RESEARCH PAPER

DIGITAL ELEVATION MODEL DEVELOPMENT OF THE VOLGA AND DON RIVER'S DELTA AND APPLICATION IN HYDROLOGICAL MODELING

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ABSTRACT. The article describes the methodology for constructing digital elevation models for the vast delta areas of the Don and Volga rivers for further use in mathematical models of flooding from surges. The initial cartographic data and features of the delta regions are described. The methods of information processing are considered in detail. An algorithm for constructing a DEM has been developed to obtain highly detailed digital elevation models. The algorithm is based on combining the DEM of individual key features - land, the depths of the hydrographic network and the bathymetry of the receiving reservoir for the river. The topographic maps, maps of the navigable route depths, hydrographic maps, and satellite images Landsat-8 and Sentinel-2 were used to create the DEM of the Don and Volga river. To build individual DEMs, a raster of the absolute depth of the channels, a hydrography DEM, a land DEM, and a shelf DEM were created using geoinformation systems. To assess the possibility of using obtained DEMs in hydrological models based on HEC-RAS, we conducted training and verification calculations of water level during wind surge phenomena in Don Delta using different surface roughness coefficients. The calculation results show good reproducibility of observed water level fluctuation in the Don Delta using obtained DEM with a roughness coefficient of 0.0125. Also, we carried out similar calculations of storm surge phenomena in the Volga Delta using obtained DEM and combinations of various riverbed and not riverbed roughness coefficients. The combination of 0.007 for riverbed and 0.02 for not riverbed surfaces reproduces the observed water level fluctuation during storm surge phenomena in Volga Delta. The constructed DEMs for the Volga and Don deltas made it possible to reproduce the observed dynamics of river discharges and water level fluctuations during surge events. Such detailed DEMs, taking into account all the complexity of the coastal and delta relief, were created for the first time for the Volga and Don.

KEYWORDS: Don River, Volga River, delta, digital elevation model, hydrological modelling

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INTRODUCTION

River deltas are among the most densely populated and economically important areas in the world (Vörösmarty et al. 2009). Deltas, as places of mutual influence of river flow and the sea, are characterized by flooding due to short-term level fluctuations caused by wind activity, river flow dynamics, tidal phenomena, or various combinations of these factors (Nienhuis et al. 2020).

Geomorphologically, the river delta is a coastal accumulative lowland at the confluence with the receiving reservoir, cut by branches and channels of the main river channel. Due to its importance in the economy, it is necessary to rationally manage the resources of river deltas, taking into account their natural and hydrological features and characteristic fluctuations in water levels. The development of simulation methods (Blumberg & Mellor 1987, Young 1999, Booij et al. 1999) makes it possible to perform experiments on the calculation of the impact of storms and surges on deltas and near-delta shallow waters, river delta and coastal flooding areas for conditional and real values of sea level and river flow, taking into account the slope of the delta, the type of underlying surface, the properties of soils, near-water vegetation, as well as the presence and characteristics of hydraulic structures on rivers. An important condition for obtaining a qualitative result in this case is an accurate and up-to-date digital elevation model (DEM) of the object of study. Publicly available DEMs with a spatial resolution of at least 30 m/pixel, based on the processing of radar satellite imagery (for example, SRTM (Shuttle…), ASTER GDEM (NASA… 2019), JAXA's Global ALOS 3D World (Takaku et al. 2020)) do not allow detailed studies for vast lowland areas. In this regard, it is necessary to develop DEMs for specific river deltas using data from various types of maps (topographic, navigation, sailing directions), satellite imagery and field data (Nelson et al. 2009).

