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EX-MARE - FORECASTING SYSTEM OF NATURAL HAZARDS IN THE AZOV SEA REGION

ABSTRACT. The paper presents approach used for the development of the forecasting system of extreme hydro-meteorological events in the region of the Sea of Azov. Due to numerous dangerous extreme events that occurred in the beginning of XXI century the issue of creation such system has become very relevant and important. The forecasting system, named EX-MARE, was started developing in 2014 as a complex of mathematical models. For each type of hydro-meteorological events, the modeling component was designed. The EX-MARE system is based on a scenario approach implied the consideration a variety of possible futures taking into account the existing uncertainty. Accurate extreme events estimation requires automated monitoring systems and long-term database application. In the paper, the detail description of the system components and the data sources is examined. Three case studies about the sea surges, flash flood and ice conditions researches demonstrate the application of the EX-MARE system and the benefits of its using. Further development of the EX-MARE system assumes adding data on exposure and vulnerability to perform the risk assessment, as well as focusing on multi-hazards exploring methodology.

KEY WORDS: extreme hydro-meteorological events, forecast system, the Sea of Azov, flash floods, sea surges, ice cover

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INTRODUCTION

Extreme hydro-meteorological events – a major threat to the safe interactions between nature and society. The assessment of the extreme events (natural hazards) impacts and their consequences is important in spatial planning and resource management.

The beginning of XXI century was marked by a number of notable disasters connected with weather in the Sea of Azov and the adjacent region:

- flash floods on the rivers of the Western Caucasus (the Adagum River, 2012; Dagomys, Khosta, Kudepsta, Mzymta rivers, 2015) with high damages and losses (Matishov et al. 2012; Matishov et al. 2014c);
- strong storm in the Kerch Strait (November

11, 2007) when 11 ships wrecked and there was an oil spill (1,200 tons) (Matishov et al. 2013);

- two extreme sea surges in the delta of the Don River in March 2013 and September 2014 (strongest flooding in a century, the similar flooding in the delta of the Don River was recorded in September 1914) when 20 and 26 settlements respectively were affected (Matishov and Berdnikov 2015);

- extremely cold winters and vast areas of ice in the southern seas – anomalous situation similar to a large-scale degradation of the ice in the Arctic. The extremal ice conditions in 2006, 2008, 2012 years in the Sea of Azov caused significant harm to navigation (Matishov et al. 2014b);

- “blooming” of water as a result of the algae mass reproduction is extremely actual and typical phenomenon of the Sea of Azov region. An excess amount of organic matter can cause a dramatic deterioration of the water oxygen regime that can be accompanied by the aquatic organisms massive death (so-called hypoxia phenomena), especially fish and benthic. Moreover, in areas with high algae concentration microorganisms can produce toxins posing a threat to human health (Matishov and Kovaleva 2010);

- during the recent decades the Sea of Azov coast has been destroying intensively by both natural and anthropogenic factors. More than 50% of the Taganrog Bay coastal zone is the area having high risk of landslide (Ivlieva and Berdnikov 2005).

Localization of such natural hazards in the region of the Azov Sea requires the development of a forecasting system based on the experience of domestic studies taking into account regional specifics. Many foreign hazards forecast systems are designed for completely different landscape and climatic conditions and are aimed at one type of extreme events, while in the region of the Sea of Azov there is a need to predict different, but interconnected hazards.

To address these issues, we started the development of the forecasting system of extreme hydro-meteorological events in the region of the Sea of Azov (EX-MARE) in summer 2014.

Currently for the Sea of Azov there is only one publicly available forecasts for wind waves. This is a product of system for operational wind wave forecasting in the World Ocean and seas of Russia developed at the Russian Hydrometeorological Centre since 2010 (Zelen'ko et al. 2014). The forecasting is performed through the computations with wind wave spectral models WAVEWATCH III v.3.14. Forecasts are available through the ESIMO operational module (<http://hmc.meteorf.ru/sea/>).

Many articles are devoted to storm surges modeling in the Sea of Azov (Tikhonova et al. 1995; Ivanov et al. 2008; Kruquier et al. 2009; Sukhinov et al. 2011; Datsyuk et al. 2014; Fomin et al. 2015; Popov and Lobov 2016; Popov and Lobov 2017; etc.). Immediately after the catastrophic flood on September 24, 2014, in Russian Hydrometeorological Centre started work on creating an operational model for level and currents in the Sea of Azov (Popov and Lobov 2016). In the spring of 2015, this model was implemented into the ASOOL system (Popov and Lobov 2017), but in public access forecasts are still not available. The mean absolute error of sea level for comparison with observations at coast stations is in the range of 5-11 cm.

There is a much less articles devoted to forecasting the ice conditions of the Sea of Azov. In (Dumanskaya 2013) presents a long-term forecast (two to eight months) of ice conditions in the ports of the non-arctic Russian seas, based on physic-statistical dependencies. The model from (Dashkevich et al. 2016), which allows perform historical reanalysis as well as operational forecasting, is used in the EX-MARE system.

Forecasting of floods in the Sea of Azov region is connected with the Kuban River. The flood forecasting and early warning system for floods on the rivers of the Caucasus Black Sea coast and the Kuban basin is described in (Borsch et al. 2015). The automated system developed for this region includes methods for obtaining a every day forecast of flows and water levels on three day for 30 river sites (but it not include sites on the Adagum River).

