The use of triangulation processing algorithms for the construction of combined model of the underwater and above-water terrain of the bed of the Bratsk Reservoir

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Abstract. The article summarizes the experience gained during processing of the data about the terrain of the Bratsk Reservoir bed. We discuss the available sources of information on the land and underwater terrain and justify the choice of the sources used in the project. To measure the actual depths in the regions of interest an echo-sounder of the consumer grade was applied, and we consider the processing of its measurements in some details. We describe the free, open source and custom software, which we apply for the processing of the data. We consider the use of the several algorithms that we have developed for processing of the terrain points. The main goal of this processing is to obtain the combined terrain model, which summarizes the data from the various information sources: the topographic maps, the pilot charts and the echo-sounder measurements. All the algorithms considered build and process the triangulations of irregular sets of points. The algorithms used are: constrained Delaunay triangulation construction; removal of artefacts of triangulation, constructed from the terrain isolines; map morphing to reconcile the terrain models; and triangulation fragment replacement. The resulting combined terrain model contains all the information about the terrain in the area of interest and allows to use the model for the further hydrological calculations.

1. Introduction

For several years the Angara-Baikal basin is in the state of severe water shortage. At the same time, the permissible range of Baikal levels is tightly limited by the RF Government decree [1], in spite of which the Baikal level has fallen below the lower limit of the regulated range and forced the Government to issue the new temporary (especially for the period 2018-2020) document [2], which relaxes the restrictions. Due to the water shortage now the Irkutsk HPP is operating at the minimum acceptable level of water discharge, which ensures the minimum permissible level of downstream water. And the only way to control the entire river cascade is to consume the Bratsk Reservoir. As a result, the threat of shutdown of water intakes located around the reservoir emerged in case of a decrease in the water level below the height marks used in their design. In the summer of 2017 an expedition was conducted at the Bratsk Reservoir in order to study the state of all the major water
intakes and some other facilities. Our team was responsible for cartographic support and processing of spatial data for the expedition.

To be able to compute the groundwater level for the wells and the water depths near the surface water intakes it is required to obtain the terrain model of the nearby area. In this paper we consider the algorithms that we utilized to process the expedition materials in order to collect the combined terrain models in the vicinity of the water intakes.

To construct the terrain models we use the following sources of information: the terrain isolines from the vector topographic base of scale 1:50000; the depth marks and isobaths, digitized from the Bratsk water reservoir pilot charts; the depths measurements made during the expedition using an echo depth sounder. It was required to reconcile the information from all the data sources to get a realistic result. To improve the quality of the ground terrain model obtained by isolines, the triangulation correction algorithm developed by the authors was applied, which makes it possible to remove the distinctive artefacts of the models resulting from isolines.

The terrain models used were represented by triangulations. All the algorithms considered in this article construct, transform or use triangulations. We utilize our own implementation of triangulation library, which is fast, robust, and can handle large data sets. Some other tasks were performed using the open source QGIS program and the free version of EasyTrace program [3].

2. Models and Methods
Let us explain our choice of the sources of information for construction of the combined terrain model, and consider the algorithms, that were used for their processing.

2.1. The sources of information about terrain
The information about ground terrain is relatively easy available in several forms. The SRTM grids exist for the whole area of interest, but the resolution of the SRTM data (3" \( \approx \) 90 m per pixel) is too low to be able to obtain the required precision of water level estimates. The ASTER grids have higher resolution (1" \( \approx \) 30 m per pixel), but the quality of the data in the Irkutsk region is inferior and prohibitive for any practical usage (an interested reader may try to observe the dam of the Irkutsk HPP, which is quite strait in real life, as well as on the SRTM tiles and on the Google Maps’ images, but looks like a saw on the ASTER grid). The high-quality (10 m per pixel) elevation model WorldDEM [4] is available commercially, but by the time of the project start the minimum order size (500 km\(^2\)) and the price per square kilometre would consume a substantial part of the project budget. More importantly, we did not had any practical experience of the WorldDEM data usage by that time to be sure of the actual quality of the data (and the ASTER case shows, that we shouldn’t completely trust the advertising promises).