The Volga Delta is the largest in Europe (more than 27 thousand sq. km. (Polonskii et al. 1998), although its area varies greatly depending on the water level in the Caspian Sea (Li et al. 2004)) seashore in the Caspian Sea forms a unique natural complex. The flora and fauna of the Delta have been under state protection since 1919, since the formation of the Astrakhan Reserve (Astrakhan...). In 1976, the Volga Delta was included in the list of wetlands of international Ramsar Convention (The List of Wetlands…). Currently, the Volga Delta occupies more than 27 thousand sq km and is a triangle in shape with a peak at the source of the Buzan River (Narimanov town), facing the sea with a height of more than 110 km with a maximum width of more than 250 km. Geographically, the Volga Delta begins at the point of separation from the Volga channel of the Buzan branch (north of Astrakhan) and has up to 500 branches, channels, small rivers and eriks. branches of the delta - Buzan, Bakhtemir, Kamyzyak, Staraya Volga, Bolda, Akhtuba, Kigach. They form systems of smaller streams (up to 30–40 m wide and with a water flow rate of less than 50 m^3/s), which form the basis of the channel network and cut through the sea edge of the delta. Most of the mouth coast of the Volga is a vast shallow area up to 200 km wide and 30-35 km long with depths of less than 1 m, significantly overgrown with aquatic vegetation. The rest of the coast, 15-20 km long, has depths from 1 to 10 m. Due to the Caspian Sea level fluctuations in the XX-XXI centuries the Delta area has changed several times over the past 130 year (Ogorodov et al. 2020). The Volga Delta is characterized by water level fluctuations up to 4-5 m, leading to flooding of large areas due to the flatness of the land surface characteristic of river Deltas. The reasons for such large fluctuations in river levels here may be fluctuations in the Volga river flow and surge processes in the Northern Caspian, caused by south and southeast winds with a constant speed of more than 10 m/s for several hours.

The Don Delta occupies a much smaller area - 540 sq. km, its length is about 30 km, width is about 20 km, the top of the Delta is the source of the river. Mertvy Donets, flowing from the main channel of the Don at the western bridge of Rostov-on-Don. Among the main channels of the Don downstream, the Mertvy Donets, the Kalancha, which is divided into the Mokraya Kalancha and the Bolshaya Kuterma, and the Stary Don branch stand out. In addition, many small rivers and channels have been formed in the Don Delta. Geomorphologically, the Don Delta is a flooded river lowland with a slight elevation in the center (up to 6 m), the hydrography of which is complicated by a large number of ponds, canals, embankments and dams. The Don flows into the Taganrog Bay - a narrow (from 25 to 50 km wide) and shallow (up to 9 m) part of the Sea of Azov, in which navigation channels are arranged in the river. Don and to the port of Taganrog. With stable strong winds (more than 10 m/s) of the western direction in the Don, a surge of water is observed, often leading to partial or complete flooding of the Don Delta, from the east - a surge, during which the small branches of the delta are drained and the bottom of the near-delta part of the Taganrog Bay opens (Matishov et al. 2014a). Since 2013 in the Don Delta area 3 level gauges of Automatic System of Monitoring of Flood Events of Krasnodar Krai (AS MFEKK) were installed – 239, 1001 and 1002 (Monitoring ...). This system allows to get water level observations every 10 minutes. Gauges receive observation in near-real time regime and make it possible to study short-term water level phenomena like wind surgse or seiches.

This article presents the result of the work on the development of the DEM of the Volga and Don Deltas based on a similar set of materials using a single methodology for further use in mathematical models of flooding from surges. Such detailed DEMs, taking into account all the complexity of the coastal and delta relief, were created for the first time for the Volga and Don. In addition, surge flood zone results obtained using hydrological models are presented.

MATERIALS AND METHODS

Features of Deltas, as flat lowlands, crossed by a complex network of permanent and temporary waterstreams, determine the complexity of obtaining plausible DEMs of Deltas using remote sensing methods - orthophotogrammetry, radar imaging. The complexity of forming a DEM based on UAV survey data is due to the large area of the Don or Volga Delta. In addition, to simulate flooding due to surge processes, the reflection in the DEM of the hydrographic network of both permanent and temporary watercourses plays a key role. To build the DEM of the Volga and Don Deltas, data were used on the land relief of the Deltas, on the bathymetry of the Caspian Sea and the Taganrog Bay, on the hydrographic network, transport and hydrotechnical infrastructure. Therefore, the following materials were used to create the DEM of the Volga Delta:

-topographic maps of FSUE "Gosgiscenter" (1:25,000) (Topographic… 2012);

-topographic maps of the USSR General Staff (1:100,000) (Maps of the USSR… 2020);

-maps of the depths of the navigable route of the Volga (Volume 7…);

-hydrographic maps of the Caspian Sea adjacent to the Volga delta (chart 32006, scale 1:200,000) (32006 From Astrakhan…).

The following materials were used to create the Don Delta DEM:

-topographic maps of FSUE "Gosgiscenter" (1:25,000) (Topographic… 2012);

-topographic maps of the USSR General Staff (1:100,000) (Maps of the USSR… 2020);

-maps of the depths of the navigable route of the Don (Volume 8…);

-hydrographic maps of the Sea of Azov adjacent to the Don Delta (chart 33147 scale 1:100,000) (33147 East part of Taganrog…);

-satellite survey Landsat-8 (Landsat 8…) and Sentinel-2 (Sentinel-2…).

