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Numerical modeling of nonlinear hydrodynamics of the coastal areas

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Abstract. The nearshore hydrodynamic fields are produced by the nonlinear interactions of the shoaling waves of different time scales and currents. To simulate the wind wave propagated to the coasts, wave generated nearshore currents, nonlinear-dispersive wave transformation and wave diffraction in interaction with coastal and port structure, sediment transport and coastal erosion, the chains of the models should be used. The objective of the paper is to provide an overview of the results of the application of the model chains for the assessment of the wave impacts on new port designed at the Ob lip, Kara Sea to demonstrate needs for further development of the nonlinear models for the coastal engineering applications. The open source models WaveWatch III and SWAN has been used to simulate wave statistics of the dedicated areas of the studied coastal areas in high resolution to calculate the statistical parameters of the extreme wave approaching coastal zone construction in accordance with coastal engineering standards.

1. Introduction

The development of interactive model of currents and wind waves in Ob lip, Kara Sea intended for modelling of changes of modes of waves and current at different synoptic situations and configurations of the planned hydraulic structures is presented. Two main tasks are studied.

The first is the verification of selected models of wind waves and currents with the data of natural measurements in the Ob lip in the area of interest. The second task is to demonstrate the possibilities of obtaining with the help of the developed model the characteristics of the waves and currents necessary for the design of hydraulic structures.

The development of interactive mathematical model of waves and currents is used as a model of own development of authors – COASTOX, and models with open source code: spectral model of generation and transformation of fields of wind waves, SWAN, model of calculation of diffracted wave fields in the water area of the sea waterworks, ARTEMIS.

Calculation of the climatic characteristics of wind waves at the specified points on the approach to the investigated area is performed on the basis of spectral models of wind waves, on the fields of wind over the sea for a long (30–50 years) period, when using meteorological fields from the reanalysis of meteorologicalfields NCEP\NCAR or ERA-40, with their possible downscaling, using numerical models of weather forecast.

Verification of the developed mathematical model with the help of the available data, as well as the data obtained by special measurements, allows to determine the adequacy of the developed model of waves and currents.

The technology of modeling and verification of models of waves and currents is presented. Brief descriptions of SWAN, ARTEMIS and COASTOX models are given. The results of comparison of

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characteristics of wave mode and characteristics of current on approach to area of researches in ice-free period, in comparison with data of measuring stations of the region received by Arctic and Antarctic Research Institute in Saint-Petersburg are shown. The results of calculations of statistical characteristics of waves on the approach to the research area, time series of data, calculated recurrence of waves, sea level and currents in key points near the design site are shown.

The modelling of wind-wave processes widely applied in the last decades for determination of calculated parameters of wind waves completely corresponds to actual Russian normative documents. Thus, in construction code [1] It is specified: "A.5. It can define the characteristics of the waves based on hydrodynamic and probabilistic modelling using spectral or spectral-parametric models. Verification of the results of hydrodynamic modelling is recommended to be carried out according to available measurements of the characteristics of waves in natural conditions or on physical models". The point A5 opens the possibility of wide and consistent with the regulations application of mathematical models of waves and currents, while emphasizing the importance of verification of the results of such modelling by natural data.

At the same time, the same construction codes are maintained as a recommendation method for calculating waves in shallow water, based on geometric refraction and applicable for relatively simple conditions of wave development, which, in our opinion, can be used for rapid assessment of wave parameters.

Russian scientists participated in the development of known models, such as SWAN. Besides, models of other Russian authors, both hydrodynamic, and realizing method of calculation of construction code are developed and used. For example, the program PLWAVE intended for calculation of wind-wave processes using wave ray method with empirical additives [2]. Or RAWM (Russian atmosphere-wave model) [3] for the calculation of the wind-wave characteristics based on the wave actions balance equations in spectral form. Or different mathematical models for solving the engineering problems of the wave hydraulics of the coastal zone [4].

Further detailed description of the structure of the interactive model of wind waves and currents, information flows between its three calculation modules based on models SWAN, ARTEMIS and COASTOX, types of input information, specified Interactive mode. The interactive features of the model are illustrated by an example of the user input information for the three-day predictive period of 2018.

2. Methods

The developed interactive model includes as the main modules: the freely distributed model of calculation of wind waves of SWAN, refractive-diffraction model with open source code ARTEMIS, based on the equations of gentle slopes, 2-D model COASTOX_UN of currents calculation based on numerical solution of non-linear equations of shallow water on unstructured triangular grid. Statistical processing of calculation results is carried out in accordance with modern approaches to the statistics of extreme hydrometeorological phenomena.

SWAN model of the Technical University of Delft (Netherland) [5, 6], distributed in open codes, in the last decade has become generally accepted in the world practice in coastal engineering the tool for calculation of transformation of wind waves from zones deep to the coastal zone.

The model is based on the equation of the balance of the density of wave action (or the balance of wave energy in the absence of currents) with sources and drains [5, 6]. The model describes the following wave processes: wind wave generation; propagation of waves in variable depth; change of amplitude of a wave, as a result of changes of depth and current; refraction, due to changes in depth and current; diffraction; blocking and reflection of waves in opposite directional currents; passing waves through flooded obstacles.

The model also considers the processes of wave generation by the wind and their dissipations: dissipation, caused by the collapse on deep water; dissipation caused by the collapse due to the change in depth; dissipation because of bottom friction; wave interaction on deep and shallow water.

At the initial stage of the work, the calculations were performed by SWAN, version 40.85, then the calculation was made based on a later version of SWAN 41. 10AB. The results of calculations were practically not different for both these versions, for calculation points of the analyzed region.