As a result we settle upon the vector topographic maps, which exist for the whole Bratsk Reservoir area with the scale 1:50000, and for some parts of the region with the scale 1:25000. The vector maps contain a precise enough representation of the strand lines, which allows to use the map morphing technique for aligning the underwater data with the ground terrain (see the section 2.3. ). The main disadvantages of the available topographic maps are high vertical interval (20 m) of all the nonclassified maps and rather old date of survey (circa 2000), but it is still the best available information source about the ground terrain.

In contrast to the ground terrain it is very hard to find any information about the underwater terrain. At the start of the project we had a hope to find some old topographic maps of the Bratsk Reservoir area before its flooding. Then it would be possible to get some information about the underwater terrain, which was on the ground at the time the map was created. Unfortunately, we have recognized later that the water-flooding of the Bratsk Reservoir began in 1961, and the topographic base of the Irkutsk Region was first created in the 1970s, so we were unable to find the maps with the terrain of the reservoir bed before flooding.

As a result, the only a-priory source of information about the underwater terrain that we have found are the pilot charts of the Bratsk Reservoir [5]. The date of survey of the pilot charts is even much
more old (1974) than that of topographic maps, but that’s all we have. Moreover, the pilot charts are not maps: they are very schematic and cannot be directly combined with the much more accurate contours of the topographic base. So we apply the special technique of map morphing, which we have developed earlier, to be able to use the data.

The actual state of the underwater terrain in the areas of interest was explored during the expedition using a portable echo sounder with its own GNS receiver in conjunction with a professional GNS receiver. The resulting tracks were used for the terrain model update in these areas.

2.2. The ground terrain model

The source topographic maps are represented in the SXF files [6] – the exchange format of the Panorama GIS. The topographic maps of the scale 1:50000 are split into the sheets of the size 10'x15'. The sheets containing the Bratsk Reservoir parts belong to the two neighbor 6-degree zones. For each of the 6-degree zones we have created a temporary map containing all the sheets from the zone (with an object attribute, containing the original sheet name). From the temporary map we have selected the list of all the water objects named “Bratsk Reservoir” to obtain the list of sheets, which contain some part of the Bratsk Reservoir. For each of the zones the sheets from the lists were merged into a single SXF file using the utility SXFUnion, developed earlier by authors, because the Panorama software doesn’t provide this kind of operation. The SXF files were opened in the GIS Panorama Mini and their layers of interest (terrain, hydrography, settlements) were exported to SHP files using the Panorama built in converter. The Panorama SHP converter export always converts the coordinates to degrees on the WGS-84 ellipsoid. We have converted them back to the Gauss-Krüger (transverse Mercator) 6-degree zone 18 using the QGIS utility ogr2ogr and then merged using the same utility. As a result we have several layers in SHP files: terrain isolines, point height marks, water polygons and so on for the whole Bratsk Reservoir region.

The layer of water polygons requires further processing: it contains the parts of the Bratsk Reservoir into which it was split by the boundaries of the map sheets. The boundaries between the parts would become the triangulation hard edges (constraints) and spoil the resulting triangulation in its water areas. To join the parts it is not enough to union the polygons: due to the small differences in the coordinates of the border points for the neighbor subobjects from the different sheets the resulting object may still be divided into several parts or have some narrow slots. So we use the following sequence of actions in QGIS to union the parts. At first we compute the “fixed distance buffer” of all the layer objects with the buffer distance of 1m and the dissolve parameter turned on. As a result all the objects will be merged in spite of the small mismatches in the coordinates of the boundary points, but also we will have a side effect: the resulting object will be replaced by its 1m buffer. To almost completely remove the side effect we perform again the operation “fixed distance buffer” but with the buffer distance of -1m and the dissolve parameter turned off. The resulting side effect of this sequence is a minor smoothing of the resulting object border, and it is absolutely acceptable.