The geomorphology of the Don and Volga Deltas is characterized by a low-lying flat surface, in which the hydrographic network of permanent and temporary waterstreams, the bathymetry of the main branches and the adjacent part of the receiving reservoir, as well as a network of hydraulic structures, including road embankments, play a key role. Such small-scale features may be important for flooding processes in the delta. It is difficult to display land topography, bathymetry and various embankments at the same time by common methods of data interpolation for building a DEM, so the algorithm for building a DEM, shown in Fig. 1, was used in the work.

To build individual DEMs, the Topo to Raster ArcGIS10 tool (based on the ANUDEM 5.3 program (Hutchinson et al. 2011)) was used, which allows interpolating height values in each cell of the resulting raster based on an array of point,

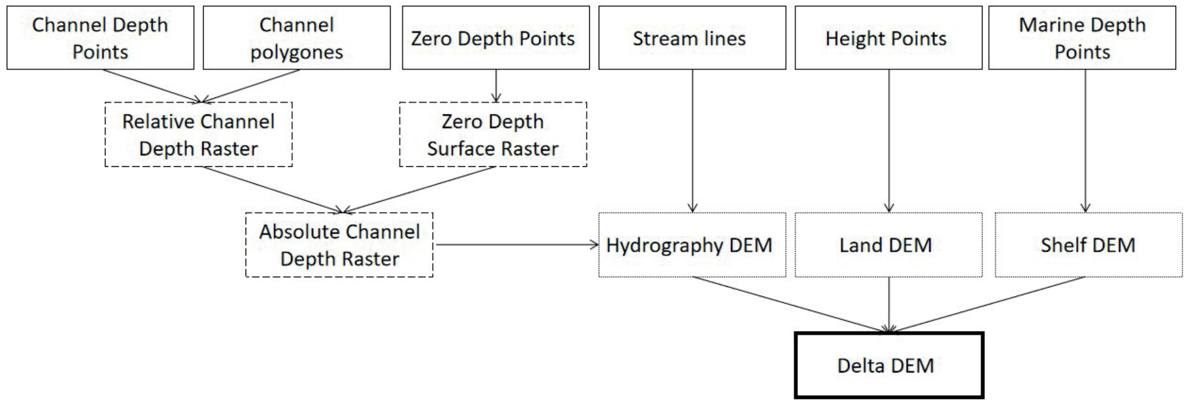

Fig. 1. Algorithm of the delta DEM construction (Yaitskaya et al. 2021)

line and polygonal objects. An important feature of this tool is that that both point values and linear (horizontals, cliff lines) and polygonal (lakes are represented by planes of equal elevation) objects are interpolated. From the point of view of geomorphology, watercourses are characterized by a special structure of the transverse profile.

The DEM of the land was built on the basis of information about the surface topography indicated on topographic maps - points of heights, contours, cliffs, lines of natural waterstreams. To construct the DEM of the hydrographic network, the polygons of the channels, the lines of the hydrographic network, as well as the height marks of the edges of the used topographic maps were used. Depth marks, major channel isobaths, and midstream lines were interpolated into the depth distribution raster within the river channel polygons. The values of the heights of the ridges were interpolated into a raster reflecting the inclined plane of the ridges of the delta hydrographic network. The lines of the hydrographic network were converted to a raster with depth values based on the depths indicated on the topographic maps, or in their absence, the value «1» was set. Further, the values of the depth distribution raster and the linear hydrographic network raster were subtracted from the raster values of the inclined surface. As a result, a DEM raster of the Delta hydrographic network was obtained. Coastal DEMs were built for the Volga Delta on the basis of bathymetric maps, and for the Don Delta on the basis of isobaths obtained as a result of deciphering the drying zones during surges using Landsat-8 and Sentinel-2 surveys (Kleshchenkov & Sheverdyaev 2020).

Checking the finished DEMs of the Volga Delta and the Don Delta was carried out in manual and semi-automatic modes:

Step 1 - sequential visual control of the obtained values of depth marks and correction of inaccuracies;

Step 2 - building «rough» GRID- and TIN-models, which were classified according to the values, the most contrasting coloring was chosen and the «spots» of emissions were already visually visible. In the case of detection of «outliers», we introduced auxiliary elevations and contour lines and built the DEM again.

