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The Integrated System of Hydrological Forecasting in the Ussuri River Basin Based on the ECOMAG Model

Andrei Bugaets [1,2], Boris Gartsman [1,2], Alexander Gelfan [1,*], Yury Motovilov [1], Oleg Sokolov [3], Leonid Gonchukov [1,2], Andrei Kalugin [1], Vsevolod Moreido [1], Zoya Suchilina [1] and Evgeniya Fingert [1]

1 Water Problems Institute, Russian Academy of Sciences, Gubkina Street, 3, Moscow 119333, Russia; andreybugaets@yandex.ru (A.B.); motol49@yandex.ru (Y.M.); kalugin-andrei@mail.ru (A.K.); moreido@mail.ru (V.M.); mezozoya1@mail.ru (Z.S.); fingerte@gmail.com (E.F.)

2 Pacific Institute of Geography, Far East Branch, Russian Academy of Sciences; Radio, 7, Vladivostok 690041, Russia; gartsman@inbox.ru (B.G.); gonchukovlv@gmail.com (L.G.)

3 Far Eastern Regional Hydrometeorological Research Institute, Fontannaya Street, 24, Vladivostok 690600, Russia; osokolov@ferhri.ru

* Correspondence: hydrowpi@iwp.ru; Tel.: +7-499-135-5456

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Abstract: This paper considers the main principles and technologies used in developing the operational modeling system for the Ussuri River Basin of 24,400 km^2 based on the automated system of hydrological monitoring and data management (ASHM), the physical-mathematical model with distributed parameters ECOMAG (ECOlogical Model for Applied Geophysics) and the numerical mesoscale atmosphere model WRF (Weather Research and Forecasting Model). The system is designed as a freely combined tool that allows flexible changing of the forecasting and informational components. The technology of inter-model and cross-platform interoperability is based on the use of the Simple Object Access Protocol (SOAP) web services and the Open Geospatial Consortium Open Modelling Interface (OGC OpenMI) standard. The system demonstrates good performance in short-term forecast of rainfall floods and reproduces complex spatio-temporal structure for the runoff formation during extreme rainfall.

Keywords: hydrological forecasting; flash flood; hydrological monitoring system; flood awareness; ECOMAG model

1. Introduction

Flood forecasting is one of several key components in flood protection systems worldwide. According to the Sendai Framework Program for Disaster Risk Reduction adopted by the Third UN World Conference on Disaster Risk Reduction (WSCRR) in 2015, it is necessary to improve the monitoring systems and better understand various types of threats, as well as enhance the forecasting and early warning systems. This should increase the awareness of responding agencies and the general population.

State-of-the-art hydrological forecasting systems are meant to provide the maximum lead time with sufficient accuracy in order for the users to take the appropriate action for hazard mitigation or optimize water use strategy. A common structure of such system includes data management blocks, modelling resources, GIS tools and more. It is crucial for the operation that the most accurate data are used. Both data-rich and data-poor national hydrometeorological services struggle with retrieving, quality controlling, infilling, formatting, archiving and redistributing data [1]. Robust algorithms are required to overcome the data processing and preparation issues.

The use of regional numerical weather models by the water management authorities in their operational practice has provided high-resolution forecasts for input into the spatially distributed hydrological models within flood protection and water management planning. Many numerical weather prediction models have been implemented into operational practice—the European Centre Medium-Range Weather Forecasts (ECMWF) Ensemble Prediction System (EPS) [2,3], the Weather Research and Forecasting (WRF) model [4], the numerical weather forecast model of the Japan Meteorological Agency [5], the China Meteorological Agency [6] and more. Coupling the weather prediction model with a hydrological forecasting model provided a new way to determine watershed flood forecasting and extended lead time [7–9].

The contemporary concept of operational activity support for hydrological monitoring and forecasting centers is aimed at combining information and modeling components to automate data preparation, analysis and presentation of results. Integrating a large number of models (heterogeneous by their structure, degree of detail, the initial information requirements) into an operational system, is a non-trivial problem, which is complicated by the continuous improvement of existing models and the appearance of new ones, the development of computer technology, information transfer means, measurement technologies, network resources and more. The use of information technologies must be constant with respect to the model features used while the means of the data storage and transfer needs to allow efficient integration of the models and databases into a unified system and change the system components by improving the models and/or emergence of new tasks and objects [10–13].

