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Research of opportunities of combined use of the runoff formation ECOMAG model and mesoscale atmosphere circulation COSMO-Ru model (on the example of floods on the Sukhona River at the Velikiy Ustyug)

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Abstract. The article devoted to development of modern forecasting methods of runoff in modern climate conditions. The main aim of the investigation is creation a new scheme of assimilation and application of initial (in situ), model (COSMO-Ru) and satellite data. The main focus of this research is creation of couple from the hydrological (ECOMAG) and the meteorological (COSMO-Ru) model and launch of the hydrological model on COSMO-Ru grid.

1. Introduction

The most promising method for the analysis of flood characteristics is the method of synthesizing models of the hydrometeorological cycle, ranging from obtaining the initial meteorological data, determining the water regime of the territory, based on global and mesoscale atmospheric circulation models, through the analysis of runoff formation in the catchment area, to the water inflow into the river network and the flow conditions on specific sections of the rivers (Fig. 1). This approach can be effective for analyzing of possible extreme hydrometeorological events and allows to solve diverse problems associated with the flooding of the territory, both in the short-term forecast mode and for various scenario simulations. At the same time, the combination of multi-scale models is expected to lead to a loss of accuracy when moving from one level to another and requires the improvement of modeling techniques.

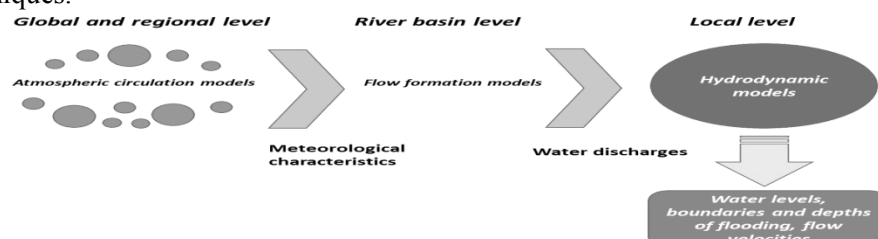


Figure 1. Schematic diagram of the synthesis models of the hydrometeorological cycle.



The article assesses the possibilities for the joint use of the ECOMAG runoff formation model (author Motovilov Yu.G., Institute of Water Problem of RAS) and the mesoscale model of atmospheric circulation COSMO-Ru for the calculation of the flood flow near Velikiy Ustyug. The relevance of the work is related to the hydrological safety of Velikiy Ustyug city, located at the confluence of the Sukhona and the Yug rivers, which having been repeatedly inundated due to floods of complex ice-jams – snow-melting genesis. The last flood was observed here in May 2016 and caused significant damage (Agafonova et al., 2017; Agafonova, Frolova, 2016).

This region has been sufficiently studied by hydrologists, including during the development of measures to reduce the adverse water effects (Alabyan et al., 2003, Frolova et al., 2014). However, a hydrological station measuring the water discharge exists only on the Sukhona River, while on the Yug River it was closed at the end of the 80s. One of the possible solutions in case of a lack of hydrological data, as well leading for the most complete and advance consideration of all the features of the floods formation in the study area, is the use of a runoff formation model. This type of model based on data of meteorological characteristics (temperature, precipitation, air humidity) and information on the underlying surface of the catchment area allows to calculate all the processes of runoff formation and, as a result, water discharge at any point in the river network. The ECOMAG model of runoff formation used in the study, has showed its high efficiency during studies of the northern rivers runoff, including for the Northern Dvina basin (Motovilov et al., 2013, Krylenko et al., 2014, Antokhina, 2011).

However, the existing meteorological stations network data, especially considering a sparse gauges network in the northern regions, is not always sufficient to correctly display the fields of meteorological characteristics. Therefore, the work assessed the feasibility of using as an input data for the runoff formation model of the meteorological information, based on simulations of the COSMO-Ru mesoscale atmospheric circulation model, which provides all the necessary meteorological data.

This model is used for the operational forecasts of the Hydrometeorological Center of Russia and provides data on surface air temperature, precipitation, air humidity and other meteorological characteristics on a regular grid with a spatial resolution from 1 to 10 km for each meteorological period (every 3 hours), taking into account the characteristics of underlying surface (Wilfand et al., 2014). The work solved the problem of data exchange between the ECOMAG runoff formation model and the COSMO-Ru mesoscale atmosphere circulation model, for which special input-output information blocks were developed, providing data exchange, and the runoff hydrographs modeling results were evaluated based on the proposed approach. Next, we consider each stage of the work in more detail.