Detailed modeled reconstruction of extreme storm in the Kerch Strait (November 11, 2007) and its consequences are presented in (Oil spill accident... 2011). The practical absence of public forecasts for the Sea of Azov (with the exception of wind waves) confirms the importance of developing such a system. At the same time, the main task of developing EX-MARE was not so much the development of new models (since the most of them was already developed and tested), how much joining them into a single system. The EX-MARE system runs in test operational mode since 2015, so there is still not enough data to fully assess the quality of all forecast models.

In this paper, we describe the system configuration, the approaches used while it was developing, and the examples of its use.

MATERIALS AND METHODS

EX-MARE development is based on a system approach. It implies a design of unified concept and architecture that allow incorporate models and techniques developed to predict and assess a risk of natural hazards into integrated software package.

The EX-MARE system has created as a decision support tool, thereby allowing user to specify "issue", receive a response and use it in the decision making process. A question addressing to the system is formulated as a scenario. In context of natural hazards risk assessment, a scenario can be defined as a possible events sequence built to research cause-effect relationships.

The key idea of a scenario approach is to consider a variety of possible futures: to make alternative calculations with data corresponding to different situations. The focus on accommodating uncertainty is fundamental to the scenario as a methodology (Selyutin et al. 2009). Such an approach yields good results under conditions of high uncertainty, where traditional prediction methods give errors due to differences in the evaluation of input

data. Scenarios allow us to understand under what conditions an unfavorable situation may arise, and help to assess how it is possible to influence the processes leading to acceptable and unacceptable outcomes. Scenarios can provide a possibility to use different forecasts, the same forecast, but with different model parameters, and the synthetic situations – not predictable, but potentially possible cases characterizing the "worst" situation, etc.

In the EX-MARE framework, we examined the following extreme hydro-meteorological events:

1. Flash floods on the rivers of the Western Caucasus.
2. Extreme storm surges in the delta of the Don River.
3. Strong storms: wave loads and ships wrecks.
4. Cold winters and extreme ice condition.
5. Algal blooms and oxygen depletion (hypoxia and fish kill).

The EX-MARE system was designed to assess the natural extreme events risk in the basin, the coastal zone and the water area of the Sea of Azov to warn local governments, households and businesses. A prerequisite for such forecast system creating is the presence of the following components:

- automated monitoring system;
- regular field studies;
- long-term databases;
- good-quality regional meteorological forecasts;
- models validated on regional observational data.

In Fig. 1, the architecture of EX-MARE system is presented. It consists of the subsystem for the data load, the scenarios constructor, the modeling subsystem, the data processing subsystem, the visualization subsystem, and the data storage.

The Modeling subsystem is based on a modular principle of models system forming, allowing a sequential simulation when the output of one module is the input of another one. EX-MARE includes the several model components implementing specific methods of the extreme hydro-meteorological events forecasting. Each model component comprises one or several numerical models and the

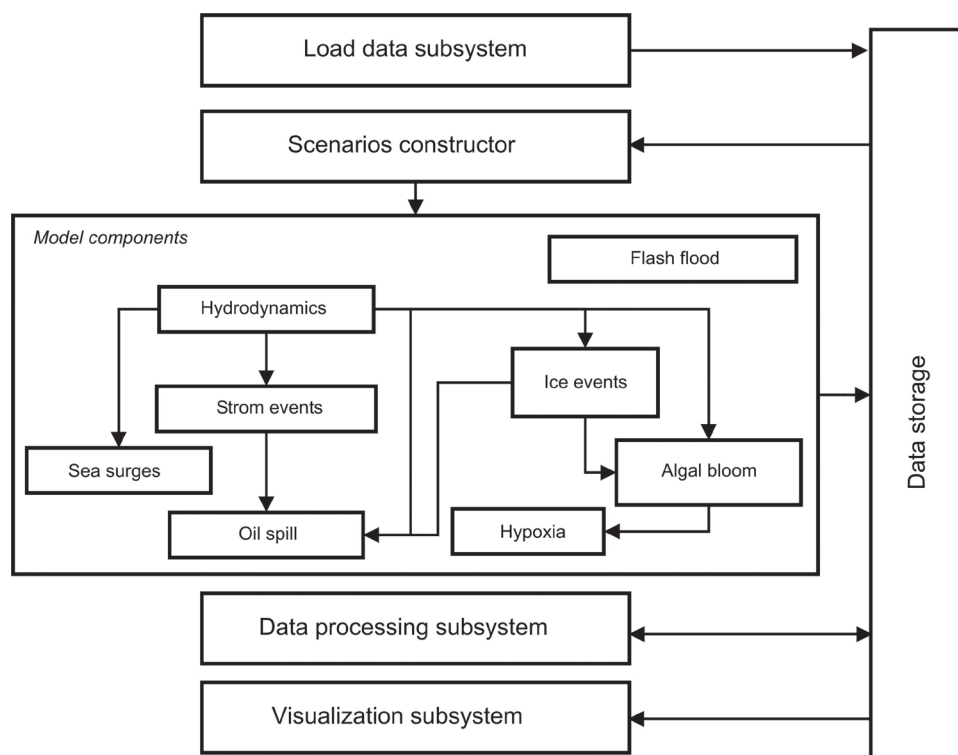


Fig. 1. Architecture of EX-MARE system

controller responsible for running the model and the data processing procedures in the desired order. It should be noted that the using models are independent software with their own formats of input and output files. Data processing procedures are designed to perform the necessary file format conversions to interact with the data storage.