SWAN model since the beginning of the century is increasingly used as a tool for calculating the wave fields of the coastal zone, in the systems of forecasting the wave mode and calculating the characteristics of waves in the engineering objects of the coastal zone (for example, [6–10]). An important step in the application of SWAN model in the Russia was the work, showed good results in comparison with measurements in calculating the regime characteristics of waves in the coastal zones of the Russian seas. SWAN model is used in the Arctic and Antarctic Research Institute as a calculation module for the coastal zone of the Arctic seas, integrated with the model AARI-PD2, as well as, in recent years, in Russian federal service for hydrometeorology and environmental monitoring it was introduced for the prediction of wind disturbance in the Black Sea with detailing in the offshore zones using SWAN.

The model was successfully applied by the MSUCE in many engineering projects of wave hydrodynamics of the coastal zone and tested according to the corresponding data of measurements. As an example of such projects, it is possible to specify: Port Taman, Port Gelendzhik, Port Belokamenka, etc.

The wide use of the SWAN model for the calculation of wave field formation of the coastal zone of the sea caused the choice of this model in comparison with other spectral regional models of wind waves as a tool of calculation wave mode in the Ob lip in the free-of-ice period.

An open-source ARTEMIS model is included in the structure of the developed interactive mathematical model of wind waves and currents in the proposed construction for the calculation of wave fields at hydraulic facilities. Model ARTEMIS [11], based on an extended version of the gentle slope equations [12], in which, along with the original features of the GSE calculation of the wave transformation in the coastal zone, considering the refractive-diffraction processes. It's also added the ability to calculate the impact of dissipation due to friction on the bottom and the destruction of waves in the coastal zone on the wave characteristics. In ARTEMIS code, the equations of gentle slopes are solved numerically by finite element method using parallel computation algorithm. The model is a part of the program complex of calculating the tasks of wave hydrodynamics TELEMAC [13], the version in open codes of which is called TELEMAC-MASCARET [14].

Models based on different versions of the GSE are widely used in engineering tasks of calculating wave characteristics in ports and near offshore hydraulic structures. From many such models we note here only the most frequently used in engineering projects, along with ARTEMIS, the model EMS: Elliptic Mild Slope Wave Module Popular commercial complex of settlement programs of marine hydraulics MIKE-21 [15, 16].

The choice of ARTEMIS as one of the three components of the computational interactive model developed in this project, along with its status as a freely distributed model, is also due to: the successful ARTEMIS testing for a large number of projects for seaports, for example [17, 18], and also a set of test calculations, which in comparison with measurement data is presented in model documentation; availability of both the version for regular waves and the spectral version of the model; modern numerical implementation of the model on the unstructured calculation grid, which provides the necessary detail of the wave fields in the calculation areas; effective paralleling algorithm, allowing to significantly reduce the time of calculations when using both multiprocessor and multi-core computer systems; user-friendly interface.

The ARTEMIS model was successfully applied by the MSUCE in many engineering projects of the wave hydrodynamics of the coastal zone of the sea and tested according to the corresponding data of measurements [19]. In the interactive model being developed, the wave characteristics are calculated on the approach by the SWAN model and, then, the mode characteristics of the waves at the entrance to the port are transferred to the more detailed in the coastal zone of the ARTEMIS model grid.

COASTOX [20, 21] using the approximation of shallow water describes the fields of coastal currents generated by the joint influence of wind, gradient currents of the deep sea, tides and wind waves. Numerical solution of the model equations is constructed by the method of finite volumes on unstructured triangular grids. The form of the two-dimensional equations of shallow water includes members describing the effects of bottom friction, wave radiation stresses, horizontal turbulent mixing. Due to the universal structure of equations, they can, except coastal currents, under corresponding boundary conditions and the disconnected module of wave radiation stresses, to describe various wave processes: currents in rivers, transformation of tidal waves, storm surges, tsunami waves. Algorithms of parallelization calculations, on multiprocessor and/or multi-core systems are realized.

The model was used in many engineering tasks to calculate the coastal fields of currents. The conducted comparisons showed its good accuracy and stability of the used computational algorithm, for complex bathymetry and coastal outlines, in comparison with widely used in the world practice programs of numerical solution of shallow water equation on unstructured grids such as Mike-11 of the Danish Institute «DHI» [22], ADCIRC USA [23, 24], CMS-Flow Corps of Engineers of the U.S. Army [25].

The choice of the COASTOX model in the version implemented on unstructured grids is due to the ability of the authors of the model to adapt it effectively to the interactive model being developed, while the model of the modules describing the physical processes and the level of numerical realization (the use of algorithms of parallel calculations on unstructured grids) is not inferior to the most known software complexes of two-dimensional modelling of sea currents noted above.

The boundary conditions when performing mathematical modeling were defined according to the simulated tasks.

So, for modeling of tides, on open borders of computational grid, in the sea of Kars the conditions of change of level were asked. Tidal wave parameters were made from the global Tide Model TPXO 7.2, which assimilates the data of the satellite altimeter TOPEX/Poseidon and Jason. The dynamics of the level at the borders was calculated based on 13 tidal harmonics.

River runoff was set on the river borders in the places of confluence of OB, Pur and Taz rivers on the average annual hydrograph of river runoff from the site http://www.r-arcticnet.sr.unh.edu/v4.0/. At the borders of the grid adjacent to the land, the normal component of the flow rate was set to zero, and tangential was not fixed.