RESULTS AND DISCUSSION

The obtained DEMs of the Don and Volga Deltas, as well as the computational grids of hydrological models based on HEC-RAS are presented in Figures 2 and 3. The DEM of the Volga Delta is a .tif raster file containing more than 7.1 million cells 100x100 meters on an area of 71100 sq km. Don Delta DEM contains 18.5 thousand cells on area 747.1 sq km. For the model of the Volga Delta, 4 boundaries were established (Fig. 3): for the discharge of the Volga, boundaries were established within the channels near the Nizhnelebyazhye (1) and the Buzan (2), for observing fluctuations of the water level of the boundary in the channel of the Bakhtemir channel near the Olya (3) and at the boundary of the computational grid in the Caspian Sea (4). Since the available daily observations of the discharge of the Volga are available for the Verkhnelyabyazhie (above the branch from the Volga river Buzan) and for the Buzan (respectively below), then for the Nizhnelebyazhie, they were recalculated as observations in Verkhnelebyazhie minus observations in the Buzan.

Within the Don Delta DEM, in the hydrological models based on HEC-RAS (HEC-RAS ...), a computational grid was built covering the Don Delta and floodplain from Zeleny Island within Rostov-on-Don up to the Don mouth area along the meridian 39°12´E (between Stefanidinodar and Morskoy Chulek). The computational grid is a set of cells 100x100 m, complicated by coastlines with a density of up to 50x50 m. Two boundaries were established: in the Don channel at Zeleny Island (upper entrance) and the border in the Delta mouth area, along the meridian 39°12´E (lower entrance). The discharge rate from the Tsimlyansk Reservoir was set at the upper entrance to the model with a delay of 3 days.

To assess the quality of the obtained DEMs and the possibility of using them in hydrological models based on HEC-RAS, we adjusted the surface roughness according to observational data in the Don and Volga Deltas and compared them with each other.

To determine the roughness coefficient in the Don Delta, the water levels were considered at level gauges 239 (the level gauge is located at the confluence of the Temernik with the Don) and 1001 (the level gauge is located in the village of Donskoy at the exit from the Don delta) of AS MFEKK in April-May 2018, when the largest flood in the last 10 years was observed on the river Don, which forced at that time to increase the discharge of water from the Tsimlyansk reservoir of the Don Basin Water Administration (O regime ... 2018). Surge fluctuations in the Don delta are reflected in observations both in the coastal part of the delta (level gauge 1001) and at the top of the delta (level gauge 239). The discharge of the Don is significantly reflected in the water level at the level gauge 239 (Fig. 4a). During April 19-24, 2018, a training period was held (Fig. 4b) - the water level in the Don delta was simulated using various roughness coefficients (0.02, 0.015, 0.0125, 0.01), the level change at the level gauge 1001 and average daily discharge in the Don (according to Razdorskaya station - about 100 km from Rostov-on-Don along the Don). The water levels of roughness 0.0125 turned out to be the most similar to the observed. During May 2018, a verification period took place, when the water levels were calculated using a roughness factor of 0.0125 (Fig. 4c). It is shown that taking into account the jump in the Don flood runoff by

