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Information Support Technology in Managing the Volga–Kama Cascade of Reservoirs

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Abstract—The paper presents the structure of information support technology and algorithms of the decision-making process in managing the Volga–Kama cascade of reservoirs, as well as the results of implementing into the operational practice of a technology for regulating reservoirs and the prospects of its use for solving water problems.

Keywords: the Volga–Kama cascade, regulation of reservoirs, computer technology, hydrological data support

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INTRODUCTION

Over the past 15 years, with the support of the Russian Ministry of Natural Resources and the Federal Water Resources Agency, an economically sound and ecologically safe methodology was developed and improved for the management of water resources in river basins with multipurpose reservoir cascades. This methodology had been implemented in the form of a computer technology, which was used for the information support of making optimal managerial decisions on regulating the regimes of reservoir cascades in the operational practice of the Federal Water Resources Agency [3].

THE ALGORITHM OF MAKING DECISIONS ON MANAGING THE VOLGA–KAMA CASCADE OF RESERVOIRS

The algorithm of making decisions with the help of the developed technology could be summarized as follows (Fig. 1). At the initial stage, suggestions on reservoir regimes are made with the help of computer technology using all available operational information about the state of water objects and hydroengineering structures, archival and prognostic hydrometeorological information, normative instruments regulating reservoir regimes, and the current requirements of water users. These suggestions are considered and discussed at the meetings of the Interdepartmental Working Group (former Interdepartmental Operational Group) on regulating reservoir regimes, with the participation of representatives of interested ministries and agencies, executive bodies of the members of the Russian Federation, as well as the biggest water user companies.

The leader of the Interdepartmental Working Group is one of the officials of the Federal Water Resources Agency senior staff. After discussing suggestions at the meetings of the Interdepartmental Working Group, basing on the recommendations drawn up by the group, the Leader (DMP-the decision-making person) makes a decision on the work regime of each reservoir of the cascade. These are brought to the System Operator (former Central Dispatching Office) of the Unified Power System in the form of orders and then sent at the facilities of the Hydroelectric Power Stations in the form of directives.

Structurally, the information support computer technology consists of the four basic interconnected components (Fig. 1): (1) the program complex of river runoff modelling ECOMAG; (2) the program complex of water systems with reservoir cascades modelling VOLPOW; (3) the databases of cartographic, meteorological, hydrological, agrometeorological, and water-related information and the corresponding managing systems of these bases, and (4) the subsystem of visualization and representation of the basic information and the results of scenario and simulation calculations of water reservoir regimes (the GIS portal of the Register and Cadaster Center-http://gis.vodinfo.ru/).

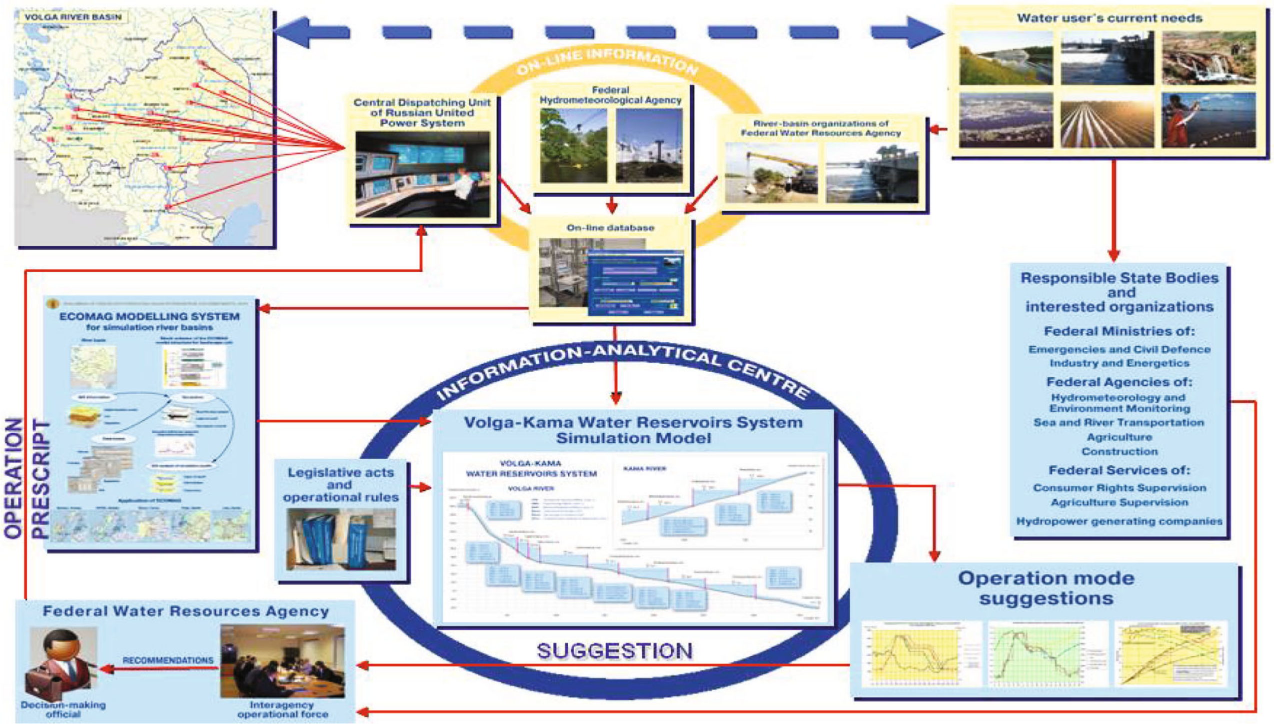

Fig. 1. The decision-making scheme for the management of the Volga–Kama water reservoirs cascade.