The article describes the main results of developing the modeling system for the upper Ussuri River Basin on the basis of the automated system for hydrological monitoring and data management (ASHM) [10,14] and the physically-based distributed hydrological model ECOMAG (ECOlogical Model for Applied Geophysics) [15]. The output of the numerical mesoscale atmosphere model WRF (Weather Research and Forecasting Model) is used to produce meteorological forecast data into the hydrological model [16]. The inter-model and cross-platform interoperability technology is based on using SOAP web-services and the open OGC OpenMI 2.0 modelling standard (Open Modelling Interface, www.openmi.org) developed by the consortium of leading European institutes and commercial organizations in the field of hydroecology [17].

2. Case Study

The upper part of the Ussuri River Basin to the Kirovsky gaging station with an area of 24,400 km^2 was chosen for the case study. The length of the river from the headwaters is 240 km and the average slope is 5.1%. The river basin has a contrasting relief: in its southern and eastern parts mountains predominate while lowlands prevail in the northwest. The Ussuri upstream river is located among the mountain ranges of the Central Sikhote Alin, which are a region of Mesozoic folding. The relief varies since some mountains have rounded and flat peaks with a height of 700–1500 m (the highest point is 1854 m) while other parts have low-hill terrain and rivers valleys. Intermountain depressions are often located near the main divide. The bottom of the depressions is usually occupied by swampy river valleys. The Ussuri River and its main stream tributaries flow mostly in the intermontane hollows [18].

The basin is mainly composed of Mesozoic aqueous and metamorphic rocks (malmrock, siltstones, argillites, etc.) breached by numerous granitoids intrusions. In mountainous areas, the eluvium and eluvium-talus of dense rocks are soil-forming rocks. The eluvium has the usual loose structure, as a result of which the atmospheric precipitation exudes freely through its rock mass. Only on extensive basaltic plateaus, the infiltration of water is difficult due to the fine-textured basalts eluvium. Within the plains, the soil forms on alluvial sediments represented mainly by clays with a high content of silts. In the river valleys, the alluvial sediments, which consist of sandy gravel, fine sandy loams, argil sand grounds and clay, are the soil-forming rocks [19].

The space distribution of soil and vegetation is highly susceptible to altitudinal zones. The mountain–tundra soils and suffruticose vegetation type refer to the highest points. In the east and southeast of the basin, the mountain brown-taiga soils and mountain podzol soils on which coniferous forests grow are observed in the mountain areas. In the southwest, the brown-taiga soil of spruce-cedar-hemlock forests are visible. The largest area of the Ussuri Basin is occupied by mountain-forest brown soils of mixed coniferous-broad leaved forests and brown forest soils of hillocky area [20].

The climate of the basin is determined by its position near the Pacific coast and by the monsoon character of the atmospheric circulation. The basin moisture regime is extremely unstable over an annual and long-term period. The summer is warm and damp while the winter is cold and dry. The average temperature in August is +21 °C while the average temperature is −20 °C in January. The mountainous part of the basin receives up to 1,000 mm of precipitation while the plain sees 600–700 mm rainfall annually. Precipitation occurs mainly in the summer. The river feeding is mainly precipitative: more than 80% of the annual runoff occurs in the period between April and September while the winter low-flow accounts only for 2%–5% of total annual runoff. Flash floods prevail in the rivers hydrological regime and can occur during the entire period from May to October. Usually in July–September, the basin is affected by typhoons (one to three per year) which lead to a sharp rise in water levels and flooding of river valleys, leading to great societal and economic damage [21].

3. Materials and Methods

3.1. Information-Modeling Complex (IMC) ECOMAG

The spatially-distributed ECOMAG Model (ECOlogical Model for Applied Geophysics) described the process of runoff generation [22]. The model was tested on a number of river basins in various physiographic conditions and spatial scales. The model also showed efficiency in both hydrograph modelling at different gages and simulation of the fields of hydrological variables, such as soil moisture, snow water storage and runoff yield in large river basins. The ECOMAG model describes the main processes of the hydrological cycle in snowmelt and rain-fed river basins: Snow cover accumulation and melting, water infiltration into soil and evaporation, thermal and water regime of soil taking into account it's freezing and thawing and overland, vadose, ground and stream flow.