The "Flash flood" component uses two hydrological software packages: HEC-HMS (Hydrologic Modeling System) and HEC-RAS (River Analysis System), which are products of the Hydrologic Engineering Center within the U.S. Army Corps of Engineers (www.hec.usace.army.mil/software/). HEC-HMS is designed to describe the physical properties of river basins and to simulate the precipitation-runoff processes. HEC-RAS models the hydraulics of water flow through natural rivers and other channels. HEC-RAS implements one- and two-dimensional modeling of flow as well as sediment transfer modeling capabilities. In "Flash flood" component the Adagum River was chosen as test object.

To model currents and surface level the three-dimensional hydrological model "The Sea of Azov Surge Model" (SASMO) was used. It was developed in SSC RAS (Chikin 2009; Datsyuk et al. 2014). For a numerical realization of SASMO the decomposition of the simulation area into the shallow-water and the deep water layers and finite-difference methods were used. Parallelization is performed in the paradigm of "shared memory" using the communication MPI library. The spatial resolution of the model in latitude and longitude is 685 m and 660 m, respectively. Vertically it has 30 uniformly distributed levels. Integration time step is 2 min. The input data include bathymetry of the Sea of Azov and the wind fields with 3 hours time step.

In the "Sea surges" component SASMO is coupled with HEC-RAS. The flood area in the Don River delta is calculated in HEC-RAS using a sea level (the SASMO output data) as the input data.

In the “Storm events” component the model SWAN developed at the Delft University of Technology is used. SWAN is a wave model for obtaining of realistic wave parameters in coastal areas, lakes and estuaries at given wind, bathymetry and currents conditions. It was customized to the Sea of Azov conditions (Tretyakova and Yaitskaya 2015; Yaitskaya 2017).

SWAN allows implementing the nested grids technology. Scheme with three levels of nested grids is applied for the Sea of Azov. The coarsest grid (first level - meshes size is $0.1^\circ \times 0.1^\circ$) is used for both the Black Sea and the Sea of Azov. The fine grid (second level - meshes size is $0.01^\circ \times 0.01^\circ$) is used for the Sea of Azov only. The finest grids (third level) are used for some coastal areas especially prone to abrasion with meshes size $0.001^\circ \times 0.001^\circ$. Time step is 15 min in according to recommendations of developers and our computer experiments (Yaitskaya 2017). The input data are the following: wind fields (from meteorological forecast) and sea currents fields (from the “Hydrodynamics” component). The wind wave forecasts perform for the ice-free period.

The “Storm events” component also uses the methodology of the Marine Hydrophysical Institute of RAS, Sevastopol (Kushnir et al. 2013) to assess the wave load in the coastal areas.

The “Ice events” component implements methods forecasting ice cover and ice thickness in the Sea of Azov. It includes the compartmental hydrological model of the Sea of Azov developed in SSC RAS (Berdnikov 2006). This model allows carrying out retrospective and predictive simulation of the ice regime based on the equations of water, salts and heat balances. The simulation results are compared with the the remote sensing data processing results. Detection of areas with the presence of sea ice is based on the Normalized Difference Snow Index (NDSI) (Hall 2014). To calculate NDSI the MODIS Terra/Aqua data are used.

NPZD (nutrient-phytoplankton-zooplankton-detritus) model of the Sea of Azov is used

in the “Algal bloom” component to allocate zones with high level of harmful algae concentrations. Depending on the time step, the NPZD model explores short-term, seasonal or interannual variability of primary production and nutrient balance associated with river runoff variations and meteorological characteristics. The model output data are primary production and biomass of phytoplankton. The model input data are the river runoff, water exchange with the Black Sea, precipitation, solar radiation and concentration of allochthonous dissolved and suspended organic matter and nutrients in river runoff. The “Algal bloom” component uses one more method to assess primary production. It is based on the chlorophyll-a concentration estimation using satellite images. It should be noted that the highly productive waters of the Sea of Azov are characterized by the high turbidity reducing the accuracy of proven methods for chlorophyll-a concentration estimation by satellite images. Therefore the NIR-Red algorithm (Moses et al. 2009; Moses et al. 2012; Moses et al. 2014; Gitelson et al. 2011) for the estimation of chlorophyll-a concentration in the productive and turbidity waters was used.

The “Hypoxia” component carries out the forecasts of the dissolved oxygen concentration in sea and generates the dissolved oxygen depletion maps. It contains 1D mathematical model of oxygen regime, describing the seasonal variation of the oxygen concentration, its vertical distribution and interaction with sediments (Kulygin et al. 2016). The input data of the “Hypoxia” component include the wind speed, water temperature, primary production and reservoir bathymetry (digital elevation model (DEM)). The output data are vertical distribution of oxygen and the labile organic material in each point of DEM. Based on this information the maps of the oxygen depletion areas and, accordingly, of the hypoxia risk are created. The risk of oxygen depletion is calculated as the frequency (probability) of situations reducing the oxygen concentration at a certain depth below a specified critical threshold.