THE PROGRAM MODELLING COMPLEX OF RIVER RUNOFF FORMATION-ECOMAG

One of the key components of the information support technology when managing cascades of reservoirs is the program complex (PC) for mathematical modelling of river runoff formation ECOMAG (ECOlogical Model for Applied Geophysics) [12]. The PC includes: the mathematical model ECOMAG, a specialized geographical information system (GIS), archival and operational hydrometeorological databases and information about the territory characteristics, as well as a managing shell (Fig. 2).

The Model of Runoff Formation in River Basins

The runoff formation model ECOMAG is designed to implement the following scheme of the processes involved [9, 13]. In the warm season, precipitation in the form of rain partially penetrates the soil. Excessive water not absorbed by the soil moves to the river network along the slope in the form of surface runoff after filling depression storages on the surface of the basin. Part of water infiltrates into the soil and can move along the slope through temporary and relatively impermeable aquicludes (subsurface and groundwater runoff). The water that does not reach the river network is spent on evaporation. During the cold season, this scheme is complemented by hydrothermal processes in the snow cover and soil (snow cover formation and melting, freezing and thawing of soil, infiltration of snowmelt water into the frozen soil).

In the modelling of the river basin, its surface is divided into elementary catchments (model elements) by an irregular mesh, taking into account the nature of the terrain, the river network structure, the distribution of soil types, vegetation, land use, etc. Modelling hydrological processes in every model element is performed at four levels: in the surface soil layer (A horizon), the underlying deeper layer (B horizon), the groundwater storage, and the storage of surface runoff formation. In the cold season, the snow cover storage is added. The scheme ends by considering runoff transformation processes in the river network.

The main equations of the ECOMAG model describing hydrological cycle processes by ordinary differential equations are obtained by integrating the corresponding equations in partial derivatives of the detailed physically based models [7] over space with some assumptions. Such simplified semi-distributed models retain the main traits and advantages of the spatially distributed physically based models and, at the same time, they are more effective in solving scientific and applied problems, since they are less demanding to the contents and completeness of the background information, and also less sensitive to errors in this information.

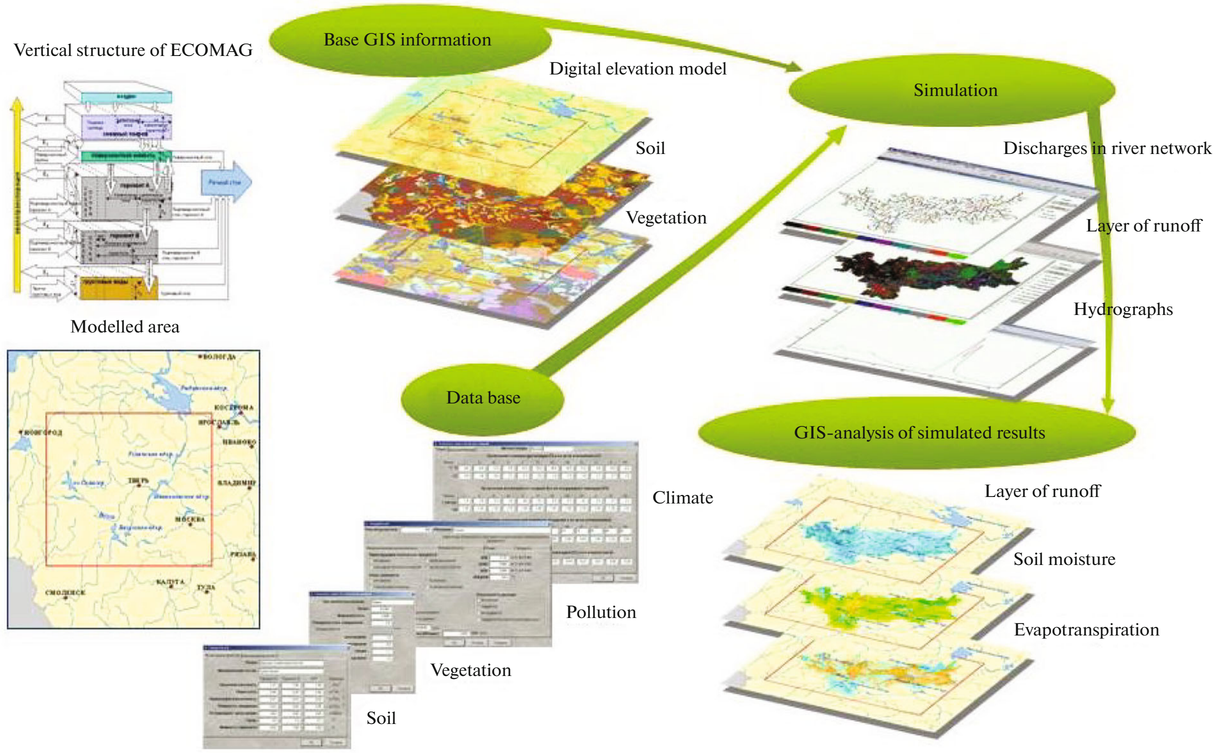

Fig. 2. Structure of a software package for modeling of river runoff formation ECOMAG.