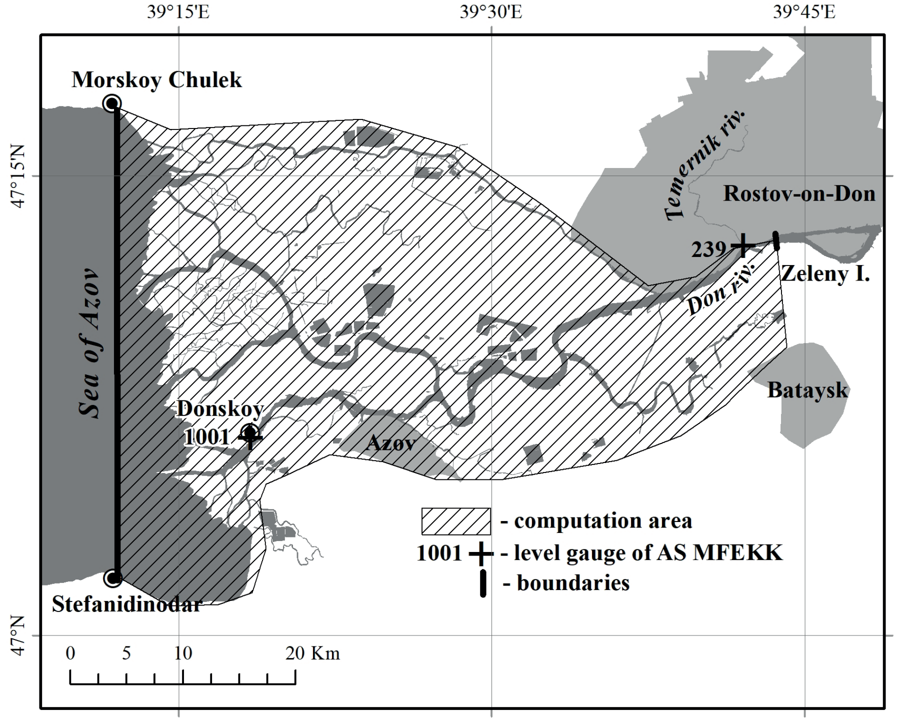

Fig. 2. Hydrography network and computation area of the Don Delta

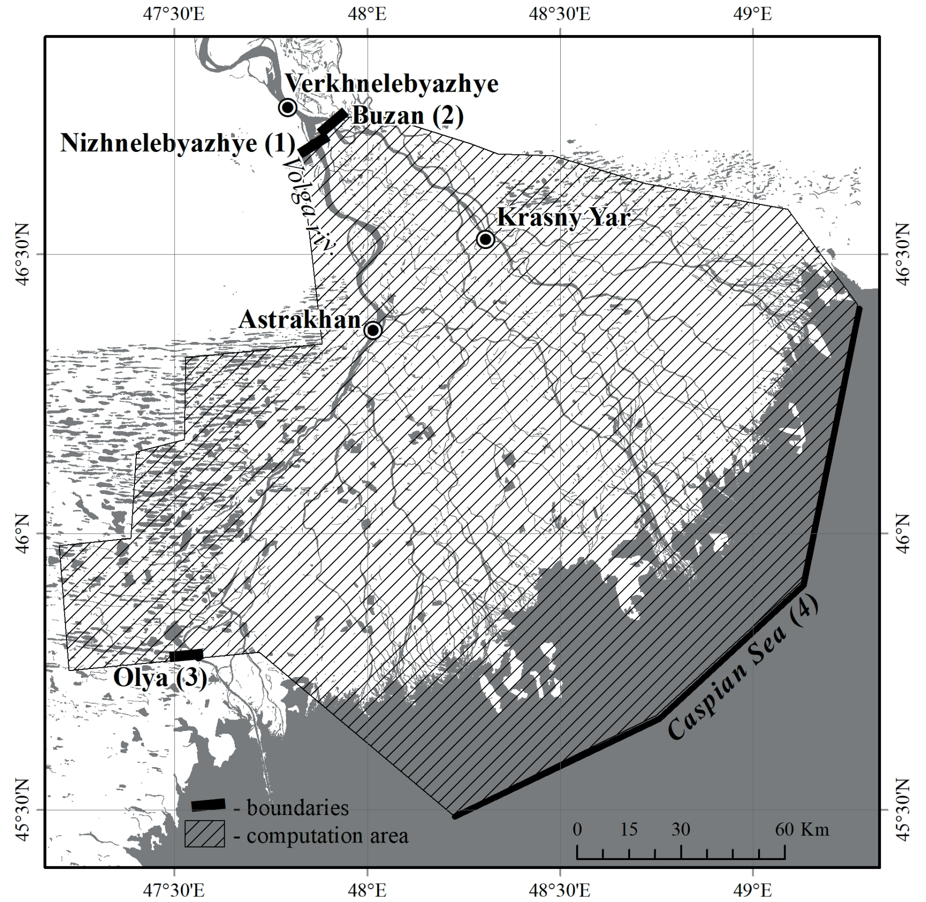

Fig. 3. Hydrography network and computation area of the Volga Delta

300 m^3/s significantly affects both the calculated and the observed water levels.

A number of calculations were carried out with different values of roughness in the channels of the Don delta (Fig. 4b) so that the course of the water level obtained at the confluence of the Temernik with the Don coincided with the value of the level gauge AS MFSKK. These calculations were carried out along the level of April 19-24, 2018, and then the optimal value was checked under the conditions of May 1-31, 2018 (shown in Fig. 4c). The presented results show that the roughness coefficient of the Don delta channel under these conditions is 0.0125, which allows the channel to pass large volumes of water without significant flooding of the floodplain.