The “Oil spill” component implements methods of the Sea of Azov oil pollution forecasting in case of the emergency spills during transportation by ships. The component includes two models: MEDSLIK (Oceanography Center of the University of Cyprus) (<http://www.oceanography.ucy.ac.cy/medslik/>) and the SSC RAS oil spill model (Kulygin and Berdnikov 2013). The input data are the following: wind fields (from meteorological forecast), sea currents fields (from the “Hydrodynamics” component), wave parameters fields (from «Storm events» component). To perform simulation the spill conditions are set: spill location and time, volume, composition of oil fractions. The models output is the distribution of the oil products concentration in the sea area and the coastal zone. It allows building maps with the probable location of oil spills in the water area, as well as a risk map of the coastal zone pollution.

The input variables of all components are exogenous hydrometeorological factors, as well as control (scenario) parameters.

For performing numerical experiments, it is necessary to have a set of scenarios characterized by a certain probability. The scenario constructor is an algorithm used to create various scenarios. It includes the environmental conditions generator simulating stochasticity effect. The constructor core is the scenario assembly module. Scenario within the EX-MARE, in addition to the description, contains a set of the input data, model parameters, initial and boundary conditions values. Thus, scenarios constructor provides input data sets for specific model calculations. One type of scenario can be used during the model validation, the other in retrospective simulations, and the third for operational practice.

The scenario approach allows to use of a group of forecasts (ensemble) for a number of slightly different initial conditions and/or different meteorological forecasts. The ensemble mean gives a better (in comparison with a single deterministic forecast) estimate of the predicted

characteristic, and the variance of the prognostic characteristics in the ensemble can be considered as a measure of the uncertainty of the forecast.

Main goal of the load data subsystem is collecting of all available observations and weather forecasts for the region of interest. Retrieving data from the databases is performed in automatic regime. The load data subsystem is a set of scripts providing timely preparation of all environmental parameters necessary for initialization of the modeling subsystem. In fact, for each data source (observations, forecasts, remote sensing data), a specialized procedure for automatic or semi-automatic data loading is implemented.

Data processing subsystem is a set of procedures performing the aggregation of the information to compare it with available observation data, convert it into spatial formats and so on. The comparison with the observational data provides a quantitative measure of the models quality as well as a possibility to identify the models parameters changes that need to be done. Visualization subsystem is based on ArcGIS (ESRI) software and consists of the projects with predefined structure of layers and its data sources.

The data storage is a hub providing the interaction between all functional components that not communicating directly, and use storage to record or retrieve data. Metadata catalog service is designed to search available datasets in the data storage. Whenever new dataset enters the data storage, the information about them is automatically added to the metadata catalog. The data storage accumulates datasets obtained as a result of computational experiments, along with data collected by monitoring systems.

The data storage includes: database, containing the service information; catalog of datasets which presented files in netCDF format containing forecasts, observing systems data and results of scenario calculations; catalog of satellite images; and spatial database.

Data sources

The meteorological forecasts are considered as “input” information for the EX-MARE system. The global and regional forecasts available for free are preferable. The main forecasts sources are the following.

Global Forecast System (GFS) is a weather forecast model produced by the National Centers for Environmental Prediction (NCEP). Gridded data (with 0.25 degree of resolution) are available for downloading through the NOAA National Operational Model Archive and Distribution System (NOMADS) (<http://nomads.ncep.noaa.gov/>).

COSMO-RU System of Nonhydrostatic Mesoscale Short-range Weather Forecast of the Hydrometcenter of Russia. Gridded data (with 7 km of resolution) are available on ESIMO portal (<http://portal.esimo.ru>).

Yr online weather service provides forecasts from Norwegian Meteorological Institute (<http://www.yr.no>). In public access there are available only forecasts for individual locations (34 location for the Sea of Azov region).

Weather service «Raspisaniye Pogodi» (<https://rp5.ru>) provides Met Office forecasts for different locations (76 location for the Sea of Azov region).

For parameterization and validation of EX-MARE model, modern and historical (for the long period) observational data are required. The following databases are used:

- database with observations at hydrometeorological stations of the Roshydromet (Federal Service for Hydrometeorology and Environmental Monitoring of Russia) network;
- database with observations at Emersit network stations;
- database with observations at SSC RAS stations;
- oceanographic database of the SSC RAS. Database of hydrometeorological stations observations contains data published at RIHMI-WDC (All-Russian Research Institute of Hydrometeorological Information – World Data Center) and ESIMO portal as

well as historical data digitized from paper archive.

The Emersit network includes about 200 stations located on the rivers of the Krasnodar and Rostov regions and on the Sea of Azov coast. Most of these stations have sensors for sea/river level observation. Some of them are equipped with sensor of the following meteorological parameters: air temperature, air humidity, atmospheric pressure, precipitation (quantity, type, intensity), wind direction and speed.