To calculate the mode of waves in the port area was chosen wave model ARTEMIS, open source, which is part of the software system TELEMAC. The model describes the reflection of the waves from the obstacles, the diffraction of the waves behind the obstacles, the refraction of the waves on the heterogeneity of the bottom, the bottom friction and the collapse of the waves. Thus, it allows to enter various coefficients of reflection of waves on sections of a boundary of the settlement area, corresponding to port constructions of various types: vertical berths, pilework, various slopes, with differing slopes and surface parameters. The model allows to simulate regular monochromatic waves and irregular waves with a given spectral distribution.

Wave pattern for each calculated storm is stationary, so the parameters obtained for the key points of excitement fully represent the time series of waves.

The results of calculations, obtained, with the help of models SWAN and COASTOX, adapted for the calculation of waves and currents in Ob lip, in comparison with the data of measurements in the region are presented. and results of prediction of wave fields of different repeatability on the structures water area with the help of ARTEMIS model.

3. Results and Discussion

Interactive Model of Wind Waves and Currents (IMWWC) can be used in two modes:

A) Mode of calculating the statistical characteristics of waves and currents

Model allows to calculate the statistical parameters of waves and currents on the wind fields for the selected archival period. Interactivity of the model for the user in this mode is provided by:

A.1) the ability to change the input information on the wind fields (another calculation period, for example, a higher number of past years or the inclusion of recent years in the estimated time series) or use of another source of data on boundary conditions – characteristics of tides on the external boundary of the calculation area;

A.2) the ability to change the configuration of structures and bathymetry, if necessary to use new refined data.

B) The mode of predictive calculations of characteristics of waves and currents interactivity of the model for the user in this mode is provided by:

B.1) The possibility of changing the input information on wind fields for the forecast period and data on the boundary conditions – characteristics of tides on the external boundary of the calculation area during this period;

B.2) The ability to change the configuration of structures and bathymetry, when new refined data appears.

As with the wind field analysis data, the data from the global models of the US Hydrometeorological service, NOAA, were the source of data on predictive wind fields. The values of the wind field component were obtained on a uniform grid with a resolution of 0.25 degrees with 1-h discreteness from the publicly available results of the global model of numerical weather forecast http://nomads.ncep.noaa.gov.

The parameters of the waves in the control points near the water area of the object, calculated in this way by SWAN model, were then transferred to the ARTEMIS model for calculations on the water area of the object.

The wave fields designed by SWAN model in interactive predictive mode, on the approach to the construction are used by the ARTEMIS model as boundary conditions for calculating the fields of waves in the water area. This procedure for the transfer of the SWAN output as an input to ARTEMIS is no different from the same data interchange between the interactive model modules to simulate the statistical characteristics of the waves in water area of the Object. Also, as in the case of statistical calculations in interactive predictive mode, the user should choose from a set of prepared calculation grids, which corresponds to the direction of the wave approach to the Object. The parameters of the waves in the control points near the water area of the Object, calculated in this way by SWAN model, were then transferred to the ARTEMIS model for calculations in the water area of the Object.

After setting the parameters of the waves and selecting the appropriate numerical grid, the model calculates the distribution of wave heights on the area of the Object and the height of the waves in control points.

As examples in Figures 1, 2, 3 and 4, the results of prediction of statistical characteristics of heights and periods of waves in the area of researches are shown, in Figure 1 – fields of heights of waves for all Ob lip, on Figure 2 – fields of wave periods for the same area. And in Figures 3 and 4 – the heights of waves in the water area of the port of South direction.