To study the roughness coefficient of the Volga Delta, daily observations of level gauges in Astrakhan, Olya, Krasny Yar (Gauge… 2019) and daily observations of expenditures in Verkhnelebyazhye (Volga River) and Buzan (Buzan River) (Gauge… 2019).

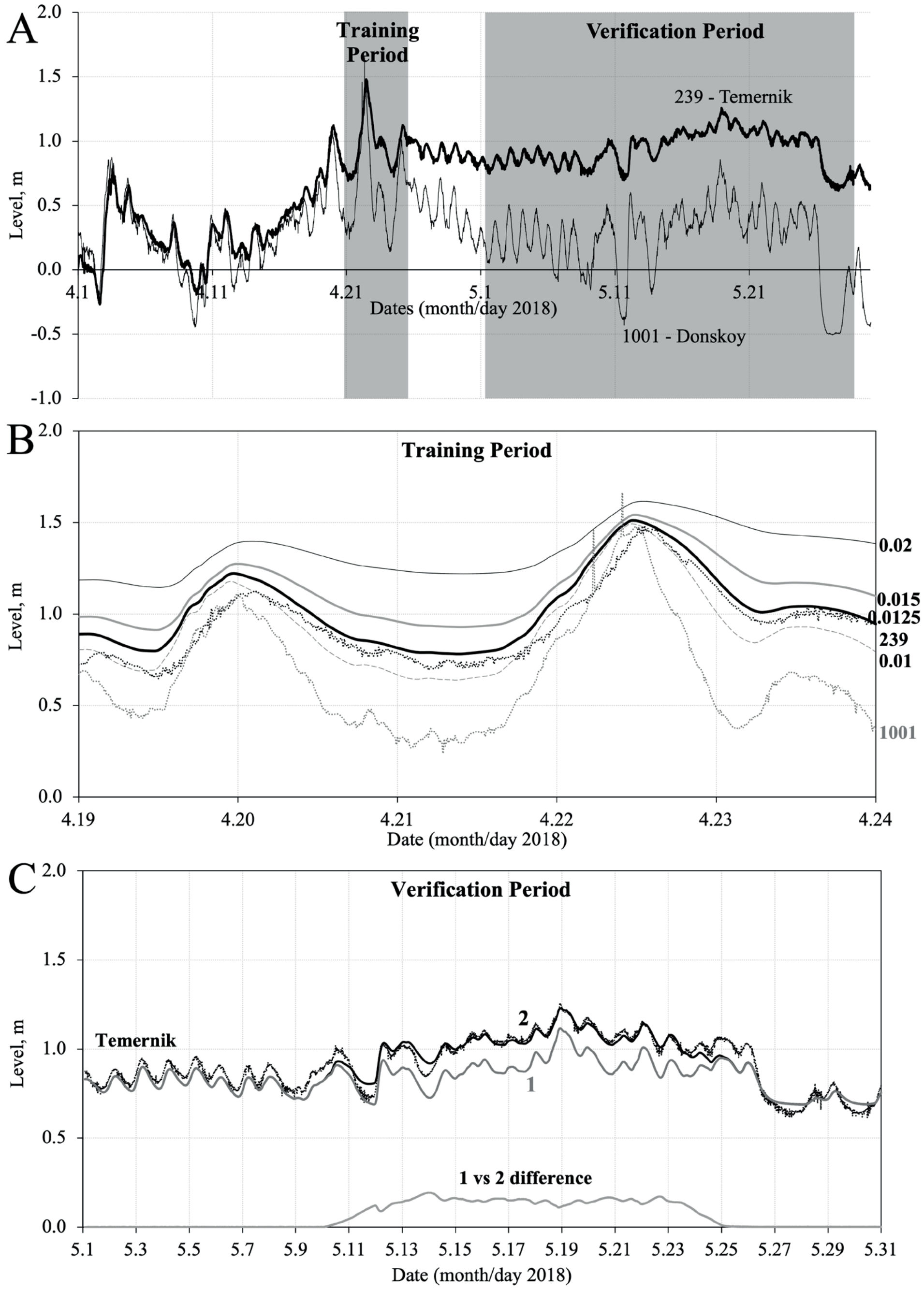

Fig. 4. A – Training and verification periods in April-May 2018 (Flooding period on Don Delta) and level observations at gauges 1001 (Donskoy) and 239 (Temernik). B – Delta roughness coefficient determining at training period in April 2018, C - modeling within Don's discharge 1500 m³/s (1), modeling within discharge 1500 to 1800 m³/s (observed increasing) (2) and Temernik - observed levels at gauge 239

