Technique for modelling flooding zones of coastal areas in the cascade of hydroelectric power stations on the Angara river

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Abstract. This article presents the method for modelling underwater three-dimensional topography and its combining with terrain under conditions of incomplete source data. The technique for constructing 3D elevation model was tested within the research projects conducted in Matrosov Institute for System Dynamics and Control Theory Siberian Branch of the Russian Academy of Sciences in collaboration with colleagues from other research institutes of Irkutsk Scientific Center under the comprehensive studies of Lake Baikal, the Angara River and the Bratsk Reservoir. We present an algorithm for combining underwater topography with terrain based on heterogeneous source data using the Delaunay triangulation. The combining yields a high-quality 3D elevation model. This model can be used to make forecasts of the changes in the coastlines of reservoirs, which are associated with water discharges from hydroelectric power stations. The described technique was used to solve some practical problems and showed its effectiveness. To combine the data on the terrain and underwater topography, we developed a special software using the Delaunay triangulation algorithms. For data layers, their roles were indicated during the triangulation. Layers contained the information about terrain, watermarks, contours of the coastline, and underwater topography. For underwater topography, we used the information about the marks of the water edge. Based on these data, we built an additional triangulation, from which we subsequently obtained the information about heights because contours of coastlines are confined to heights, and depths are measured relative to heights. As a result of this study, we processed some settlements and estimated possible flooding.

1. Introduction

The channel of the Angara River has a rather complex structure with many islands, backwaters, anabranches and estuarine areas of the inflowing rivers. In terms of potential flooding, the 67 km section from the dam of the Irkutsk Hydroelectric Power Station (Irkutsk HPS) to the town of Angarsk inclusive is the most dangerous. Here, approximately one million people live, and the largest enterprises of the Irkutsk Region are located. Taking into account high risks of flooding in urban areas with increased discharges through hydrometric stations of Irkutsk HPS, it is necessary to develop models that will determine the potential zones and boundaries of flooding. Regular satellite monitoring of an area of interest clarifies the boundaries of coastlines with an accuracy of several meters. This is an expensive endeavour requiring regular satellite images of good quality.
The basis of the river modelling is the generation of a three-dimensional model of its underwater part and combining it with generalized digital models of the terrestrial part. Vector electronic maps of various scales present terrain with varying degrees of detail, whereas the information about underwater topography of the Angara River in electronic form is limited, not systematized and, according to specialists operating with navigation equipment, has a large error.

The atlas “Map of the Angara River from Irkutsk HPS to 142 km on a scale of 1:10000” printed in 1994 was adopted as the basic information about the underwater topography of the Angara River. In this regard, it became necessary to digitize the presented data and combine them with the existing topographic base.

To digitize the printed Atlas of maps of the Angara River, we used the free-distribution cartographic vectorizer, Easy Trace version 7.99. We digitized contour lines of depths, marks of depth points and coastline.

Combining the contours of the vectorized coastline with the coastline of topographic base revealed that some fragments of the Atlas maps were drawn schematically. The Atlas reflects typical coastline bends, but it is impossible to combine this line through rotation and shift with more accurate contour (for example, the satellite image data). Refinement of transformation parameters of rotation and shift of characteristic points on the maps did not improve the result.

To generate a topography model from heterogeneous data with different accuracy, we developed software for morphing (transforming) electronic maps. For morphing, we searched for a continuous plane transformation that allowed us to combine inaccurate coastline contours with more accurate ones. To combine maps, we used coastline layers located on both maps. We also used this transformation for other layers of the underwater topography map (isobaths and depth marks).

The resulting data appeared to be better combined with the information about the terrain (transformed isobaths and depth marks did not go beyond the coastline).

With a sufficiently accurate topographic model, it is possible to assess potential zones and boundaries of flooding, taking into account the discharges from Irkutsk HPS. Moreover, the period of extremely low water level in the basins of Lake Baikal and the Angara River since 2014 [1-9] arose the problem of obtaining the shallowing boundaries in the downstream of Irkutsk HPS and the coastal areas of the Bratsk Reservoir to determine possible potential sites of water intake, which can be in the risk zone.

2. Models and methods
Using the modern GIS-technologies: QGIS and original software (TINSmith, figure 1), with the Delaunay triangulation [10], we modelled zones of the possible flooding during the rise of water level in the HPS water cascade of the Angara River. We identified dangerous sites and settlements threatened under various scenarios of the water content [3, 9].

![Figure 1. Special TINSmith software for the Delaunay triangulation.](image-url)
For these methods, the topography from the open sources, SRTM and ALOS, pilot maps and vector map on a scale of 1:50000 were also used. Due to significant inaccuracies of measurements from the open sources near the coastline of water bodies, we decided not to use them and take the terrain from vector topographic maps as a basis.

To generate a topographic model, various layers of the topographic base are used, which can play a different role in triangulation that describes topography. All this is adjusted in a special way in the TINSmith original software: horizontal and vertical control (topography), surfaces of reservoirs (surfaces with a constant height), rivers, and streams (linear and areal objects) are used to correct the topography, the marks of water edges and data on the underwater topography are used in the work with the underwater part. We implemented an algorithm for correcting the topography generated from contour lines. This enables us to correct errors typical of these algorithms: artifacts that create a terrace effect.

At first, we take an underwater topography (the triangulation correction algorithm). We have proposed a technique for terrain and underwater topography, which suggests a separate construction of the underwater topography triangulation. For this, an algorithm of horizontal sites is used. After that, the points and rigid edges of the resulting triangulation are saved to files. These files are used in a combined triangulation. Therefore, the edges added to the triangulation for correction will be included in the final combined triangulation and will correct the stair-stepping (terrace) effect. We cannot directly apply the triangulation corrections to mixed triangulation because after subtracting the depth from the water level, horizontal triangles become non-horizontal.