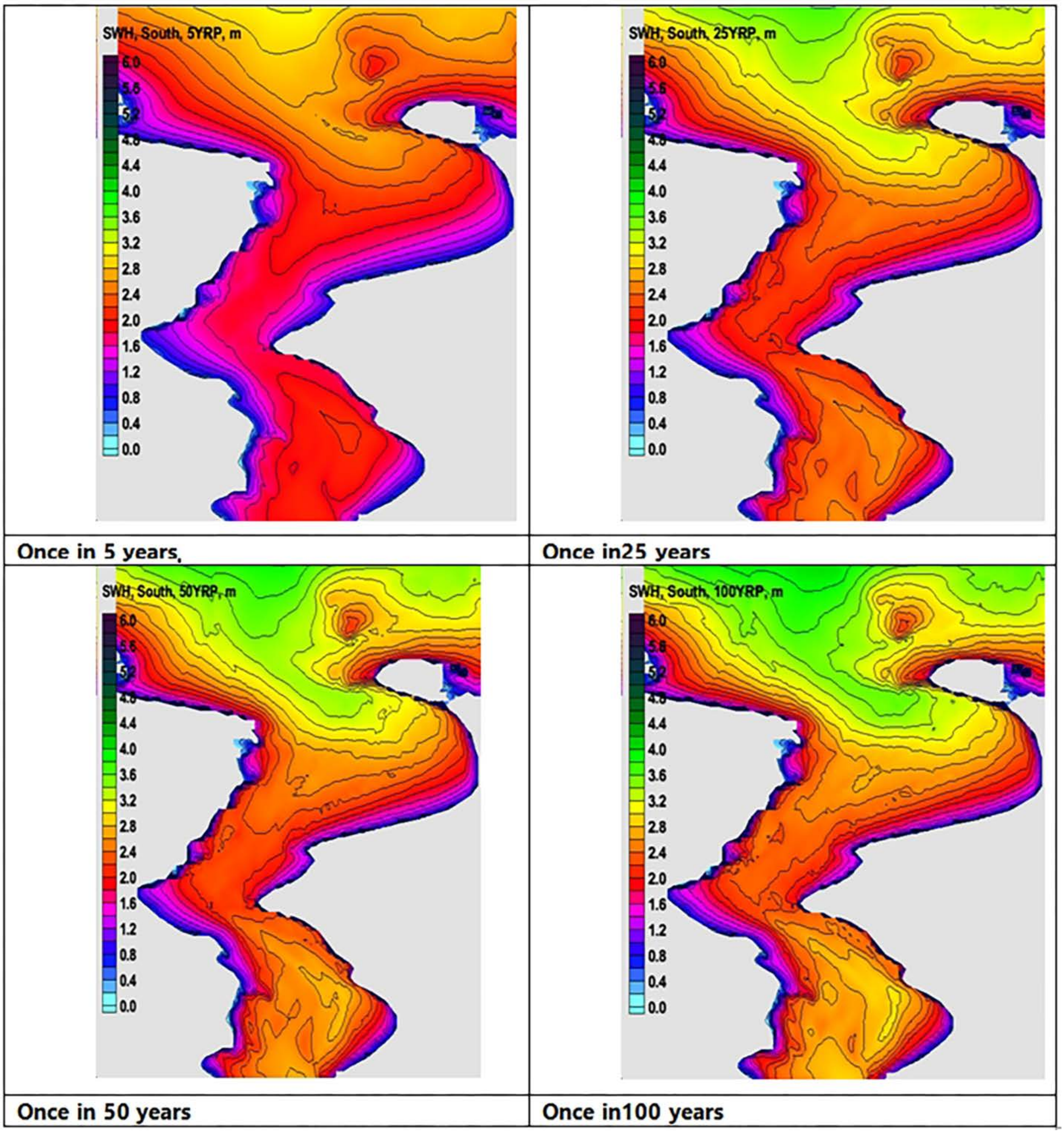

Figure 1. Fields of heights of significant waves with a direction of approach – Southern, possible once in 5, 25, 50 and 100 years.

The interactive model can use the input characteristics of tides on the external boundaries of the calculation area, and scenarios of wind fields and pressure for the calculation period.

Wind forecast is obtained on a rectangular grid in geographical coordinates, covering a rectangular area of 66–82.5° latitude, 55–106° longitude, with a step of 0.25° in both directions. Temporary discreteness of the forecast is one hour.

The global tidal model TPXO 7.2 [27] is used to set the tides. The dynamics of the level at the borders is generated based on 13 tidal harmonics.

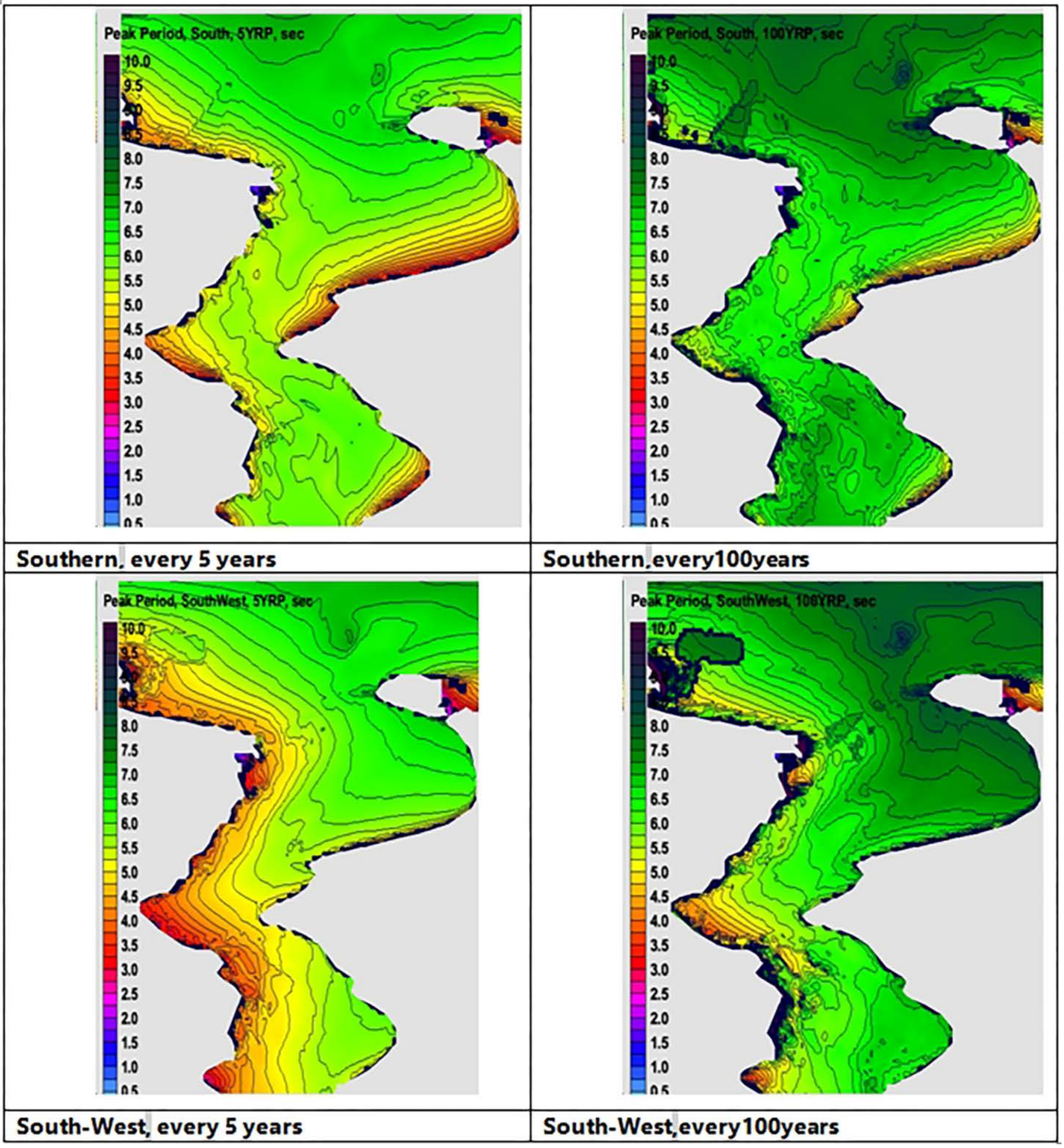

Figure 2. Fields of peak wave periods with the direction of the approach – South and South-West, possible once in 5 and 100 years.