2. Adaptation of the ECOMAG model for runoff hydrographs modeling in the area of Velikiy Ustyug

To adapt the model of runoff formation of Northern Dvina River in the area of Velikiy Ustyug the data of average daily water discharge for the gauges of Kalikino settlement, located 36 km above the confluence on the Sukhona river (catchment area 49200 km²), and Gavrino settlement (catchment area 34,800 km², closed in 1989) were used. Model parameters obtained for the entire basin of the Northern Dvina (Krylenko et al., 2014) were used as initial data. At this stage, all model simulations were carried out according to meteorological stations data in the basin. The data for the 1969 - 1984 years were used for calibration of the model, and the data for the period 1985-2014 - for the model verification (Fig.2).

Three catastrophic rises of the water level, exceeding the level of hazard events, were observed on the Northern Dvina during 1969-1984 (15 year's period) in the area of Velikiy Ustyug due to the formation of ice jams. During 1985-2014 (30 year's period) in the area of the city there were five floods, the highest flood in this period took place in 1998. For river catchments above Velikiy Ustyug there were obtained slightly different values of two parameters associated with hydroclimatic conditions, compared with the average values for the Northern Dvina basin: a factor for the

evaporation coefficient (EKOPT) and a critical melting temperature (TCRst). These differences are due to the fact that Velikiy Ustyug is located in the southern part of the Northern Dvina basin, which is characterized by higher values of evaporation and an earlier start of snowmelt.

As a result, there was obtained a good correspondence between the modeled and observed hydrographs at the gauges of the Sukhona River (Kalikino) and the Yug River (Gavrino), determining the water discharge in the city of Veliky Ustyug area. According to the calibration results, it can be concluded that for 1969 – 1984 period on the basis of the S/σ criteria the model with satisfactory quality describes the maximum water discharges and the flood volume for gauges of the Sukhona River (Kalikino) and the Yug River (Gavrino). According to the Nash-Sutcliffe criteria, the model gives good results for the gauges under consideration (Table 1). For 1985 – 2014 period, according to the Nash-Sutcliffe criterion, good results are observed for all the gauges under consideration, and according to the S/σ criterion the results are satisfactory for Kalikino and unsatisfactory for Gavrino (due to the small length of the data series, since the Gavrino station was closed in 1989).

Table 1. The conformity assessment of actual and calculated hydrographs on the basis of calibration and verification of the model in the gauges of hydrological stations of the Sukhona River (Kalikino) and Yug River (Gavrino).

Gauge	1969 – 1984			1985 – 2014		
	S/σ		NSE	S/σ		NSE
	Max. Water discharge	Flood volume		Max. Water discharge	Flood volume	
Kalikino	0,59	0,52	0,81	0,62	0,52	0,83
Gavrino	0,47	0,65	0,84	1,15	1,05	0,79

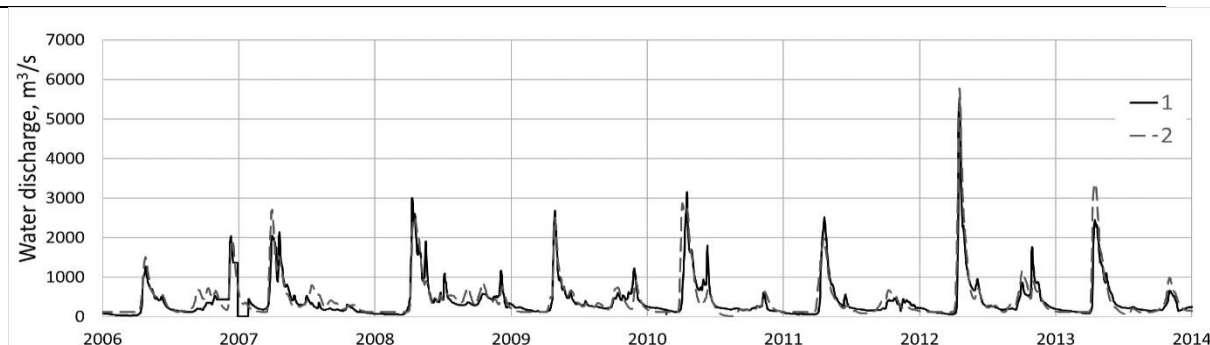


Figure 2. Actual (1) and simulated on the basis of the ECOMAG model (2) hydrographs for the years 2006 -2014 for the hydrological station on the Sukhona River – Kalikino.