2.3. The underwater terrain model

To obtain the vector representation of the pilot charts we scan the paper sheets and vectorize the resulting files using the program EasyTrace 7.99. As a result we have several SHP files for the layers of the vectorized chart sheet. The pilot chart sheets are arbitrary oriented, and we should rotate and shift them to initially align the sheets with the topographic map. To find the correct initial coordinate transform we find some distinctive points, which are present on both maps. We prepare the list of the coordinates of the distinctive point pairs. The list should contain at least two point pairs. We have developed a utility program, which takes the list of coordinate matches, computes the coordinate transform, and performs it for the list of shape files specified in its parameters.

After rotation and shift the match between the topographic map and the pilot chart still won’t be perfect, because the pilot chart is very schematic. Both maps contain a representation of the shore lines and we can compare the representations. The water level of the Bratsk Reservoir object on the map is
402 m. And the water level on the pilot charts is almost the same – 401.65 m. This difference can be neglected – it allows matching the shore lines.

We have developed earlier the technology and software for map morphing, which allows to specify the matches between the line points, and to shift the coordinates of the imprecise map to their correct positions. The field of coordinate shifts is represented here by triangulation. As a result we move the shore line points to the more precise positions. In fact the shifted shore lines themselves are not required at all (because we already have the correct ones), but the coordinate transform obtained allows to smoothly shift all the other pilot chart layers to the positions, that don’t interfere with the topographic map features. For example, the depth marks or isobathic lines will be placed into the water areas, and not on the land. The process of map morphing was discussed in more details in [7].

Only the sheets of the pilot chart, that contain the areas of interest, were processed. Finally the resulting map layers of the same kind (depth marks, isobaths lines) from all the pilot chart sheets were merged into a single layer by ogr2ogr.

2.4. The triangulation software

Although triangulations are widely used in QGIS, there is no special data structure for triangulations in QGIS and its accompanying products (SAGA and GRASS GIS) like that of TIN in the ESRI products. In QGIS using a triangulation in the intermediate algorithm steps we can compute a raster or a polygonal layer of triangles, but can’t store the triangulation itself for a later use.

Our triangulation program TIN Smith is based upon the ideas of dynamic hashing from [8] and uses the robust predicates from [9]. It also implements the constrained Delaunay triangulation [10] algorithm and a family of original triangulation flood fill algorithms. In contrast to [10] our implementation of the constrained Delaunay triangulation algorithm is incremental [11] and allows intersection of the hard edges (constraints) [12]. The program uses the data structure called nodes and triangles in [8], which is also used in [11]. The algorithms were already applied to very complex practical problems like generalization of the whole map of Irkutsk and have been thoroughly tested during the application. As a result the algorithm works correctly on the very complex data sets, like that with intersections of almost identical hard line segments (which may crash some implementations for example as a result of repeated segment breaking and intersection due to the limited precision of the float coordinate values).

One of the possible data sources for the construction of triangulations in the TIN Smith are the SHP files. The point height may be taken from the Z-coordinates of the shape points or from an attribute field of the map object or from a field of a joined table. When combining several source files they may take different roles: ground terrain, water level marks, underwater terrain.

2.5. The combined a-priory terrain model

Using the layers of isolines, height marks, the Bratsk Reservoir object boundaries from the topographic map, and the depth marks and isobathic lines from the pilot chart we have created the a-priory (before the expedition) terrain model as a triangulation with constraints.

Besides from the low precision of the pilot charts, the main problem with the underwater terrain of the model is that the current water level of the Bratsk Reservoir is far below its levels on the maps and the pilot charts. In particular, the water level of the Bratsk Reservoir object on the map is 402 m, and during the expedition the actual level was slightly above 395 m. The difference is almost 7 m, and all the isobathic lines on the pilot charts have only the two possible depth values: 3 m and 5.5 m. So, all the isobathic lines describe the terrain, which now become the above-water one, and the only source of the a-priory information about the current underwater terrain is the depth marks, which are rather rarely spaced.
Figure 1. The overview of the a-priory terrain model.