Based on the source data, the current model predicts the distribution of sea level and dimensional the velocity field in the entire area for the selected period. And, the level, seas and velocity of current in the selected control points in the northern part of the Ob lip, near the port of Sabetta and in the area of construction of the facility.

The simulation results are shown in Figures 5 and 6. Figures 5 shows the simulated sea-level distributions in the middle and northern part of the Ob lip and the currents velocity fields, for the full and small water of quadrature and seizing tides in the area of the proposed construction of the Salmanovsky NGKM facility.

Figures 6 show the fields of velocities of currents for full and small water, quadrature and sizing tides, in the area of the intended construction of the object.

Special studies were performed to verify the results of the mathematical simulation. Data of the field measurements of level, currents and waves have been provided by the Arctic and Antarctic Research Institute. The data used included archival materials for 2012, 2013 and 2015–2016. The special measurements were performed in 2017.

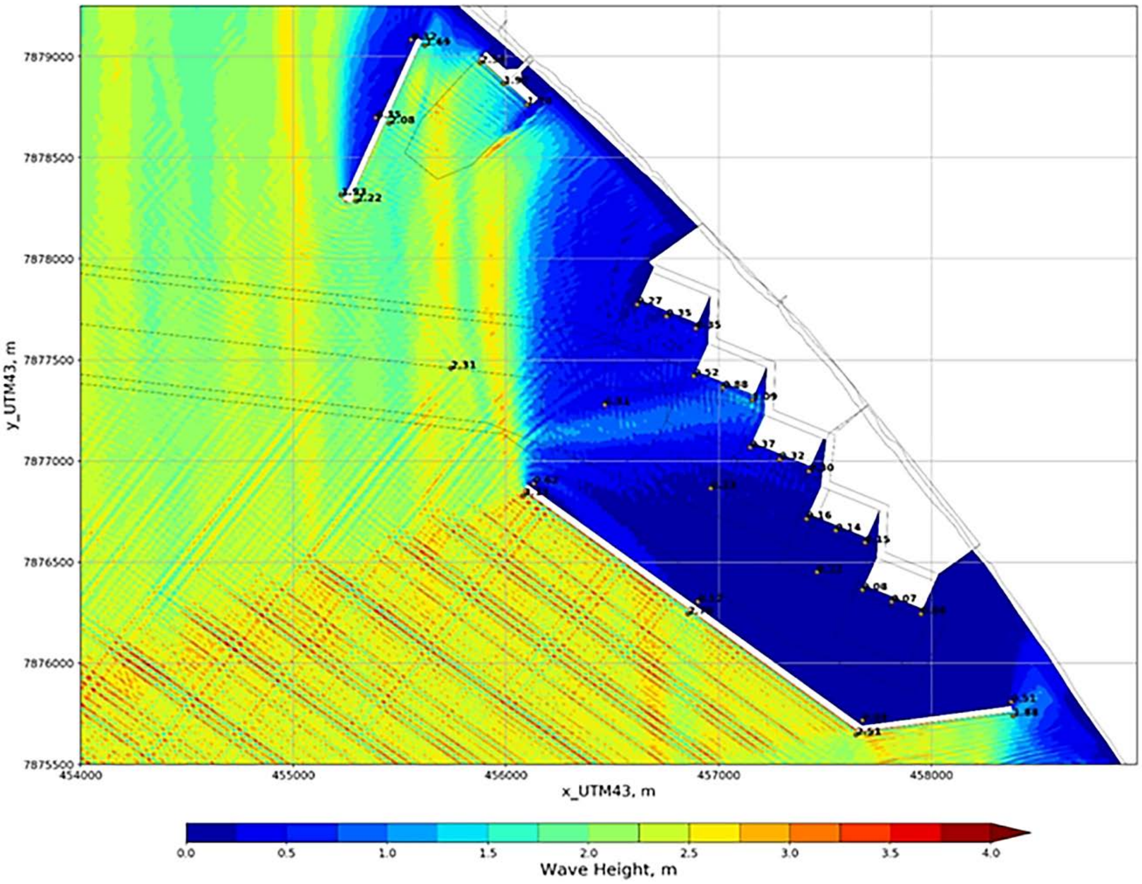

Figure 3. Wave heights in the waters of the remote Terminal “Utrenny” of the seaport of Sabetta, the layout version of no. 3, for a wave of repeatability once in 50 years, 13% of accidence, South direction of approach.