The spatial structure of the ECOMAG model computational network is composed from the natural stream network, the basin's morphometry and landscape characteristics. Taking into account the basin's topography, river network structure, soil, vegetation and land use types and spatial variability of hydrometeorological forcing, the river basin is subdivided into sub-basins of relevant size. The main ECOMAG model equations describe the processes of the hydrological cycle for each of the delineated sub-basins. These are the ordinary differential equations derived from the detailed physical-mathematical models [23] either by spatial integration or by discarding the secondary members, which have some impact on the hydrological processes in the basin. Several equations are taken from lumped models in order to reasonably match the selected spatio-temporal scales of the described processes.

The basin's hydrological regime modelling is divided into two main routines: the effective runoff generation within the sub-basin and the subsequent runoff transformation by the river system. The ECOMAG model vertical layers structure (as seen in Figure 1) for effective runoff generation is set up according to the following scheme of the accounted processes. During the warm period, the liquid precipitation is partially infiltrated into the soil. Water surplus, after filling the local depressions, moves down the basin's slope into the river network. Part of the infiltrated water may also be subjected to lateral movement over the slope of the partially impermeable surface. The water that has not been infiltrated or captured by the river network either evaporates or percolates into the deep ground layers. During the cold part of the year, the described scheme is extended by taking into account the hydrothermic processes in the soil and snowpack (snow cover build-up and melt, soil freezing and thawing and infiltration into the frozen soil).

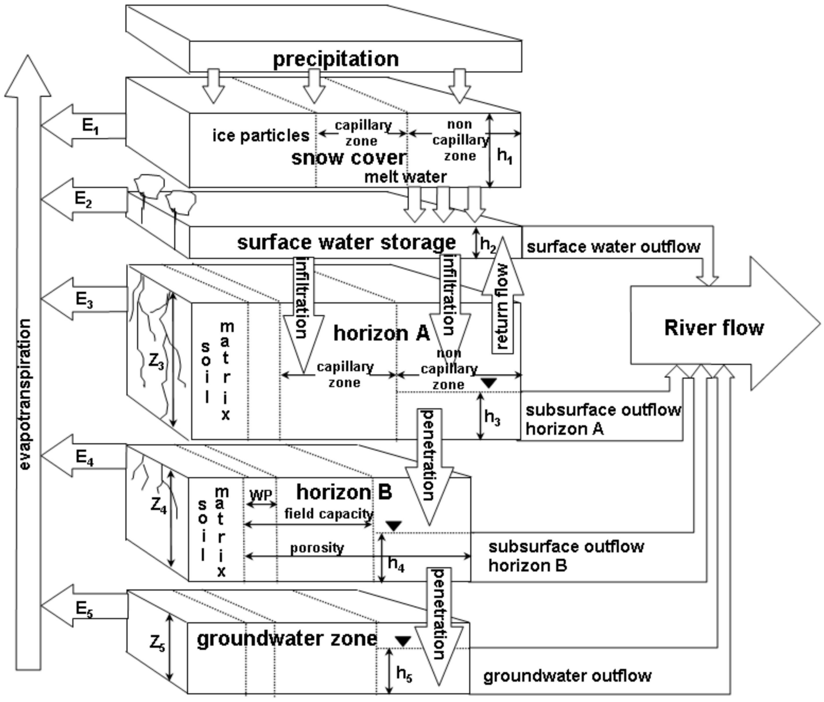

Figure 1. Schematic representation of water pathways in ECOMAG elementary watershed.

For each of the sub-basins the modelling is divided into four layers: topsoil (horizon A), subsoil (horizon B), ground water storage and overland flow. The snow storage is added during the cold period. For each of the sub-basins the modelling is divided into four layers: Topsoil (horizon A), subsoil (horizon B), ground water storage and overland flow. The snow storage is added during the cold period. The model was driven by daily precipitation amounts, mean daily air temperature and humidity values that were input at weather station locations from the observed time-series or taken from global climate or reanalysis models.

The ECOMAG calibration procedure is described in detail by Gelfan et al. [24]. Here, we emphasize the two issues concerning this procedure. First, the values of several key parameters pre-assigned from literature or from the available measurements were considered as the initial approximations of the optimal values and the latter were sought within the neighborhood of the initial, pre-assigned values. Second, during the calibration process, the ratios between the initial values of the distributed parameter corresponding to different soils, landscapes and vegetation are preserved. The Nash and Sutcliffe efficiency criterion NSE [25] was adopted to represent the goodness of fit of the simulated and measured variables.