In 2016, the Southern Scientific Center of the Russian Academy of Sciences and the Institute of Arid Zones of the SSC RAS joined to the Pan-Eurasian Experiment (PEEX, <https://www.atm.helsinki.fi/peex>) as associate members. Since 2004, a network of meteorological and hydrological posts in the Azov-Black Sea region has been developing by SSC RAS to monitor and predict the impact of climate change and human activities on the marine environment. Four stations of the SSC RAS are included in the PEEX catalog: “Kagalnik”, “Donskoy”, “Vzmore”, and “Manych”. The first two stations are located in the Don River delta, the third one – in the Taganrog Bay, the fourth one – in the Manych River valley. The database of SSC RAS stations contains observations of the sea level, ice conditions, meteorological and hydrochemical parameters for the period 2004-2017.

The oceanographic database of the SSC RAS was formed as a result of the ecosystem researches conducted in the South of Russia by the SSC RAS and IAZ SSC RAS, as well as a result of the search and archiving of historical data. In 2014, a new version of the Atlas of Climate Change (Matishov et al. 2014a) was published. It contains the most complete publicly available oceanographic databases of the Sea of Azov (about 66 000 marine stations for the period 1891-2012). Remote sensing data are presented by free satellite images (Landsat, MODIS, MERIS etc.) available from the following data sources:

- NASA Physical Oceanography Distributed Active Archive Center (PO.DAAC) (<http://podaac.jpl.nasa.gov>);

- NASA Ocean Biology Distributed Active Archive Center (OB.DAAC) (<https://oceancolor.gsfc.nasa.gov/>);

- Copernicus Marine environment monitoring service (<http://marine.copernicus.eu>).

The EX-MARE utilizes datasets with different processing levels (L1 to L4).

Workflow of the EX-MARE system

The interaction between the components is implemented in form of the task queue with using the Advanced Message Queuing Protocol (AMQP). AMQP is a messaging protocol that enables conforming client applications to communicate with conforming messaging middleware brokers. Messaging brokers receive messages from publishers (applications that publish them, also known as producers) and route them to consumers (applications that process them).

One of the EX-MARE components (publisher) is the initiator of the task. At some point in time, it sends the task message to the queue. The other component (consumer) is in the waiting mode while there is no any message in their queue. When message is in the queue AMQP brokers deliver it to consumers subscribed to queues and consumer immediately begins task execution.

The main types of EX-MARE tasks are downloading information from external sources and starting modeling calculations. Tasks related to the first type are processed by the load subsystem, tasks of the second type - the modeling subsystem. After the completion of the task, if it was successful, the task is placed in the archive, in case of an error in a special errors queue. This allows you to restart the task (moving it back to the working queue) after finding out the cause of the error.

Since AMQP is a network protocol, the publishers, consumers and the broker can all reside on different machines.

RESULTS AND DISCUSSION

The EX-MARE computer equipment consists of 4 computers (Intel Xeon Processor 4 core, 2.80 GHz; 16GB RAM), located in the local network of the SSC RAS, and 16 virtual machines (VM), running on this computers and joining in one sub-network. Each EX-MARE component (model components, data storage, load data subsystem, etc.) is running on one of the VMs. The system organization as a private "cloud" allows, if needed, to deploy the developed software to the global "cloud" systems. The time for preparing the forecast for 72 hours is about 10 minutes.

The EX-MARE system has been running in test mode since 2015. It was used for both operational forecasts and retrospective/special case scenarios.

Operational forecasts are prepared according to the schedule. In the automated mode, the following processes are performed: loading data from external sources into the data storage; creation of basic (daily) scenarios as inputs for corresponding model components; simulation and subsequent results processing with their publication in the data storage.

Some examples of the EX-MARE using for modeling extreme hydro-meteorological events are presented below.

Modeling of the extreme storm surges in the Don River Delta

Since the launch of the EX-MARE in 2015, more than 60 calculations of storm surges have been carried out. Forecast of the water level in the delta was performed each time when the forecast wind has western component and velocity exceeded 8 m/s. The actual number of dangerous surges in the Don River delta (when the water level exceed 1.3 m in Baltic height system (BK77)) according to the data of the automatic level gauge on the "Donskoy" station was 25 for the period 2015-2017. Five of them took place in 2015, 10 in 2016 and 10 in 2017. Most dangerous surges were within the April.

The forecast of the level dynamics (maximum value and its achievement time) in general corresponds to the observation data (Fig. 2) (Tretyakova et al. 2016). The mean absolute error (MAE) of the water level is 10 cm (mean relative error (MRE) is 12%) for the first 24 hours. MAE of time reaching the maximum level is 3 hours. The forecasting error significantly depends on the accuracy of the used wind forecast. Analysis of the calculation results and input wind fields showed that the deviation of the wind forecast from the actual within the range of up to 3 m/s slightly affects the result of the calculations. With increasing this difference, the error of level forecast becomes larger. The most frequent case is overestimate value of wind speed, which leads to a higher simulated water level.

The EX-MARE also was used to reconstruct two catastrophic surges occurred in March 2013 and September 2014. The results of the calculations showed a good coincidence of the dynamics in the water level rise and its maximum value, however, the decline of water level was inaccurate (Fig. 3) (Yaitskaya and Tretyakova 2016).

Modeling of the extreme flash flood in the Adagum River Basin

Models of "Flash flood" component were tune on the observations of July 2012 flood. The extreme intense rainfall 6-7 July 2012 in the mountain area of the northwest Caucasus caused the formation of the flash floods in the basins of the rivers Adagum, Tseme, Yashamba, Abin. This flood has led to large property damage and numerous human deaths, especially in Krymsk town.