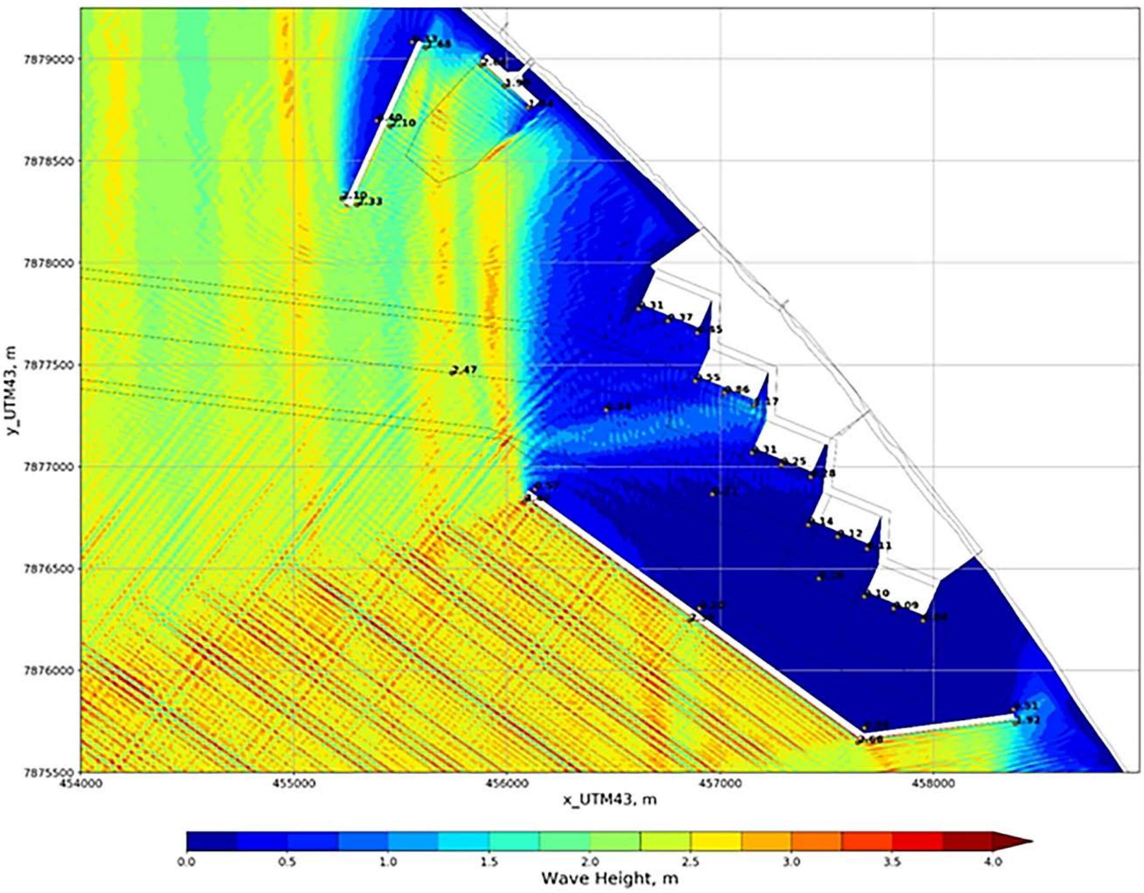

Figure 4. Wave heights in the waters of the remote Terminal «Utrenny» of the seaport of Sabetta, the layout version of no. 3, for a wave of repeatability once in 100 years, 13% of accidence, South direction of approach.