The Methodology and Technology of Schematizing the River Network and the Catchment Area on the Basis of the DEM

In order to model the processes of the hydrological cycle and water flowing along the catchment slopes and in the channel network, it is necessary to carry out the schematization of the river basin and the river network. The information about their tree-like structure (which river flows into which one; the length of a tributary; the adjacent slopes, from which the water reaches the given part of a river; the types of soil and land use in these areas; etc.) is programmed into the model. To automate the process of river basin schematization, the program module Ecomag Extension was developed, which, basing on the digital elevation model (DEM), allows one to automatically single out the model river network with the necessary spatial resolution, outline catchment areas of tributaries and parts of the channel network, carry out the structural–hydrographical analysis of river networks, implement overlapping of different fields, calculate statistical characteristics of spatial fields and carry out other mathematical operations with them that are necessary for solving hydrological and water-related problems. The methodology of automated highlighting elementary catchments and the model river network consists in drawing the streamline and pathline fields and fields of stream accumulation on the basis of the digital elevation model. Cells with a high stream accumulation form a model channel network. After that there is a procedure of "splitting" the basin into elementary catchments, representing separated catchment areas among the junctions of the river network, which are model spatial elements.

The ECOMAG Data Bases

The ECOMAG data bases contain information about river basins, soil parameters and landscape types, meteorological, hydrological, and water-related characteristics.

The data bases of river basin characteristics, meteorological, hydrological, and water-related blocks of information mainly include the description of objects and ways of access to the volume boot records for objects (the structure of model river network and elementary catchments, the spatial distribution of soil types and vegetation in the river basin, the network of monitoring stations, etc.) and to the electronic archives of observation data sets when estimating corresponding river basins.

From the thematic data bases, the data on the characteristics of soils and land use are taken. The database Soil contains hydrophysical characteristics of soil types on the territory of the former USSR, which are parameters of the ECOMAG model. These include the soil type, mechanical composition, bulk density, porosity, field capacity, wilting point, hydraulic con-

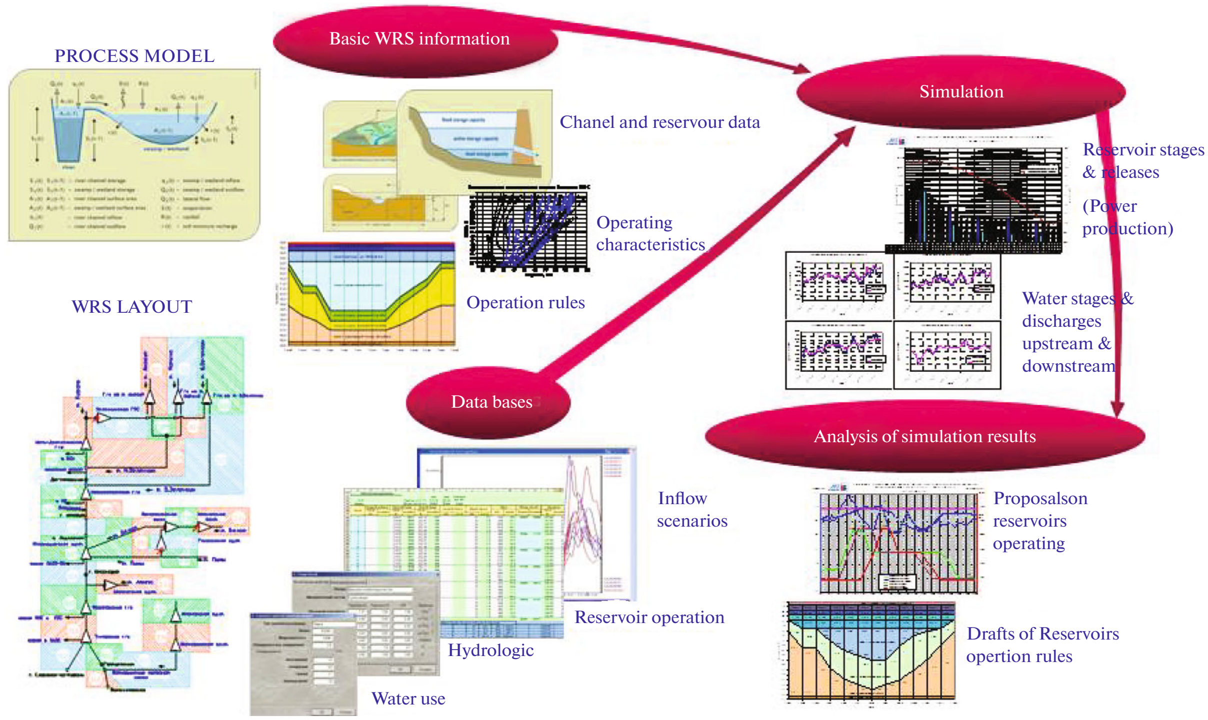

Fig. 3. Structure of a software package for modeling of the functioning of water resources systems with reservoirs cascades VOLPOW.

ductivity, etc. The information sources for the actualization of the Soil database were regional reference books of agro-hydrological soil properties. Overall, the database contains characteristics of more than 700 soil types. The data base Land Use contains the ECOMAG model parameters that change depending on the type of landscape, vegetation, and land use (ploughed field, virgin soil, forest, etc.). Overall, the database contains information about 32 types.

The Computer Shell of the PC ECOMAG

The managing shell with a user-friendly interface allows one to combine the cartographic information of the specialized GIS for a river basin with the information from the databases, to configure the necessary calculation variant, to start model calculation, and to show the results of the calculations in the form of various graphs and schematic maps, including the cartographic basis and estimation hydrological maps, in the form that is suitable for analysis and the decision making by PMD.

THE PROGRAM COMPLEX VOLPOW FOR MODELLING WATER SYSTEMS WITH CASCADES OF RESERVOIRS

The development of another key component of the technology-the program complex of mathematical modelling of water systems with reservoir cascades (VOLPOW-VOLga POWer) started in the mid-1980s at the All-Union Institute of Water Structure Projecting, the USSR Ministry of Water Resources, and Water Problems Institute, the USSR Academy of Sciences. Its practical application on the Volga–Kama reservoir cascade started after the near-catastrophic flood of 1991.