Thus, pairs of scenarios with the same roughness distribution were calculated. Surface roughness was divided into two classes: Riverbeds and Not Riverbeds surfaces (land). It is assumed that the channels of the channels have a reduced roughness due to regular flow, and the land surface, on the contrary, has an increased roughness due to the reed vegetation characteristic of the Volga Delta (Table 1). For the control pair of scenarios, the same roughness was set for both classes - 0.0125 (pairs of coefficients were selected based on the idea that the Volga and Don deltas are in similar climatic conditions according to (Matishov et al. 2014b)).

Table 1. Calculated roughness distributions by class

Scenario	Riverbeds	Not riverbeds
control	0.0125	0.0125
1	0.01	0.02
2	0.0125	0.01
3	0.007	0.02
4	0.0125	0.05

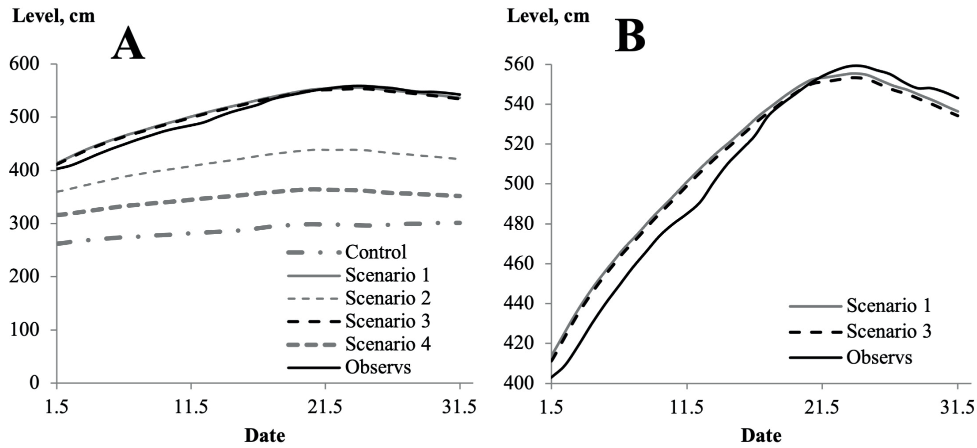

Fig. 5. Comparison of the test calculations results for different scenarios (table 1) with observations from the Astrakhan level gauge: A – results for all scenarios in comparison with observations; B – scenarios 1, 3 and observations, cm

The choice of the optimal variant of the roughness coefficient distribution was carried out on the basis of a comparison of the model level fluctuations in Astrakhan and Krasny Yar with those observed for the corresponding months. Figure 5 shows a comparison of the results of the calculated scenarios with observations in Astrakhan in May 2017.

The control scenario, corresponding to a roughness of 0.0125 for both riverbeds and not riverbeds, does not reproduce the observed level increase in Astrakhan. This is due to the rapid runoff of water both in the channel and on the land surface. Even a small increase in land roughness results in a larger level increase, as scenarios 4 and 2 show. Scenarios 1 and 3, for which the land roughness was 0.2, reproduce the observed level dynamics. We chose the roughness combination for scenario 3 due to the fact that under such conditions the level formed by the river runoff before the surge is somewhat closer to the observed values (Fig. 5B).

CONCLUSIONS

The final result of the work for constructing a DEM for Don and Volga Deltas is presented in the article. This DEM has constructed on the basis of observation data, is the most realistic and has a high level of detail. A method for constructing a DEM is proposed, based on the combination of DEM of individual key features - land, depths of the hydrographic network and bathymetry of a reservoir receiving a river.

The constructed DEMs for the Volga and Don Deltas made it possible to reproduce the observed dynamics of river discharges and water level fluctuations during surge events. However, at the same time, the roughness of the surface of the delta for the Volga and Don was different, and for the Don channels the roughness coefficient was 0.0125, and for the Volga channels – 0.007-0.01, i.e. less. DEMs can be used for retrospective analysis of effects of storm and wind surges in Deltas.

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