For the coordinated combining the contours of the terrain coastline with the vectorized coastline of underwater topography, the problem of matching these lines (topographies) was solved because the underwater topography was obtained from one data and the terrain from other. To solve the problem of verifying reliefs, the model of obtaining a consistent topography was implemented based on the following stages:

- obtaining source data (vectorization of the printed version of the map in the absence of an electronic version);
- conversion of the vector topographic base and digitized pilot map to a single coordinate system (WGS 84);
- setting morphing parameters and conducting morphing itself;
- obtaining a terrain coordinated with underwater topography.

During morphing (a mechanism for transforming and combining underwater topography with terrain), there is a continuous plane transformation that can combine inaccurate contours of the coastlines with more accurate ones. To combine maps with various types of topography, layers of the coastlines located both in underwater topography and terrain are used. The transformation is applied to various layers of the underwater topography map (isobaths and depth marks). The data resulting from morphing appear to be consistent with the information about the terrain.

The contour combining (the problem arises from the inconsistency of terrain with underwater topography) was implemented as a special task in the IrkGV electronic map viewer. The operator working with the program adjusts the parameters in a certain way, which combines the points of the source (inaccurate) and target (accurate) maps. When the contours are combined, the start and endpoints of the arrows drawn by the user are projected onto the contour points of the corresponding maps nearest to them. Next, a mapping of each contour section of the object on the source map is generated into a specified object on the target map for each pair of arrows that are adjacent on both contours.

The points of contour sections that are combined with each other are displayed through a linear transformation of the parametric coordinates of the curves. If the result obtained is not suitable, then to guarantee the combining some characteristic points of contours, it is necessary to compare these points with each other. After entering information about the combining maps, a file of displacements is
formed, in which, in addition to the obviously specified displacements, there are displacements calculated for intermediate points of the contours.

The generation of the topography of the Angara River fragment for a section of 135 km in the interval from Irkutsk HPS to the town of Svirsk and the Irkutsk Reservoir resulted in obtaining a comprehensive digital model (figure 2) of the underwater topography combined with the terrain. A digital elevation model of this kind has been obtained for the first time and has no analogues.

![Figure 2](image2.png)

**Figure 2.** Triangulation for a given area and an example of possible flooding under various scenarios of the water content (the Irkutsk Reservoir). Contour lines are plotted every 20 cm.

Based on the modelling various scenarios of water level rise using the QGIS standard methods, we obtained an album with maps of the settlements (103 objects) that are subject to flooding. A map with contour lines was generated for the level rise of up to 5 m and contour lines every 20 cm (figures 2-4). An expert assessment of the risks of the possible flooding was carried out for each settlement.

### 3. Result and discussion

Based on the technique described above, we developed digital elevation models of the Irkutsk, Bratsk and Ust-Ilimsk reservoirs (figures 2-4), including the zones of possible flooding (in the form of contour lines) under various scenarios of the water content. Based on this technique, we generated an electronic map of the coastline (buffer zone from 4 to 10 km) and obtained a digital album for the Angara River within the Irkutsk Region. We processed 103 settlements within the Irkutsk Region and constructed contour lines with flooding threat levels for each of them.

![Figure 3](image3.png)

**Figure 3.** The Bratsk Reservoir and a fragment of the Bratsk city.
4. Conclusion

In conditions of elevated and extremely high influx to Lake Baikal, taking into account the current rules for regulating water levels in the lake, there are high risks of flooding in the downstream of Irkutsk HPS. To assess the possible damage, we have developed a technique for modelling the channel of the Angara River as well as special software components that allow us to investigate flooding zones at various discharges through HPS.

Using this technique and the developed digital elevation model, we can make various forecasts about the scenarios and threats under different water level regimes for all settlements adjacent to the bank of the Angara River in the section from the river source to the Bratsk Reservoir. We have identified dangerous sites and settlements that are threatened under various scenarios of the water content.

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Reference

[1] Grachev M A 2016 Maybe-bag and let it be. Ecological crisis on Baikal: A mystery of the century Science First-hand 68 6-19
[2] Bychkov I V and Nikitin V M 2015 Control of level of Lake Baikal: problems and possible issues Geography and Environmental Resources 3 5-16
[3] Bezrukov L A, Saveliev V A, Nikolskii A F and Podkovalnikov S V 1997 Baikal and hydropower: ecology and economy Geography and Environmental Resources 4 158-68
[4] Autova A A, Promina N M and Tulohonova A K 1999 Hydropower and Condition of an Ecosystem of Lake Baikal (Novosibirsk: Publishing house SB RAS) p 280
[5] Itskovich V B, Shigarova A M and Glyzina O 2015 Change in the Hsp70 content in the Baikal endemic sponge Lubomirskia Baicalensis during decolorization and under hypothermia Aktual'nye Problemy Pribaikalya 4 135-8
[6] Vashchenko B 2015 Aliens in Baikal National Geographic Russia 146 6
[7] Kravtsova L S, Izboldina L A and Khanaev I V 2014 Nearshore benthic blooms of filamentous green algae in Lake Baikal J. Great Lakes Res. 40 441-8
[8] Timoshkin O A, Samsonov DP and Yamamuro M 2016 Rapid ecological change in the coastal zone of Lake Baikal (East Siberia): Is the site of the world’s greatest freshwater biodiversity in danger. J. Great Lakes Res. 42 487-97
[9] Abasov N V, Bolgov M V, Nikitin V M and Osipchuk E N 2017 On Regulation of the Urovenny Mode of Lake Baikal Water Resources 44 407-16
[10] Skvortsov A V 2002 Delaunay Triangulation and its Appliance (Tomsk: Tomsk University press) p 128