At present, the program complex VOLPOW includes: an imitation mathematical model VOLPOW, archival and operational hydrometeorological and water databases, the information about bathymetry of water objects, and the managing shell (Fig. 3) [4].

The program complex VOLPOW allows one to conduct a wide range of water resources and water and energy supply calculations and can be used as an instrument of decision-making support when setting the work regimes of water systems, as well as implementing projects and researches [2].

The Model of a Water System with a Cascade of Reservoirs

The hydraulic block of the model is based on the Saint-Venant equations for unsteady flow. The water block includes requirements and limitations contained in the reservoir operation rules, representing the dependence of the required (and permissible) water discharges through reservoir waterworks on water level in the upper pool and the calendar date. The correlation of hydraulic calculations with the water resources block is realized by setting boundary conditions for the Saint-Venant equations, related to the reservoir operating rules and the hydraulic structures capacity.

Generally, the solution of the problem requires detailed information about channel cross-sections, slopes, roughness coefficients, etc. In engineering practice, there is often a lack of such detailed information. As a rule, there is some integral information in the form of reservoir volume curves, discharge–level dependencies, dynamic volume nomograms, etc. [4]. Therefore, in the model VOLPOW, the algorithms of finite difference approximation of equations are modified by combining separate terms into some functional relations, which allow one to use both detailed and integral morphometric and hydraulic background information. A system of algebraic equations is solved at every time step with the help of two iterative cycles: the inner one designed to search for the agreed values of functional dependencies, determining the water volume on the site and the position of water levels on the borders of the sections of the modelled water resource system (MWRS); and the outer one, to coordinate water levels and discharges at the adjacent ends of the sections of the MWRS, as well as the boundary conditions, determined by the hydraulic structure capacities and reservoirs operation.

The Schematization of the Water System and the Background Data

The modelled water system is presented in the form of sections of the MWRS, which describe reservoirs, riverbeds, or channels. For every section of the MWRS, the existing integral and point morphometric and hydraulic characteristics are used. On the sites of reservoir waterworks, boundary conditions are formulated, defined by the hydraulic structure capacities and reservoir operating rules.

When it is necessary to model the work of a water system, realizing compensated regulation, or for complex and branched water resource systems, including circular ones, the program complex VOLPOW provides the possibility to set the second special operating rules for separate reservoir structures. The graph helps to realize models of different variants of runoff regulation.

The background hydraulic information for VOLPOW is the time series of the lateral inflow to sections of the MWRS (in particular, calculated using the ECOMAG model). For every section of the MWRS in the PC VOLPOW, several inflow vectors can be introduced, allowing one to take into account the separate inflows in several rivers that flow into this segment, or set characteristics of additional water withdrawals or losses in the form of vectors with negative values for the segment. Besides, using this vector allows one to calculate the balance residual of factual inflows and discharges when solving the reverse problem with the help of VOLPOW—defining the usable water inflow into reservoirs, according to the factual regimes of reservoir facilities.

Performing Calculations with the Help of the Program Complex

The program complex VOLPOW allows one to calculate the following groups of water and energy characteristics:

water levels: average over the length of reservoirs, near the dams of a hydraulic structure, and in its downstream part (average over the regulation interval and at the end of the interval);

water levels at gaging sites located in river sections of a water system (average over the regulation interval and at the end of the interval);

discharges of hydraulic structures, including discharges through turbines, outlet works, filtration, and locking discharges (averaged over the regulation interval);

net heads, turbine discharges, the generating capacity of the Hydroelectric Power Station (average over the regulation interval), hydropower generation at the Hydroelectric Power Station;

heads, water supply, power consumption (average over the regulation interval) and electricity consumption on pumping stations (PS).

The calculation results are water balance for every reservoir of the cascade and estimated regimes of discharges and levels in every measuring section.

INFORMATION RESOURCES

The existing information resources attracted for performing calculations using the computer systems ECOMAG and VOLPOW are sufficient (in terms of the volume and the spatial coverage of Russia's territory) for performing calculations for any big river basins of the Russian Federation.

The Cartographic Supply of River Basins

As the main types of information for forming cartographic databases required for setting characteristics and parameters of mathematical models, the following materials are used:

digital topographic maps of various scales for the territory of the country;

digital elevation models with the resolution of 1 km and 90 m;

series of digital thematic maps (water resources, soils, landscapes, etc.), reflecting the characteristics and state of natural resources.

Hydrometeorological and Water-Related Supply

The operational and archival information of hydrometeorological monitoring is one of the pillars for conducting hydrological and water-related calculations. The operational hydrometeorological and water-related information is transmitted in real time through the channels with the Russian Hydrometeorological Service and the System Operator of the Unified Power System (the SO of the UPS), decoded and integrated in the databases of the computer complex.

The hydrological database contains data on the level and discharge regimes and hydrometeorological situation for hydrometric stations on rivers, lakes, and reservoirs. The hydraulic structure database contains daily data on the characteristics of reservoirs and the operation of hydraulic structures of the biggest hydroelectric power stations (information about the level regime in the upstream and downstream pools of the facilities, the lateral and total inflow to the reservoirs, reservoir discharges, etc.). The meteorological database contains daily information about the characteristics of the surface atmospheric stratum (air temperature and the dew point, the amount of precipitation over a certain time, direction and speed of the wind, the amount of clouds, etc.) at meteorological stations. The agrometeorological database contains information with the parameter values of the surface of the earth and the zone of suspended water (layered reserves of productive moisture in the soil, the depth of soil freezing and melting, the height and density of the snow cover on fields, etc.) at agrometeorological stations. The databank of snow cover characteristics accumulates data from snow measurements in forest and field areas (the height, density, and snow cover water equivalent, taken three and six times per month).