Since 2012 catastrophic floods in the Adagum River basin have not been observed. At the same time, "Flash flood" component was used to assess the impact of the littering of the bridge openings in Krymsk on the flood. There were considered two scenarios: open and close bridge openings. Fig. 4 shows the flood zones in the vicinity of Krymsk and the profiles of the water surface under different scenarios. Total flood areas of both scenarios are similar, but there are differences in the flooding mechanism: in case of "close" scenario, hydraulic heads are formed near the bridges. Nevertheless, we can conclude that in the case of so extremely high runoff as was in July 2012, the degree of littering of

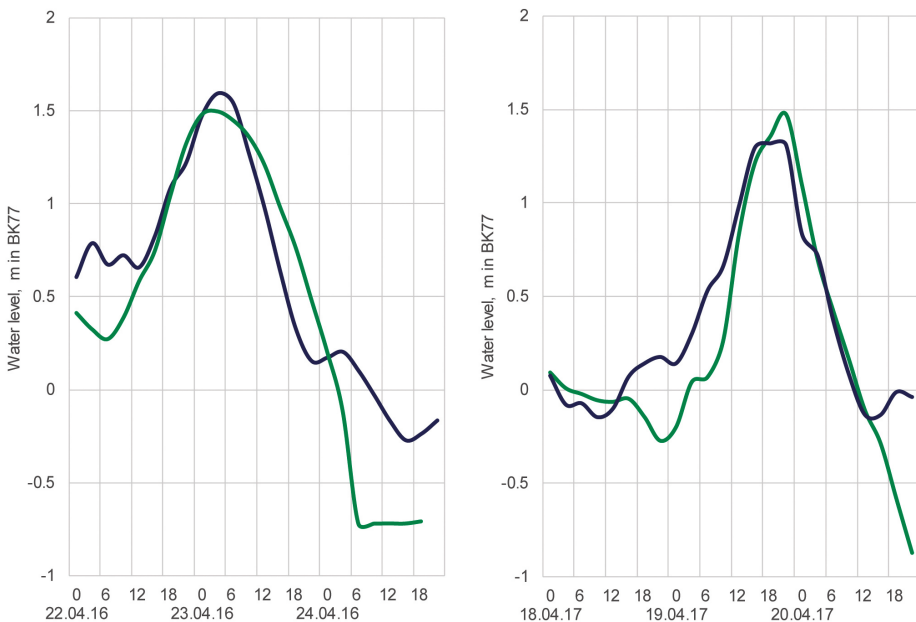


Fig. 2. Forecast of surges in April 2016 and 2017 (green line - forecast, blue line - actual values)

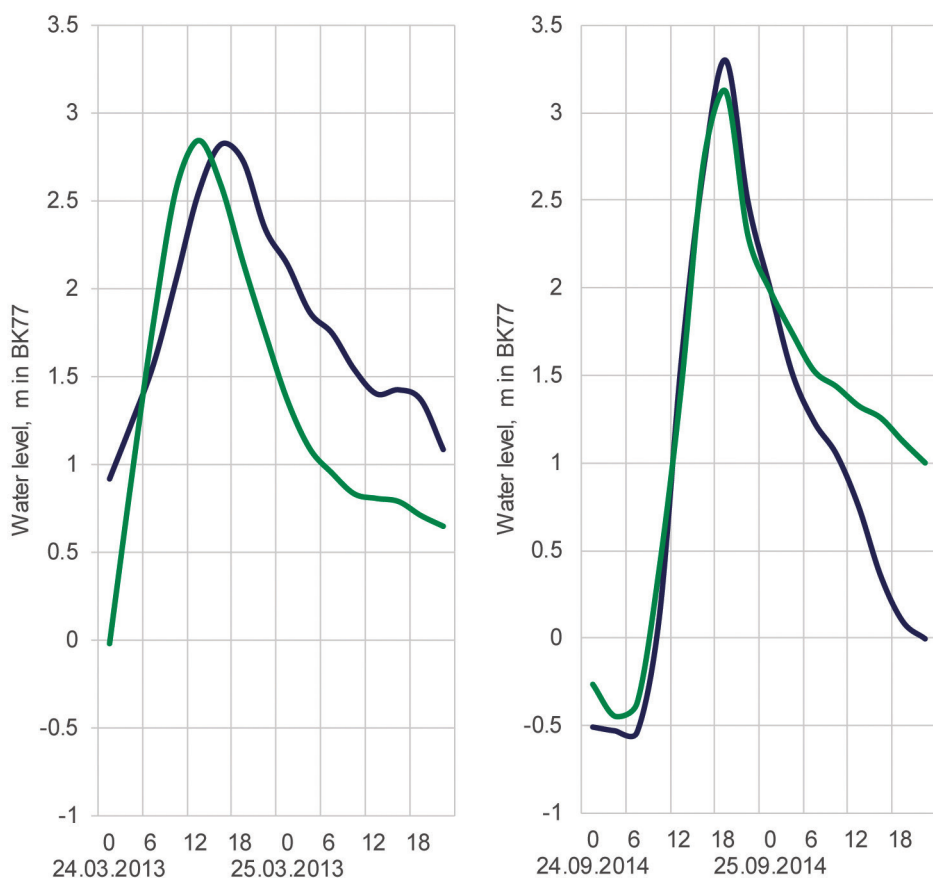


Fig. 3. Reconstruction of extreme surges in March 2013 and September 2014 (green line - forecast, blue line - actual values)

the bridge openings did not have a major influence on the flood development.