3. Provision of meteorological data for the Northern Dvina river basin according to the COSMO Ru mesoscale model

The fields of meteorological data from the COSMO-Ru hydrodynamic mesoscale modeling system based on the incoming data from the system of assimilation of the German Weather Forecasting Service (DWD) were used to provide meteorological information. The data from standard meteorological observations received in the SYNOP synoptic code via communication channels of the World Meteorological Organization was used for comparison.

Since 2009 Roshydromet has been a full participant in the European Meteorological Consortium for Mesoscale Modeling COSMO (<http://www.cosmo-model.org/>). Participation in the consortium involves the development and improvement of methods for mesoscale modeling. Rosgidromet since 2009 has developed and introduced a short-term weather forecast system based on the non-hydrostatic mesoscale model COSMO, called COSMO-Ru. The COSMO-Ru model allows reproducing

meteorological processes online with different spatial steps (Fig. 3) (Blinov et.al, 2017) for the territory of the Russian Federation. In addition, the model can be used for different research tasks, for example, to calculate the characteristics of the underlying surface in the river catchment area. At the initial stage of work, it was decided to use the mesoscale atmospheric model COSMO-Ru because this model gives the best results based on the evaluating of the operational meteorological forecasts precise of various lead times for the territory of the Russian Federation [<http://method.meteorf.ru/>].

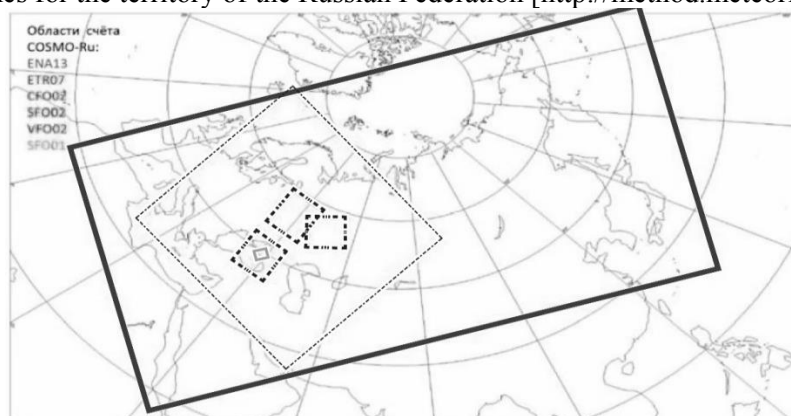


Figure 3. The simulation areas based on COSMO-Ru for the June 2017. Black line shows the boundaries of the ENA13 calculation area, gray hatching represents the ETR07 area, black hatching shows the counting areas with a step of 2 km, gray line with a step of 1 km.

The task of meteorological data providing for the Northern Dvina River catchment using the COSMO-Ru model was implemented for the ETR calculating area (European territory of the Russian Federation) with a 7 km step between the regular grid nodes (which is the most detailed model grid available for the study area). Additionally, in order to speed up the process of working with the model and outgoing data fields, it was decided to create a restrictive area (catchment area of the Northern Dvina River) with the center of the model grid in the city of Velikiy Ustyug. As a result of working with the COSMO-Ru ETR model, meteorological data fields for the period from 01/01/2011 to 18/09/2018 with a time step of 3 hours were obtained. For the task, fields with information about the surface air temperature, dew point temperature, relative humidity and precipitation were used. The use of model data has significantly increased the meteorological knowledge of the region and create an information base for the application of the hydrological model.

Study of this region only from model data would be incomplete without the use of actual meteorological stations. In the study data from 68 meteorological stations located on the catchment area of the Northern Dvina River or near it was used. The data with information about surface air temperature, temperature of the soil surface, dew point temperature, atmospheric pressure, wind speed and wind direction at a height of 10 m and precipitation were of greatest interest. Meteorological data is obtained in the form of a SYNOP synoptic code with a discreteness of 3 hours. For the assimilation of meteorological data by the hydrological model, the data obtained were averaged to daily discreteness.