THE IMPLEMENTATION OF INFORMATION SUPPORT TECHNOLOGY IN THE OPERATIONAL PRACTICE OF MONITORING THE VOLGA–KAMA CASCADE OF RESERVOIRS

In the implementation of the technology, combining the program complex of modelling river runoff formation ECOMAG and the program complex of mathematical modelling of water systems with reservoir cascades VOLPOW, was started by the Russian Ministry of Water Resources at the beginning of the 2000s in order to manage the reservoirs of the Volga–Kama cascade (in the context of the special federal program "The Volga Revival").

The Volga–Kama cascade, including 11 reservoirs with hydropower plants, is unique and one of the biggest multipurpose water systems in the world. The main objective of the cascade is to redistribute in time the natural runoff of the Volga River, which is extremely unevenly distributed within a year, when about 2/3 of the annual runoff occurs during a 2–3-month period of spring flood.

Implementing special annual spring releases into the lower parts of the Volga is a function of the cascade that is unparalleled in the world water practice. Basically, this is a long practiced large-scale ecological release that can be traced back to the times when the Lower Volga reservoirs were constructed. According to the international experts [8], this is what makes the Volga positively different from other regulated rivers in the world, where the dam construction does not allow the required length of the flooding period to be maintained. The annual spring discharge through the Volgograd Hydroengineering Structure is implemented according to a special schedule during the second quarter mainly in order to provide for the needs of the Lower Volga agriculture in floodplains and filling floodplain ponds (ilmens), as well as for the needs of fisheries in terms of spawning of valuable fish species, particularly, sturgeon.

The ambiguity of the requirements of different water users to the regimes of spring discharge through the measuring section of the Volgograd Hydroengineering Structure significantly complicates their planning. Under these conditions, the choice in favor of this or that variant should be based, in the first place, on getting the maximal economic effect with the fewest negative ecological and social consequences.

Operational Management of the Volga–Kama Reservoir Cascade Using the Designed Technology

The long-term strategic planning algorithm for the work regimes of the Volga–Kama hydroengineering structures with the developed technology can be summarized as the two following stages:

(1) a series of scenario (ensemble) calculations of lateral inflows to the reservoirs of the cascade are performed over the previous period with the help of the program complex ECOMAG for modelling runoff formation;

(2) possible work regimes of the Volga–Kama cascade hydroengineering structures are estimated on the basis of the lateral inflow scenario calculations for the simulation water model with the help of the program complex VOLPOW.

Let us characterize these stages in more detail. The ECOMAG model calculations are carried out using operational meteorological data (weather reports), received through channels of communication from the Russian Hydrometeorological Service on a continuous basis. Fields of meteorological data on the territory of the basin are the inputs to the model. In total, about 350 operational meteorological stations are involved in the Volga basin.

The model calculates snow cover fields with a 24-hour time step, as well as fields of soil humidity and freezing, snowmelt, river runoff in the channel network and, in the long run, lateral influxes into the reservoirs. The hydrographs of reservoir inflows over the previous years, as well as snow cover fields according to the snow measurement data, fields of soil humidity and freezing according to the measurement data from the agrometeorological stations can be used in the model for calibrating its parameters and checking the accuracy of the model [10]. To control the calculation results, daily information about the inflows into the Volga–Kama reservoirs is received from the operational base of the UPS System Operator. Over time, the calculation results are periodically specified (during the flood period, once in every five days).

The carrying out of scenario (ensemble) calculations of the inflows to the Volga–Kama cascade reservoirs, as well as the lateral inflows to the river segments according to the ECOMAG model, can be summarized as follows.

(1) The new prognostic meteorological and operational hydrological information that has been received for the current date (for the next 6 days, according to the data from the Russian Hydrometeorological Service) is copied in the data archives of the model complex.

(2) According to the model, hydrological calculations are performed with the help of the factual and prognostic meteorological information for the finishing date of the meteorological forecast.

(3) In order to calculate scenarios of runoff formation and reservoir lateral inflow for the following period (for instance, until the end of the current or next quarter), it is necessary to specify the scenarios of the meteorological processes for this period. In view of the fact that long-term meteorological forecasts with 24-hour resolution cannot be made for such periods, the model sets the same meteorological scenarios for the period from the finishing date of the forecast to the end of the quarter as for the similar calendar period in the previous years. After this, the model ECOMAG helps to calculate hydrograph ensembles of lateral inflows to the reservoirs and to separated riverbed segments [5]. These output data of the PC ECOMAG are the input information for the simulation model VOLPOW for regulating work regimes of reservoir cascade hydraulic facilities.

Solving the problem of spring flood release in the most rational (optimal) way under modern conditions is realized basing on multivariate calculations of work regimes of the cascade hydraulic facilities for the whole range of possible hydrological conditions (forecasted by the Russian Hydrometeorological Service and the ensemble ones according to the ECOMAG model) with the help of the simulation model VOLPOW. Let us demonstrate this by an example of 2005 spring flood that had the highest water level over the past years.

The volume of the total useful inflow to the Volga–Kama reservoir cascade that had been calculated before the 2005 flood with the ECOMAG model (on the basis of the hydrograph suggested as the main variant) was 171.9 km^3. The forecast of the total inflow to the cascade reservoirs issued at the same time by the Russian Hydrometeorological Center indicated the expected total inflow volume range to be 161–191 km^3. The total free storage capacity of all Volga–Kama cascade reservoirs was estimated at 32 km^3 for the April 1, 2005, i.e. it was almost equal to the inflow range forecasted by the Russian Hydrometeorological Service.

