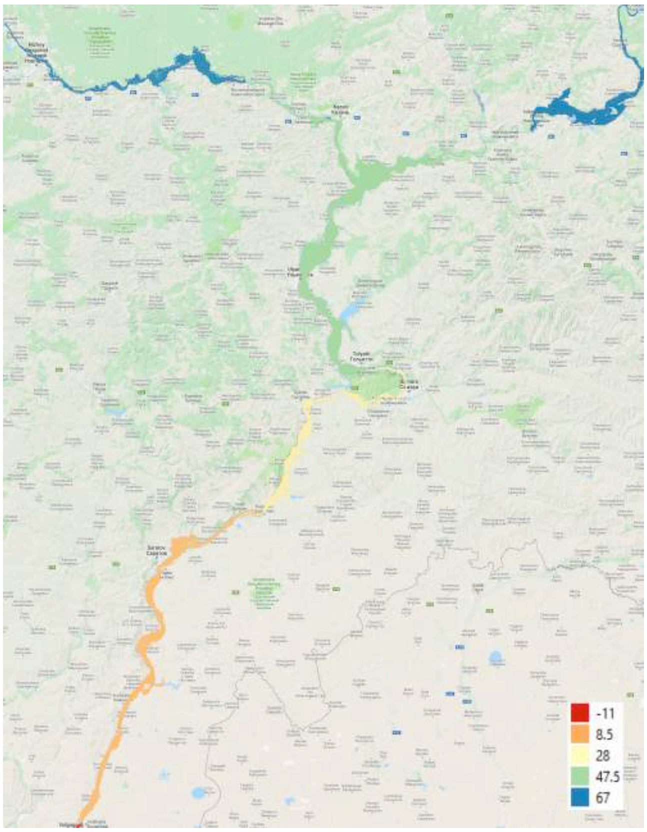

Fig. 5. Water surface elevation (in meters) at Volga-Kama river basin

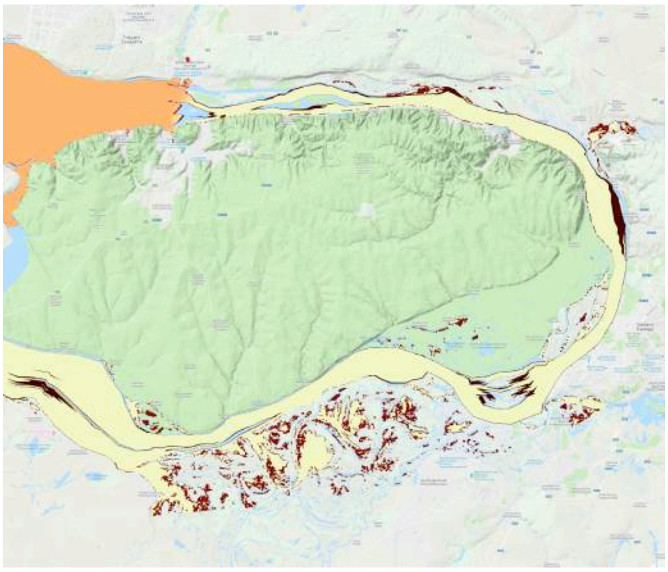

Fig. 6. Comparison of two scenarios for water surface elevation: the proposed water management scenario (lighter color) and given by RusHydro scenario (darker color).

Thus, the developed water flow model perfectly corresponds to the data provided from the river manager – RusHydro and may be considered as validated.

A proper comparison of the two water elevations (scenario 1 and scenario 2) may be seen with a closer view at Fig. 6. Where the lighter color indicate water surface elevation with the proposed water discharge (Scenario 2) and the darker color stands for additional water overflow with the given by RusHydro discharges (Scenario 1).

Obviously, it may be seen that there is much more are covered with water in the first scenario compared to the second one. However, the proposed discharge flows are developed in a way to mitigate flood impact and allow water to overflow in the regions where it is safe, while maintaining necessary water levels in the regions where there is high risk of damage.

C. Flood Impact Estimation

In order to provide a proper estimation of the flood impact obtained water surface elevation values have been exported to the QGIS 3.0 model.

QGIS – open-source cross-platform desktop geographic information system that provides editing and very broad analysis of geospatial data [20].

As was indicated in the introduction part, flood impact may be evaluated as a product of water height and population density.

Population of the modelled region was provided by NextGIS Data [21] that includes a vast set of GIS data for different countries of the World and different regions, such as administrative borders, roads, hydrology, railroads, buildings, land uses, power supply lines, populated localities, rivers, vegetation, etc. In our case a data set of populated localities was used in the form of polygons. A zoomed view of such polygons is shown in Fig. 7. Each of the polygons in its attributes has its population according to the population census held in Russia in 2016.

After data being extracted, it has been corrected in a proper way in order to remove any errors, such as overlay of the polygons onto the inhabitant areas (rivers, lakes, deserts etc.).