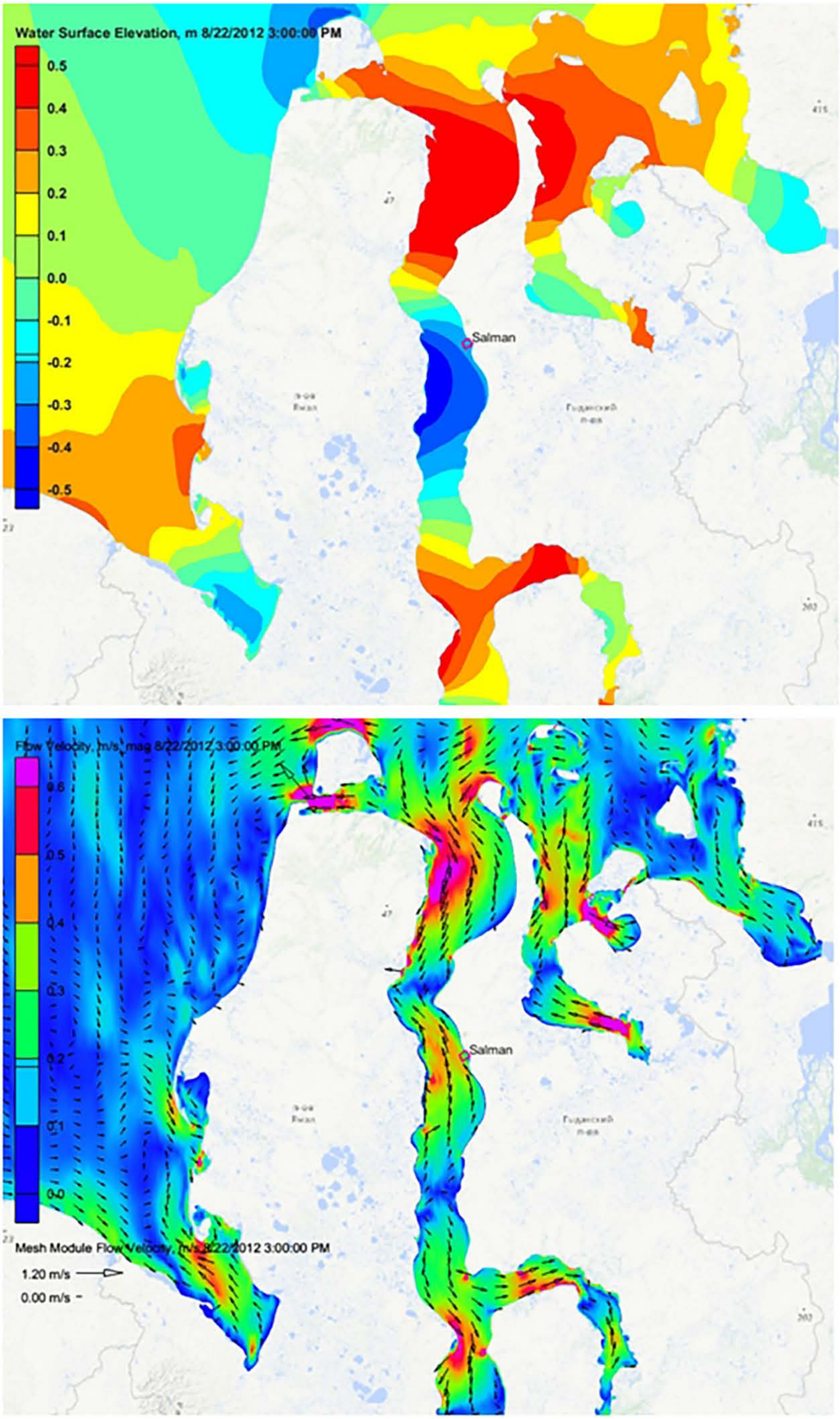

Figure 5. The distribution of sea level and velocities in the middle and northern part of the Ob lip, calculated by the model COASTOX-UN at the time of the small water of the seizing tide in the area of the proposed construction of the facility near the Salmanovsky NGKM. Web Mercator, EPSG: 3857.

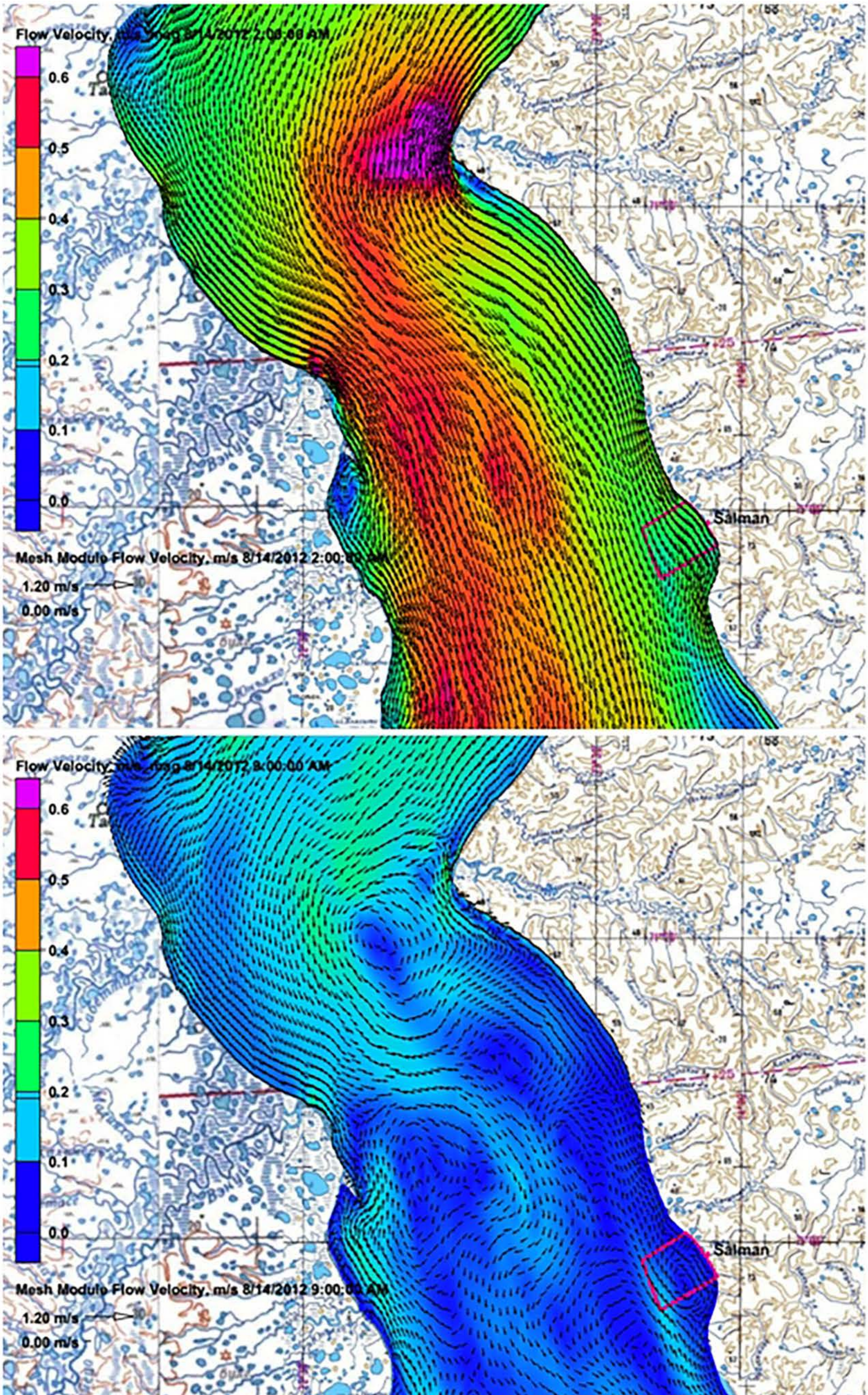

Figure 6. Velocities in the middle part of the Ob lip, near the area of the expected construction of the object, calculated by the model COASTOX-UN for the quadrature tide in the area at the time of full water (above) and at the time of low water (bottom). Web Mercator, EPSG: 3857.

For summer-autumn, 2012 (27.07.2012 – 04.10.2012) data on 15 measuring stations were provided: 9 stations in the northern part of Ob lip, closer to the exit from the bay, and 6 stations near the port of Sabetta.