With the program complex VOLPOW, basing on the choice of the main variant of the useful reservoir inflow and taking into account the obtained estimates of the possible variability around the expected inflow, a range of work regime scenarios for all cascade reservoirs was determined, as well as the variants of estimated graphs of maximal and minimal volumes of the special spring flood releases from the Volgograd Reservoir (special release) in the period of the 2005 spring flood. The estimated volume of the special release was 135.4 to 144.4 km^3, i.e. the uncertainty associated with the wide inflow range forecasted by the Russian Hydrometeorological Center was reduced more than three times.

The results of these calculations were reported as baseline estimates at the Interdepartmental Working Group regulating the work regimes of the Volga–Kama cascade on April 12, 2005. On their basis, the strategy of the 2005 spring flood release through the cascade of hydraulic structures was formulated and adopted. Subsequently, in accordance with the designed technology, specifying calculations were carried out every 5 days, taking into account the factual inflow and work regimes of cascade hydraulic facilities over the previous period: the expected inflow estimates were specified for every reservoir of the cascade, as well as the suggested work regimes of the hydraulic facilities, to the end of the planned period. At the IWG meetings, when considering a certain hydrological and water-related situation, on the basis of the formulated suggestions regarding the work regimes of hydraulic facilities, recommendations on setting these regimes were adopted after discussion. These recommendations served as a basis for making appropriate managing decisions by the Russian Water Resources Agency.

Based on the findings of the release regime of the 2005 spring flood, the factual total volume of useful inflow to the Volga–Kama reservoir cascade was 171.2 km^3 for the second quarter, with the estimate of 171.9 km^3 presented at the beginning of the flood. The factual total inflow to the cascade reservoirs was 182 km^3, according to the data provided by the Russian Hydrometeorological Center. The residual of the general and useful inflow values had reached almost 11 km^3, or 1/3 of the free reservoir storage capacity by the beginning of the flood. The volume of the special spring flood release through the Volgograd facility

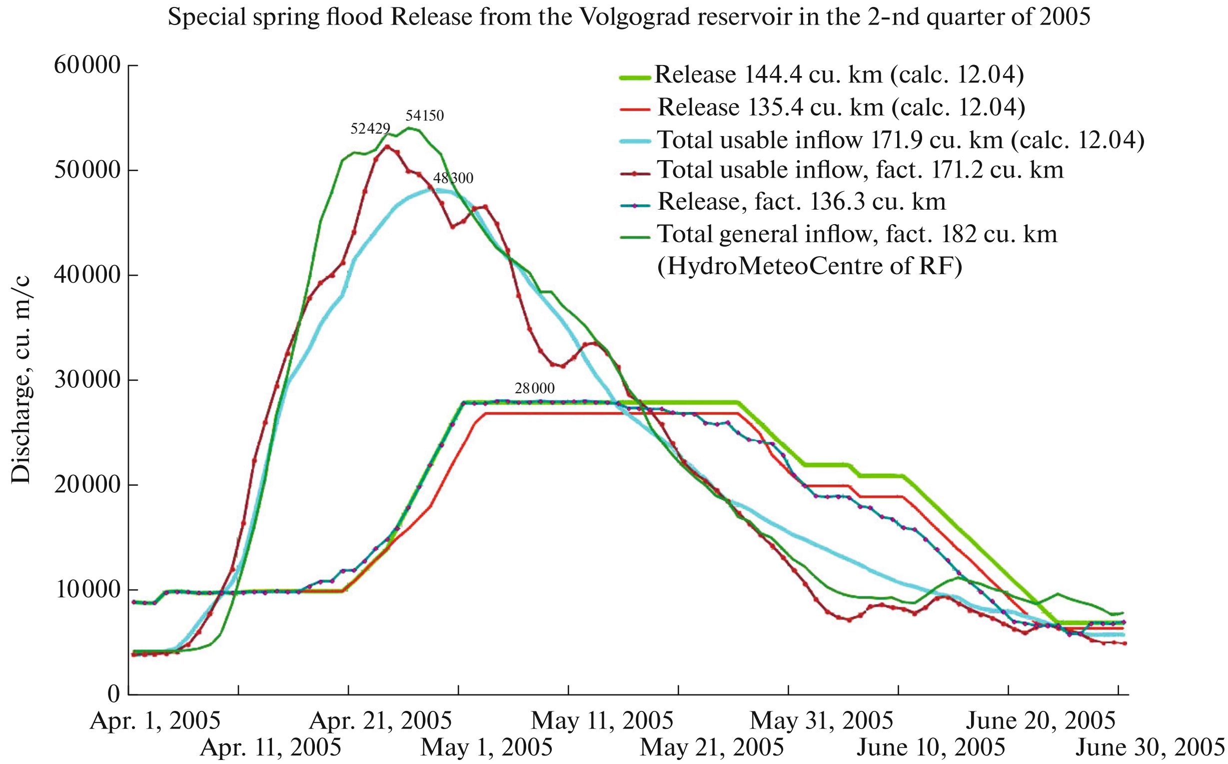

Fig. 4. Graphs of the total inflow to the Volga–Kama reservoirs Cascade and special spring release from the Volgograd Reservoir in the second quarter of 2005.

amounted to 136.3 km^3, while it had been planned from 135.4 to 144.4 km^3. The configuration of the special release graph and its main characteristics were in close agreement with the one projected at the beginning of the flood (Fig. 4).