In (Alekseevsky et al. 2014) presented results of similar experiments. Maximum flood depths in Krymsk were calculated a) without bridges in the Adagim river and b) in conditions of consider bridges as dam. In (Alekseevsky et al. 2014) was shown, that bridge backwater influence only 2-km zone upstream and downstream of bridges. These results are consistent with the flood zones on Fig. 4.

"Flash flood" component was used to compare impact of different river channel transformation on development of floods. After the 2012 flood, the channel of the Adagum River was transformed: straightening and concreting of the channel was made to decrease channel bed roughness and length of flow path,

and increase flow velocity. It was shown that effective reduction of the flooding area in the case of strong floods (like in July 2012) requires not only straightening and concreting channel bed, but regular cleaning of the transformed channel and existing bridge openings or significant reconstruction of bridge structures.

The using of the "Flash flood" component for different areas is also possible in case of existence of detailed digital terrain model and a surface roughness map (vegetation cover, built-up areas, etc.).

Modeling of the ice condition in the Sea of Azov

"Ice events" component makes automated forecast of the Sea of Azov ice condition only in cold season from November until April. Monitoring and forecasts data from

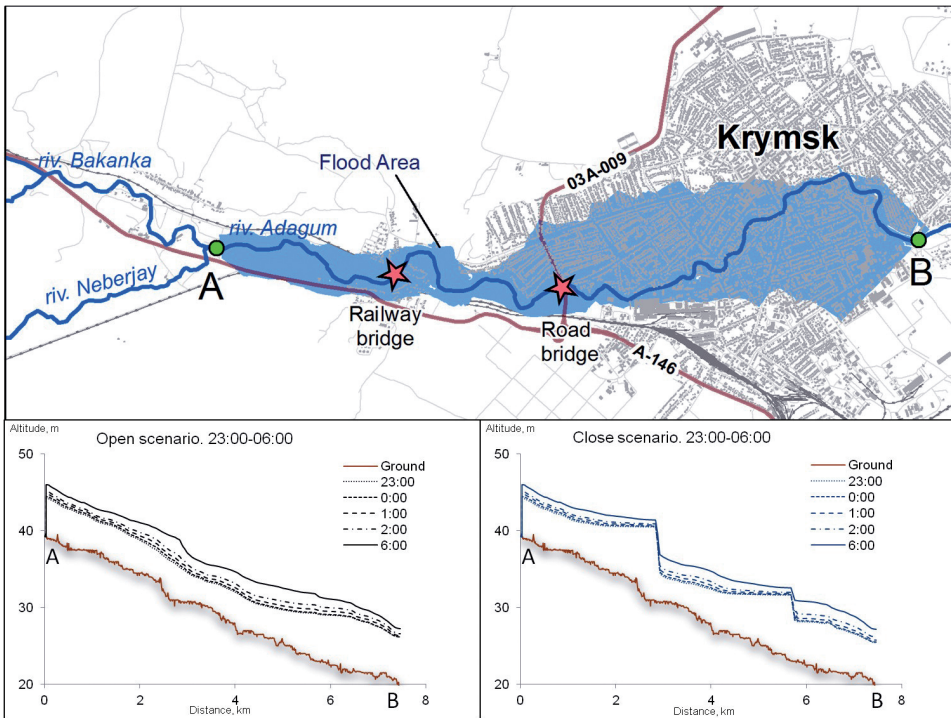


Fig. 4. Flood area and water surface profiles of "Open" and "Close" scenarios (6-7 July 2012)

the coastal weather stations are using as model inputs. The simulation results are compared with values of ice cover and water temperature from MODIS (Terra/Aqua) satellite data and with observations of the ice thickness in the ports and in the "Kagalnik" station. It was shown (Dashkevich et al. 2016) that the model can be used for creating a historical reanalysis of the Sea of Azov ice cover, as well as for operational forecasting.

Fig. 5 shows long-term dynamics (1920 to present) of the Sea of Azov ice cover and thickness annual values. Easing of ice conditions in the modern period can be noted. Average ice extent of the Sea of Azov in the beginning of the XXI century is 16%, which is almost 2 times less than in the middle of the XX century. However, despite a significant decrease of ice cover square and duration of ice period, in the last decade the average ice thickness according to the simulation results has been decreased slightly.

Modeled ice cover averaged over the winter season for the period of 1920-2016 (Fig. 5) are in good agreement with observational data in 1950-1977 (Hydrometeorological... 1986) and assessment of the ice cover based on the MODIS images in 2005-2017 (Dashkevich et al. 2016): mean absolute error is 5.2%, correlation coefficient is 0.92. During the winters 2015/16 and 2016/17 model was work in the short-term (3 days) forecasting mode (Dashkevich et al. 2016). The predicted ice cover was compared with the satellite monitoring data for individual compartments (only compartments where there was no cloud were used in comparison). The MAE was 20% with a standard deviation of 32%. The model reproduces period of the ice cover development better than the ice decreasing period. This is probably due to not taken into account the ice drifting, which has a significant role in the spread of ice in the Sea of Azov. The relatively low quality of short-term forecasts, compared to the long-term retrospective, can be explained by the low spatial resolution of the model.