The COSMO-Ru grid nodes nearest to the meteorological station were found and the shortest distances were determined, after which the bundles between the meteorological station and the shortest grid node were formed for comparison with the model data. As a result, on the catchment area of the Northern Dvina River and near it 52 pairs were formed and the obtained data were evaluated (Fig. 4). The assessment results are presented in Table 2. The results show that the COSMO-Ru ETR model data reproduce the course of the main meteorological elements and can be used to launch the hydrological model.

The use of the COSMO-Ru mesoscale model made possible to obtain meteorological data fields not only for the current day, but also to use forecast fields up to 72 hours in advance, which enabled to launch test calculations based on the hydrological model in the forecast mode.

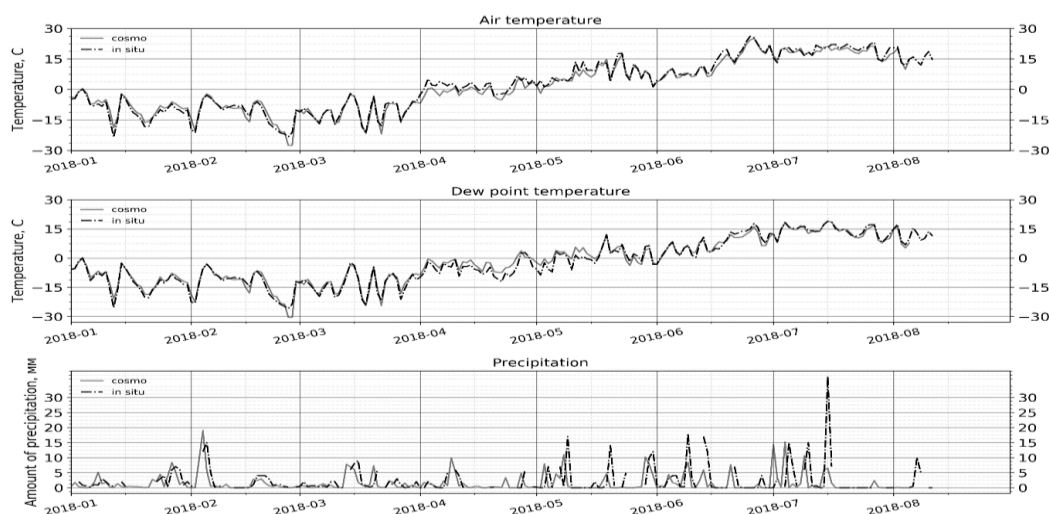


Figure 4. The graph of in situ and model data at the Syktyvkar meteorological station for the period from 01/01/2018 to 10/08/2018. The model data is shown black line, the in situ is hatching line.

4. The first results of the joint use of the ECOMAG model and the COSMO-Ru model and their discussion

Modeling of hydrographs of floods based on the joint use of ECOMAG and COSMO-Ru models was carried out over the period 2013 – 2018 with a daily step. Thereto, the surface air temperatures, dew point, precipitation for each calculation cell obtained by the COSMO-Ru model for meteorological periods were reduced to daily averaging, and converted to the formats, required for calculations based on the ECOMAG model. For comparison, similar calculations were carried out on the basis of the ECOMAG model according to COSMO-Ru data and on the basis of the meteorological stations data, based on the same parameters obtained during the model calibration at the first stage. The main gauge, according to which the obtained simulation results were compared with the observations of hydrological station, was key for the formation of high-water hydrographs near Veliky Ustyug gauge of the Sukhona River – Kalikino.

The first simulation results show that, in general, based on the data of the COSMO-Ru model, there can be obtained hydrographs, adequately describing the real dynamics (Fig. 5). Especially important is the good correspondence of the hydrographs modeled according to the data of meteorological stations and according to the COSMO-Ru model for outstanding floods of 2013 and 2016, when combined runoff and ice-jams induced floods were observed. In 2013, the maximum discharges for the simulation results are obtained on the same day as the actual maximum, however, the model overestimates the maximum discharges both in the simulation based on COSMO-Ru data and in the simulation based on meteorological stations data by about 30%.

For the flood of 2016, when more than half of the city of Velikiy Ustyug was flooded during a combined runoff and ice-jams induced flood, the maximum discharge modeled on the base of COSMO-Ru data was 3380 m³/s, which coincided with the observed discharge of 3120 m³/s as for the value (with relative error less than 8%), as for the time of passage.