Table 1 shows data on the total inflow to the Volga–Kama cascade forecasted by the Russian Hydrometeorological Service before the beginning of the second quarter. Moreover, it contains the useful inflow to the Volga–Kama reservoirs and the Volgograd reservoir discharge, which were calculated with the help of the technology developed for this date and presented by the IWG for providing decision-makers with information support. Table 1 also contains factual data after the second quarter over the technology exploitation period of 2004–2016.

As can be seen from the data analysis, the average errors in the forecasts of the total inflow volume in the reservoir, provided by the Russian Hydrometeorological Service, proved to be close to the errors in the calculation of the useful inflow with the help of the developed program complexes, which amounted to –7.1 and –4.0 km^3, respectively. Statistical estimates of the forecast reliability according to the s/σ criterion (where s is standard forecast error, σ is standard deviation) equaled 0.89 and 0.75 respectively, which also demonstrates some advantage of calculating inflow using the suggested hydrological information technology.

On the average over the period under consideration, the deviation of the factual release volume from the planned (estimated) one was –1.5 km^3 (column 12 in Table 1), whereas over the previous period, 1959–2003, it amounted to +7.8 km^3. The maximal difference between the factual and expected release volumes varied from –29.3 to +21.8 km^3 during the period of 2004–2016, while in the previous period, it varied in the range from –33.0 to +52.0 km^3. Thus, the quality of planning spring flood release regimes has improved, as well as the realization of special spring release into the Volga lower parts. The criterion s/σ for the considered range of special release volume was 0.59, which allows the effectiveness of the considered special release planning technology to be estimated as satisfactory.

Let us consider the residuals of the total and useful inflows to the Volga–Kama cascade of reservoirs (column 13 of Table 1), which, apart from the irreversible losses from the reservoir and water-usage expenses, include the errors in determining the total inflow using hydrometric data. In 5 years out of 13, these residuals exceeded 10 km^3, i.e., they are suspiciously large, requiring further consideration and critical analysis.

It is also important to remember that the earliest (preliminary) forecast by the Russian Hydrometeoro-

Table 1. Estimated and actual data (km^3) for inflow to the reservoirs of the Volga–Kama Cascade and releases from the Volgograd Reservoir in the second quarter of the year for the period 2004–2016

Years	Forecasts & Calculations					Factual			Deviations			
	Total General Inflow Forecast by HydroMeteoCentre			Total Usable Inflow	Special Release Volume	Total General Inflow (TGI)	Total Usable Inflow (TUI)	Special Release Volume	Total General Inflow	Total Usable Inflow	Special Release Volume	TUI–TGI
	min.	max.	mean	calculated					7–4	8–5	9–6	8–7
2004	133	163	148	141	113.2	146	136.4	106	–2	–4.6	–7.2	–9.6
2005	161	191	176	171.9	135.4	182	171.2	136.3	6	–0.7	0.9	–10.8
2006	124	154	139	137.8	85.7	128	126.1	76.4	–11	–11.7	–9.3	–1.9
2007	138	168	153	134	113	140	138.9	120.2	–13	4.9	7.2	–1.1
2008	127	157	142	126.4	103	131	121.5	101.9	–11	–4.9	–1.1	–9.5
2009	122	152	137	126.2	98.7	125	117.2	92.7	–12	–9	–6	–7.8
2010	150	180	165	134.1	92.5	133	126.4	91	–32	–7.7	–1.5	–6.6
2011	158	178	168	161.4	106.5	132	123.9	77.2	–36	–37.5	–29.3	–8.1
2012	122	152	137	125.9	76.6	158	147.1	98.4	21	21.2	21.8	–10.9
2013	156	186	171	165.6	129	173	159.3	125.4	2	–6.3	–3.6	–13.7
2014	120	146	133	114.3	92.6	117	104.4	86.1	–16	–9.9	–6.5	–12.6
2015	115	143	129	111.4	69.5	124	112	65.5	–5	0.6	–4	–12
2016	130	158	144	138.7	107.9	161	154.5	127.3	17	15.8	19.4	–6.5
Average	135.1	163.7	149.4	137.6	101.8	142.3	133.8	100.3	–7.1	–3.8	–1.5	–8.5

logical Service regarding the inflow **volumes** for the second quarter is released in the middle of March. As for the calculations using the program complexes, they can provide daily inflow **hydrographs** for every reservoir. The first estimates of the inflow and spring flood release characteristics are produced in February and actualized since March 1 at least every 5 days.

The Adaptation of the Designed Technology for the Major River Basins of the Russian Federation

Following the results of the system functioning within the Volga–Kama cascade in the mid-2000s, R.Z. Hamitov [6], who was the leader of the Federal Water Resources Agency at that time, initiated, organized, and deployed large-scale works for adapting this system to other major river basins of the Russian Federation and its specification for smaller sub-basins and the corresponding water systems within the Volga–Kama basin.

In 2007–2010, the system was specified for the basins of Moscow [1] and the upper parts of the Volga and the corresponding reservoir system—the sources of Moscow water supply; for the basin of the rivers of Ufa and Belaya and the corresponding reservoir system. In 2008–2009, the system was adapted for the whole basin of the Lena River and the basins in the upper part of the Yenisei and the Angara and the Angara–Yenisei reservoir cascade; in 2009, the whole basin of the river; in 2009–2010, the whole basin of the Kuban River and its complex water system with reservoirs and tracts of inter-basin transfers.