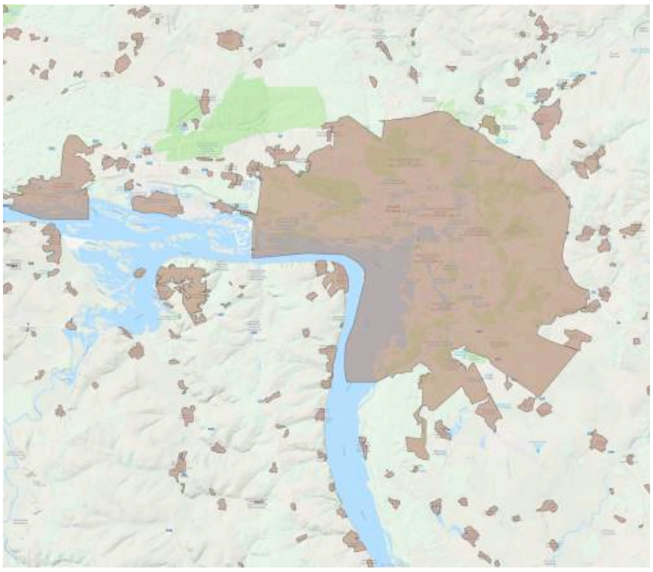

Fig. 7. Populated localities in polygons along Volga river: Kazan city and surroundings

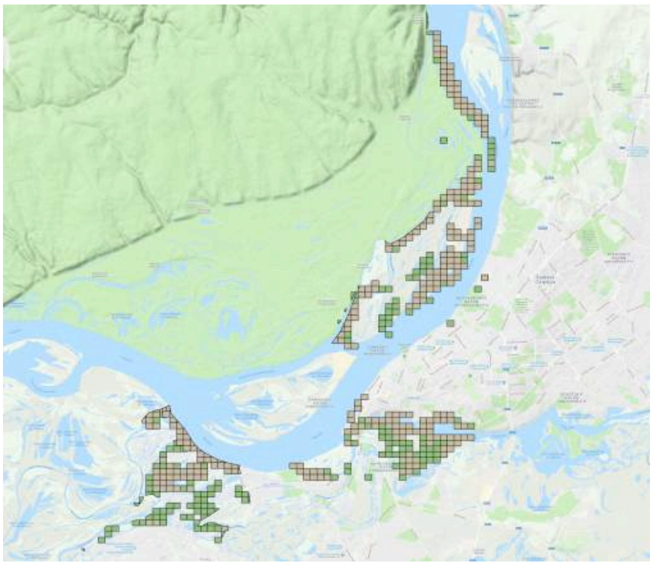

Fig. 8. Intersection of the flooded and populated areas clustered in 30 m size pixels (lighter color – Scenario 2 overlaid to darker color – Scenario 1).

Fig. 9. Flood impact incurred after implementing RusHydro water management scenario (Scenario 1).

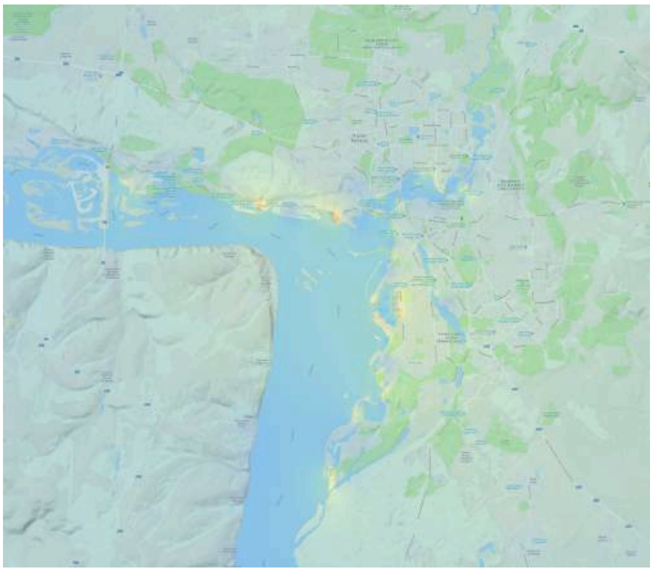

Fig. 10. Flood impact incurred after implementing proposed water management scenario (Scenario 2).

Then the QGIS model performs calculation of the intersection of the flooded and populated areas in pixels with 30 m size each. The size of the pixel may be altered in order to improve the resolution or increase the speed of calculation. The result of this operation is shown in Fig. 8. On the Fig. 8 lighter pixels stand for the flood in Scenario 2 and are overlaid to the darker pixels that stand for Scenario 1.

Basing on this spatial analysis impact is estimated for each pixel as a product of population of the locality and flooded water height above surface level. Then all the specific impacts for each pixel corresponding to each scenario are integrated in order to obtain a total impact incurred by floods that can be compared between each other.

III. RESULTS AND DISCUSSION

Results of the spatial modelling are presented in Fig. 9 for the given by RusHydro scenario (Scenario 1) and in Fig. 10

for the proposed scenario (Scenario 2). In the both cases on the figures the impact incurred by the flood for both scenarios is shown. The brighter the region the higher impact is, which is a function of population and water level.

Same images may be obtained along all Volga-Kama river basin.

The comparison of two images show that in case of proposed scenario number of bright areas is less on the map and their intensity is much lower compared to the RusHydro scenario.

Thus, it may be observed that it is not the case that the higher water level the more severe the impact is. On the contrary, it turns to be that the highest impact is incurred in the small localities. This stands for the correctness of the suggested approach to minimize the impact in highly populated areas and let water overflow in low populated areas.

Calculation of the total impact values for both scenarios results in it decrease by two times after implementing the proposed scenario.

IV. CONCLUSIONS

It is obviously shown in the paper a validity of the suggested approach to minimize flood effects of highly populated areas by means of controlled organization of proper water discharge along the river dam system. Such proper water discharge aims maintaining certain water level at each segment of the river system, while producing required financial revenue and minimizing the risk of flooding highly populated areas. Comparison of the suggested approach with the implemented one by the river management company – RusHydro was performed. It consisted of water flow modelling with HEC-RAS software and estimation of water surface elevation, and evaluation of the impact incurred by floods to the populated localities situated along the river system. Implementation of the optimized water system management algorithm allows to minimize by two times total impact incurred by the flood at Volga-Kama river basin. This is performed by strict control of the water surface elevation at highly populated regions while allowing water overflow in the desert areas or areas with low population.

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