It should be noted that for some years, modeling based on COSMO-Ru data leads to a significant discrepancy with the results of modeling based on data from meteorological stations and observational data of the hydrological station. The largest discrepancies in the maximum discharges and volumes of floods are observed in 2015 and are most likely associated with significant inaccuracies in the total amount of precipitation in the autumn-winter period for the studied catchment area according to COSMO-Ru, which caused that model hydrograph is several times lower than that actually observed (850 and 2800 m³/s, respectively), while based on the meteorological stations data, the model reproduces this flood well, and the relative error for maximum discharges rates is 14% with coincidence of hydrographs peaks in terms of time.

Table 2. Results of statistical processing of the data obtained for the Syktyvkar meteorological station for the period from 01/01/2018 to 10/08/2018.

Parameter	Characteristic	Time range	01.12.17 - 02.28.18	01.03.18 - 31.05.18	01.06.18 - 31.08.18	Where
Air temperature	mean		0.749	-0.08	0.412	In point
	std		0.985	1.516	0.857	
	min		-1.85	-4.15	-2.37	
	max		4.63	4.94	3.26	
	mae		0.927	1.076	0.719	
	median		0.62	-0.03	0.45	
	rmse		1.233	1.51	0.947	
Dew point temperature	mean		0.194	0.135	0.041	In point
	std		1.287	1.779	0.882	
	min		-2.4	-5	-1.95	
	max		5.29	3.9	2.12	
	mae		0.884	1.388	0.732	
	median		0	-0.23	0.1	
	rmse		1.294	1.774	0.878	
Precipitation	FBI		1.16	1.2	1.107	In point
	EDI		0.727	0.86	0.624	
	TSS		0.475	0.686	0.491	
	mean		-0.189	-0.258	-0.16	
	std		0.572	1.647	2.615	
	min		-2.67	-10.07	-10.71	
	5%		-1.254	-1.933	-3.799	
	95%		0.408	0.814	1.998	
	max		0.92	3.43	13.92	
	mae		0.36	0.601	0.986	
	median		0	0	0	In 15 km radius
	rmse		0.599	1.658	2.606	
	ETS		0.276	0.475	0.374	
	FBI		1.24	1.286	1.25	
	EDI		0.716	0.883	0.737	
	TSS		0.418	0.678	0.583	
	mean		-0.173	-0.223	-0.14	
	std		0.569	1.557	2.462	
	min		-2.66	-9.19	-10.59	
	5%		-1.194	-1.881	-3.79	
	95%		0.386	0.746	1.871	In 30 km radius
	max		0.88	3.15	11.25	
	mae		0.358	0.577	0.946	
	median		0	0	0	
	rmse		0.592	1.565	2.452	
	ETS		0.245	0.364	0.322	
	FBI		1.42	1.571	1.714	
	EDI		0.856	0.942	0.87	
	TSS		0.37	0.59	0.585	
	mean		0.2	0.44	0.943	
	std		0.753	1.655	3.229	
	min		-2.12	-7.43	-6.89	
	5%		-0.66	-0.434	-0.629	
	95%		1.32	1.85	5.309	
	max		3.31	8.58	18.72	
	mae		0.486	0.754	1.317	
	median		0.11	0.12	0	
	rmse		0.775	1.703	3.347	

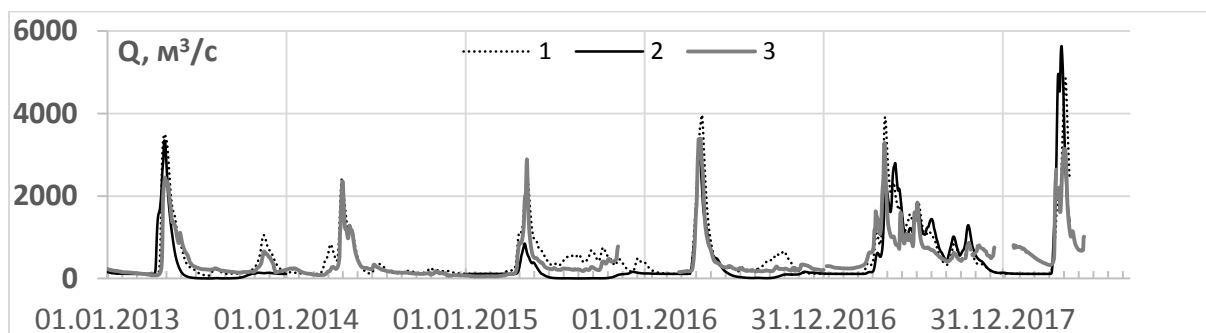


Figure 5. Comparison of water discharges of the Sukhona River - Kalikino: modeled on the basis of the ECOMAG model according to meteorological stations data (1), according to the COSMO-Ru model data (2), discharges according to the data of the Kalikino station (3).