Risk assessment and multi-hazards

EX-MARE has been designed to simulate the physical, chemical and biological causative factors, but it does not provide a hazard risk assessment in terms of economic objectives or performance criteria of activities.

Risk is defined as the probability of harmful consequences, or expected losses (deaths, property, or environment damaged) resulting from interactions between natural or human-induced hazards and vulnerable conditions (EC 2011). Risk can be schematic represented as the multiplication of three components: hazard, vulnerability and quantification of the exposed elements-at-risk.

Hazard is a potentially damaging physical event, phenomenon or human activity that may cause the loss of life, property and infrastructure damage, environmental degradation (UNISDR 2009). This event has a probability of occurrence within a specified period and within a given area, and has a given intensity.

Exposure (i.e. elements potentially at risk) represents the presence of people, livelihoods, environmental services and resources, infrastructure, or economic, social or cultural assets in places that could be adversely affected (UNISDR 2009). The way

to characterize the amount of elements-at-risk (e.g. as number of buildings, number of people, economic value) also defines the way in which the risk is presented (Van Westen and Greiving 2017).

Vulnerability represents the propensity or predisposition of a community, system, or asset to be adversely affected by a certain hazard (UNISDR 2009). It can be subdivided into physical, social, economical, and environmental vulnerability.

The multiplication of risk components given above is not only a conceptual equation, but can also be actually calculated to quantify risk from different hazards. EX-MARE can be used to generate hazard data. For each hazard type (e.g. flooding, storm, oil spill) so-called hazard scenarios should be defined, which are hazard events with a certain intensity and frequency. Modeling components are used then for the hazard scenario analysis. To perform complete risk assessment it is necessary to extend EX-MARE system with exposure and vulnerability data.

One of the difficult issues in natural hazards risk assessment is how to analyse the risk for more than one hazard in the same area, and the way they interact (Van Westen and Greiving 2017). Nowadays EX-MARE is utilized standard single hazard approach,

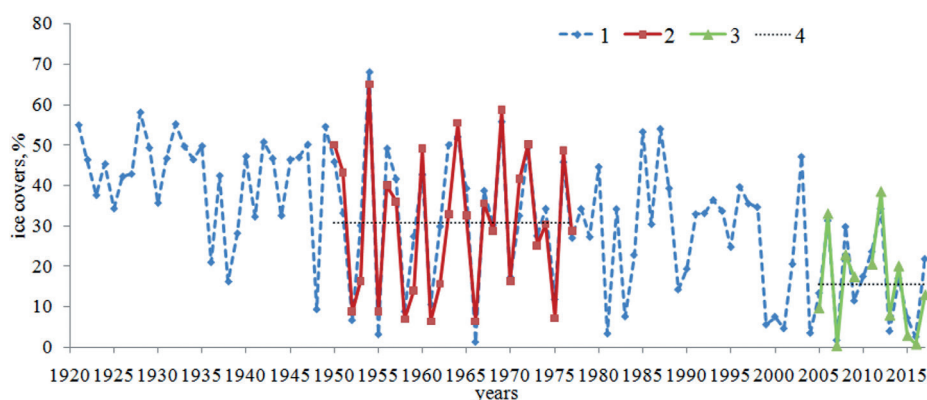


Fig. 5. Long-term ice cover of the Sea of Azov. 1 – simulation data; 2 – data according to (Hydrometeorological..., 1986); 3 – assesment based on the MODIS data (Dashkevich et al. 2016); 4 - average value

in which hazards are treated as isolated, independent phenomena. Compared to single processes, methodological frameworks for multi-hazard risk assessment are less common in the literature, which is related to the complex nature of the interaction between the hazards, and the difficulty to quantify these (Kappes et al. 2012). Total risk within EX-MARE can be assessing as weighted sum of all considered hazard risks. The methodology (Kulygin 2017) allows estimating the weights of hazards taking into account their interaction.

The successful implementation of a comprehensive multi-risk assessment into management strategies should require the identification of the final users (e.g. local administrations, national institutions). Therefore, only after identification of stakeholders and their needs, and involvement them in the process it is possible to obtain adequate results.

CONCLUSIONS

The proposed EX-MARE system is a complex modeling platform, containing tools for the preparation and execution of calculations. It provides short-term forecasts for such hazards in the Sea of Azov region as flash floods, sea surges, strong storms, extreme ice conditions, algal bloom and oxygen depletion, oil spillage.

The structure of the EX-MARE allows expanding the system both by adding new methods of hazards risk assessment and by adding new hazard types. Presented approaches to development and organization of this system can be used while the forecasting systems for other regions are designing.

The practical application of the system would increase reliability of the decision making process results concerning the public informing about the expected hazards, thereby reducing the possible socio-economic damage.

At present, the accumulation of prepared forecasts continues, and later a detailed assessment of the quality of all EX-MARE models will be made.

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