For August-September 2013 (07.08.2013 – 29.09.2013) – data on 3 measuring stations: 1 point in the northern part of the Ob lip, 1 near the port of Sabetta and 1 in the area of the Salmanovsky field.

Data from the beginning of autumn 2015 to the end of summer 2016 are provided for 3 points in the area of the Salmanovsky field.

11 control points of the Ob lip in the area of prospective construction of the facility near the Salmanovsky field were applied for measurements in 2017.

The results of verification are partially published [28], partially shown below.

Results of comparison of calculated and measured heights of waves at two AWAC stations, taking into account the standard deviation of calculated heights of waves from measured about 0.2 m, at altitudes of waves up to 1.5 m and RMS deviation of calculated periods of waves from measured up to 0.47 sec, at periods of high waves in 3–4 sec, it is possible to recognize good consent of the results of the model measured data.

Typical examples of comparisons are shown in Figures 7 and 8.

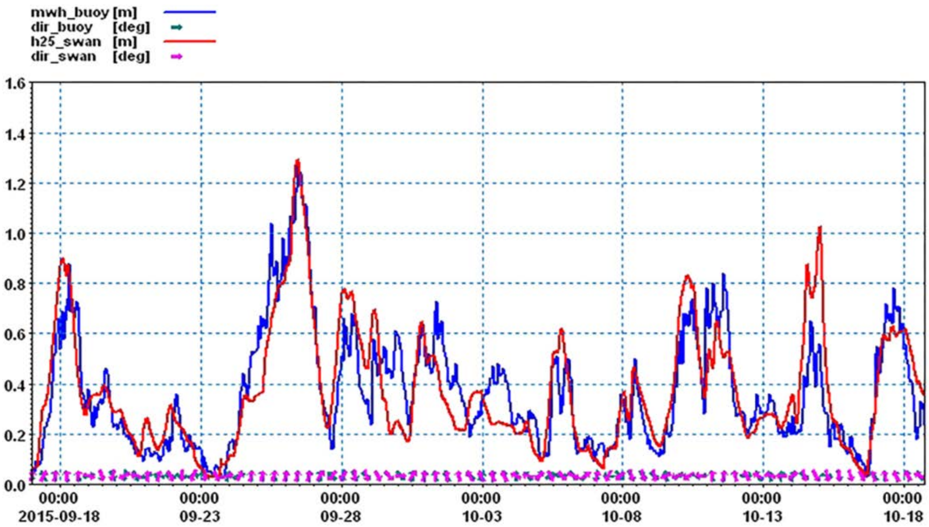

Figure 7. Comparison of calculated and measured heights of waves according to archival data (example).

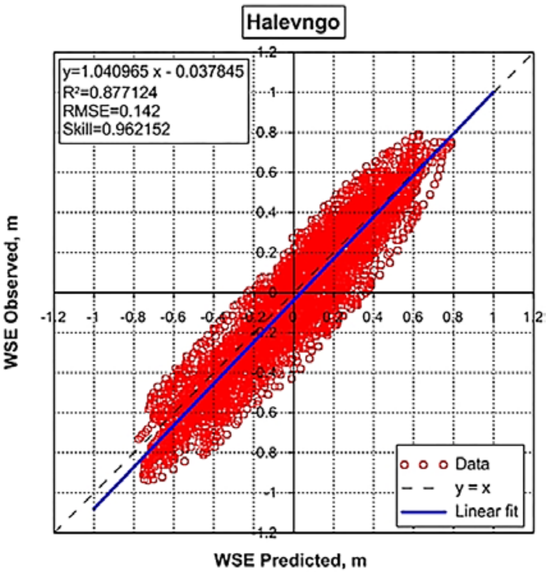

Figure 8. Comparison of measured and simulated sea level values (example).

4. Conclusions

The structure of the developed interactive model of wind disturbance and currents for the area of construction in Ob Guba, information flows between its three calculation modules based on models SWAN, ARTEMIS and COASTOX, types of input information are presented That is specified by the user in interactive mode. The interactive features of the model are illustrated by an example of calculation based on input information for the three-day predictive period 2018.

The developed mathematical model of waves and currents can be used for the solution of such problems as: determination of the calculated parameters of waves in berthing structures for providing safe conditions of mooring of vessels; determination of the calculated parameters of the waves at the structures for the design of structures (elevation of crests, wave loads, etc.); determination of current fields for prediction of sediment transfer, assessment of the port water area, navigation channels, local washouts at the structures.

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Численное моделирование нелинейных гидродинамических процессов береговой зоны

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Ключевые слова: численное моделирование, береговая гидротехника, цепочка численных моделей, интерактивная модель

Аннотация. Гидродинамические поля в береговой зоне образуются в результате нелинейного взаимодействия трансформирующихся волн различных временных масштабов и течений. Цепочку моделей необходимо использовать для моделирования ветровых волн, распространяющихся к берегу, волновых береговых течений, нелинейно-дисперсионной трансформации волн, дифракции волн при взаимодействии с береговыми и портовыми сооружениями, транспорта наносов и береговой эрозии. Цель статьи продемонстрировать обзор результатов применения цепочки моделей для определения волнового воздействия на сооружения проектируемого порта в Обской губе, Карское море, и обсуждения требований к дальнейшему развитию нелинейных моделей для применения в береговой гидротехнике. Модели открытого доступа WaveWatch III и SWAN используются для моделирования статистики волн в выделенных районах береговой зоны с высоким разрешением для определения статистики экстремальных волн, подходящих к береговым конструкциям, в соответствии с нормативами.

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