The most difficult for modeling are multimodal floods, which are observed with repeated transition of air temperatures through 0°C point, interrupting snowmelt. A similar situation was observed during the high water period of 2017, in this case in general the simulation results reproduce several flood peaks, but they do not always coincide with actual data in terms of time and magnitude, especially when simulating performs according to COSMO-Ru data.

The indicated discrepancies between model hydrographs, obtained on the basis of calculations from COSMO-Ru with actual ones, lead to lower values of modeling quality estimates from these data. So, the Nash-Sattcliffe criterion for the period 2013-2017 (excluding 2014, according to which COSMO-Ru data for snow accumulation period was absent) was 0.44 for the Kalikino gauge, when simulated based on the data of the regional climate model, and 0.62 when calculated using meteorological stations data. The simulation results are considered satisfactory for NSE values in the range from 0.35 to 0.75, however, due to a small length of period for modeling using COSMO-Ru data, it is difficult at this stage to indicate a stable result due to some years where the flood hydrograph is described unsatisfactorily (for example, 2015). The possibilities of adjustment of the simulation results based on the runoff formation model using the regional climate model COSMO-Ru are associated both with adjustment of the parameters of the runoff formation model, and reducing the size of subbasins taking into account the density of the climate model grid. It is also possible to clarify the amount of snow reserves according to the COSMO-Ru model using technology SnoWE, which is developed for calculations of snow cover characteristics (Chyryulin et.al, 2018).

When switching to the prognostic mode while joint use the ECOMAG model and the COSMO-Ru model, it is most appropriate to carry out simulations up to the release date of the forecast from meteorological stations, and for the forecast lead time (72 hours) according to the COSMO-Ru model with the setting of the forecast correction algorithm with taking into account the difference between the actual and the simulated hydrograph in the days preceding the release of the forecast. Test calculations for this technique were carried out for the flood in 2018 (Fig. 6) and show its high potential, since ECOMAG model takes into account the main processes of runoff formation for the entire period, starting from the autumn freezing of the catchment, snow accumulation, snowmelt, etc. throughout the catchment area above the studied sections, and the COSMO-Ru model allows to take into account the short-term forecast of the synoptic situation.

5. Conclusions

The combined use of the COSMO-Ru mesoscale atmospheric circulation model and the ECOMAG runoff formation model allows a quantitative assessment of the flood characteristics with a lack of data from hydrometeorological observations and to solve problems related to the study of the water regime of river basins and the hydrological safety of the territory. The application of this approach is especially relevant for the ice jam sites, since data on water levels during the flood rise period do not reflect the actual amount of water in the river and do not allow to carry out hydrological forecasts based on classical methods. A short-term forecast technique of water discharge at Velikiy Ustyug,

currently being developed on the basis of ECOMAG and COSMO-Ru models, can serve as the main component of the operational forecasting system used in test mode in the study area (Alabyan et al., 2016).

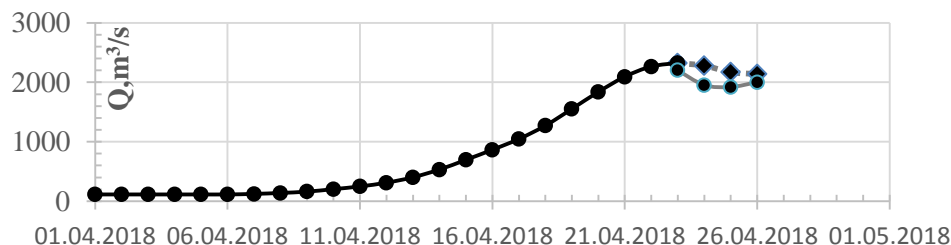


Figure 6. The example of the 3-day test forecast of water discharges, released on April 23, 2018 using the ECOMAG model based on data from the COSMO-Ru model (gray hatching), water discharges simulated on the base of meteorological station data until the day of forecast release (black line), the actual discharges for the Sukhona River – Kalikino (gray line).

Acknowledgments

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