The works completed at the Angara–Yenisei cascade with the help of the developed technology allowed the necessary calculations to be carried out as soon as the second day after the Sayano-Shushenskaya Plant disaster of the August 17, 2009. They also enabled the simulation of possible model scenarios of the hydrological and water-related situation for the period before the following year's flood and made it possible to give operational recommendations on the work regime of the Sayano-Shushenskoye Reservoir, taking into consideration all the limitations concerning the use of hydromechanical equipment of the facility, permissible schemes of manipulating water outlet closures, as well as safety requirements.

The post-disaster situation at the Sayano-Shushenskaya Plant was complicated by the abnormally high-water hydrological conditions of the 2010 winter–spring period. Therefore, in order to monitor and forecast the hydrological situation in the catchments of the Sayano-Shushenskoye and Krasnoyarsk reservoirs, all terrestrial networks of hydrometeorological and water-related observations were activated, and the information from remote sensing of the Earth and the prognostic possibilities of the technology were incorporated. Subsequently, the technology was used as the main operational regulating instrument of the Sayano-Shushenskoye Reservoir work regimes during the period of its non-designed exploitation until the recovery of the plant, as well as of other cascade reservoirs, including the Boguchanskoye Reservoir under construction.

The Economic and Social Effects of Implementing the Technology

For the large-scale and complex water systems, such as the Volga–Kama or Angara–Yenisey cascades, the system of water-supply reservoirs in Moscow, or the Kuban River system, the assessment of the economic and social effect of making decisions on regulating reservoir regimes is extremely difficult because of the large number of water users, often making diametrically opposite demands to these regimes.

The inevitable contradictions between the environmental conservation requirements, water demands, and safety requirements of hydraulic structures should be regulated within the framework of developing work regimes of water resources systems that would be optimal from a comprehensive and integrated perspective. The 50-year practice of planning and realizing spring release through the Volgograd facility into the lower reaches of the Volga has not been yet assessed objectively and accurately, taking into account the exact hydrological conditions of each flood and the accompanying effect on the water and water-related ecosystems. Most agencies consider the release results only in their narrow departmental aspect and reduce them to calculating the damage (more often than not using absolutely outdated and unjustified methodologies). It is necessary to note that, even within one industry, the requirements to the operation regimes of cascade facilities can be radically different. For instance, the demands of the fishery in the Lower Volga reservoir to maintain stable water levels in the reservoirs during spawning period contradict the corresponding requirements of the fisheries located in the lower reaches (delta) of the Volga to provide the necessary volume and schedule of discharge from the Lower Volga reservoirs.

However, the estimates of the production increment due to the use of the technology, compared to the restrictions set by the existing regulations (for example, additional power generation), and the comparative analysis of changes in the losses of individual industries, while implementing reservoir regimes under similar conditions before and after the implementation of the technology (the damage to the fisheries and agriculture), can be used to assess their economic effectiveness. This estimates are based on the expert data on the results of the realization of Volga–Kama reservoir regimes, presented by the designated organizations at the meetings of the Interdepartmental Operational Group. According to these estimates, as of the beginning of 2010, several years after the start of operation of the Volga–Kama basin system, the average annual economic effect of its application was at least 200 million rubles with annual exploitation expenditures of 6–10 million.

PROSPECTS AND DIFFICULTIES OF USING THE TECHNOLOGY

The technology has a high potential as far as its application sphere and improvement are concerned. Distributing the technology among water systems of catchment basins is promising for the Don R. (including its Ukrainian part); the Irtysh R. (including its Kazakhstan and Chinese parts); Lake Baikal (including the Selenga R. and its Mongolian part); and the rivers of the northwest of Russia (the Volkhov, the Narva, etc.). A trend in improving the technology is the incorporation of sub-models of water quality formation in water objects, which will enable its fuller use in managing water resources for applied ecological objectives [11].

The hydro-information support technology for decision-making in the development of recommendations for regulating reservoir cascade regimes needs to be constantly backed up by new operational hydrometeorological and water-related data, which characterize the change of the current situation in the reservoir catchment areas. Therefore, meteorological, hydrological, agrometeorological, and water resources databases are to be kept updated (Fig. 1). Most information comes through the channels of communication from the Russian Hydrometeorological Service under the agreements and treaties with the Russian Water Resources. Unfortunately, for some (mainly economic) reasons, these agreements on transferring the operational hydrometeorological information, necessary for information back-up of the hydro-informational technology to the Russian Water Resources, were not resumed in 2016. As a result of the lack of the complex operational information support, one of the key technology components, the model ECOMAG for modelling the reservoir lateral inflow hydrographs, is switched off. In this case, another technology component, i.e., the model VOLPOW, used to simulate the functioning of reservoir cascade water system, must be oriented only to the hydrographs derived from archival data, adjusted for the quarterly and monthly inflow volumes forecasted by the Russian Hydrometeorological Service, and the evolving hydrological and water-related situation in the reservoirs. This can lead to increasing uncertainties in setting the reservoir regimes and strategic planning of the annual spring release through the Volgograd facility, as well as the higher risk of undesirable situations with possible material and economic losses. Thus, due to the lack of understanding among the departments regarding the exchange of hydrometeorological information, required for the technology, basing on the advanced and unparalleled innovation technology water practice, created as a result of long-term research by scientists and engineers of hydrological expertise, the reliability and quality of the PMD information support on regulating reservoir cascade regimes are threatened.

CONCLUSIONS

The paper describes the information support technology and the decision-making algorithms for managing the Volga–Kama cascade of reservoirs, as well as the results of implementing the technology into operational practice of regulating the reservoirs, the economic effect and the prospects for its application in order to solve water-related problems. The creation of the technology aims at solving the problems of increasing the economic efficiency and ecological safety for the Russian water complex.

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