Figure 2. A fragment of the a-priory terrain model.

Figure 3. The terrain model fragment with artefacts – horizontal steps.

Figure 4. The same fragment after fixing the artefacts.
The triangulations obtained from isolines always contain the artefacts, which are clearly visible on the figure 3 – the horizontal steps formed by the points of the isolines of the same height. We have developed the algorithm, which allows to fix the artefacts by adding the hard edges and auxiliary points, which cause removing of the horizontal areas. The results of the algorithm are shown on the figure 4. The fixed triangulation of the Bratsk Reservoir area contains 6610182 points.

The TIN Smith program allows to cut a rectangular fragment from the triangulation and save it into a separate file. All the other processing was performed using this capability: we cut the fragments of interest and add the a-posteriori information to them.

2.6. The echo sounder measurements processing
During the expedition a portable echo sounder with its own GNS receiver was used for the depth measurements. The main disadvantage of the data collected by the echo sounder is the rounding of the measured coordinates to integer values in meters – it produces strong aliasing (steps) of the measured paths. The precision of the GNS receiver of the echo sounder is that of consumer electronics (several meters). That’s why together with the echo sounder, in most cases a professional GNS receiver was used: The professional GNS receiver allowed to determine the exact water level markers with respect to which the depth is measured, and in most cases it was placed in the boat along with the echo sounder.

Subsequently, the GNS track of the professional receiver was combined with the marks of the depths produced by the echo sounder using the time measurements stamps. Fortunately, both devices record the GPS-time [14], which is very precise for our purposes. The output file of the professional GPS receiver records the position of its rover every second, and the echo sounder records its measurements with a higher frequency. The echo sounder stores the time in milliseconds as an integer value, but the rounding of the horizontal coordinates to meters may place several measurements into the same point. We use the linear interpolation between the professional GNS coordinates to estimate the echo sounder position at the time recorded in its measurement. We have developed a special utility program to perform this task.

The figure 5 presents the results of the hardware test performed before the expedition. Note the aliasing of the echo sounder measurements and their error, which is mostly systematic in its nature.
3. Results and Discussion
Since the pilot chart data give a fairly rough idea of the underwater terrain it makes no sense to try to combine it somehow with the more precise data. So, an algorithm was developed to replace the triangulation fragment, which allows to remove all the marks of depth obtained from the pilot chart in the area where the real measurements exist. It removes all the target triangulation points that fall into some triangle of the source (being added) triangulation and then adds the points of the source triangulation.

Thus, to obtain the resulting terrain model in the area of interest we first cut the rectangular fragment from the a-priory terrain model, then create the auxiliary triangulation(s) for the echo sounder measurements in the area and replace the corresponding fragments in the terrain model. An example of the resulting triangulation is shown on the figure 6 (the black lines are the hard edges). Due to the low quality of the a-priory underwater terrain model the replaced fragments usually stand out against the rest of the terrain.

![Figure 6. The combined terrain model with the fragment replaced by echo sounder measurements.](image)

Using the triangulation computed we can build profiles along any polylines. The profiles are required to perform the hydrological computations for the wells. We can also build isolines of the terrain model, for example, to improve the underwater terrain representation using the echo sounder measurements.

4. Conclusion
We have considered the experience gained during preparation and processing of the terrain data around the Bratsk Reservoir. To handle the data we use free and open source software, some custom utilities and our own program TIN Smith, which implements several original algorithms of triangulation processing. We have briefly described those of the algorithms, which were used in the project.

In spite of that our knowledge about the underwater terrain of the Bratsk reservoir (as well as for almost all the other water bodies) is extremely limited and inaccurate, as a result of the application of the algorithms developed it become possible to obtain the terrain model with the accuracy sufficient for performing the further hydrological calculations.
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