3.2. The Automated Hydrological Monitoring System (ASHM)

The ASHM was created due to the modernization and development of the hydrological and meteorological observation network and the hydrological forecasting system in the Amur River Basin after the catastrophic flood of 2013. It is based on the generalizing the international experience when creating the software for the control of hydro-meteorological data of various types and resolutions [14]. Common data types for the system are air temperature, precipitation amount, vapor pressure, wind speed, snow water equivalent, water stage, streamflow discharge and ice cover thickness. However, the ASHM is suitable for storing any type of data including observations and model output results. Conceptually, the monitoring system is organized as a collection of data sources, metadata and analysis tools united via web-services including local and controlling servers. The local servers' network is organized on a territorial or basin basis to support the data collection and storage. The controlling servers ensure the accuracy and consistency of the metadata among the local servers' database and allow the local servers information integration to interact with external systems and users.

The basis of the ASHM local instances is composed by the modules for receiving, processing and storing the information coming from various sources including measurements quality control, data visualization and presentation (as seen in Figure 2). The ASHM local software package is divided into client and server parts. The server part consists of the database, processing services and automatic data control modules. The client part of the ASHM with the graphical user interface provides data viewing, editing and critical controlling, generation of reports and bulletins of various forms and data importing and exporting to widely used formats (DBF, PDF, ASCII, etc.).

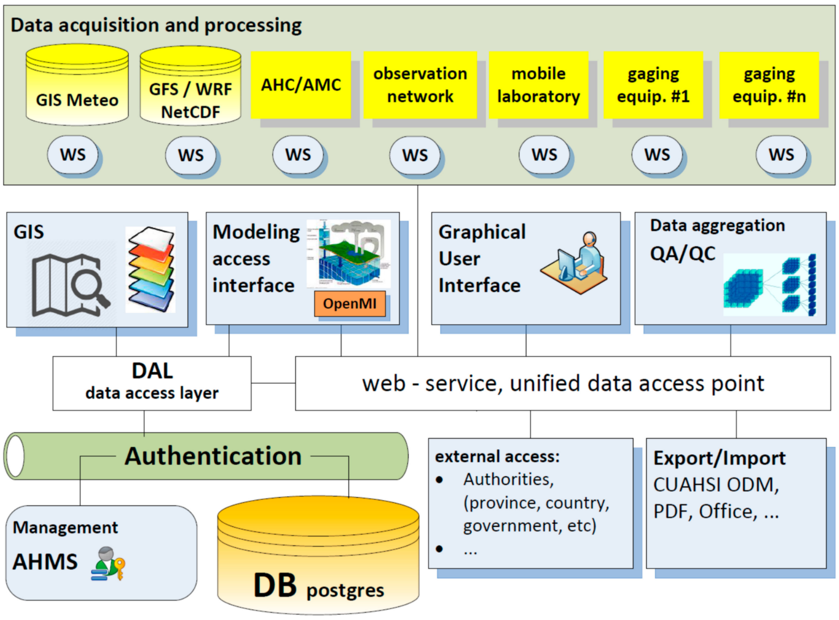

Figure 2. Flow-chart of local AHMS server (AHC/AMC—automatic hydrological/meteorological complex, WS—windows service; DAL—data access library, QA/QC—quality assurance/quality control).

The structure of the CUAHSI ODM (Observation Data Model) database [23] was used as the prototype of the metadata scheme. The tests showed that, from the technical point of view, this database structure corresponded to the established norms of all data and information types storage in the framework of hydrological monitoring [14]. To improve functionality, the CUAHSI ODM scheme was supplemented with the ability to store the incoming messages (text and other files), the data value changes history and to provide the data accompanying descriptions, the forecast information metadata and other practical daily activities instrumentation.

To facilitate the operational activity of the spatially distributed hydrological models, the ASHM possesses important properties like the observational network data quality monitoring, automatic data aggregation, the ability to represent all types of measurements and consistent calculation and forecast results using the metadata scheme. The web-service of the database access ensures data integrity and cross-platform interaction. With the open modeling standard, OGC OpenMI, the ASHM can be easily integrated with most well-known modern modeling and forecasting systems (DHI, Deltares, etc.).

3.3. The ECOMAG Operational Scheme

The ASHM-ECOMAG integration is based on the OGC OpenMI 2.0 (.NET wrapper) and web-service technologies. The data exchange is organized in a two-level scheme (as seen in Figure 3). The first level provides the external interaction between all components of the integrated system using the OpenMI standard. Regardless of their roles, all the units of the system implement the basic, standard interface and can be combined according to the plug and play principle while also exchanging data during the runtime. The second level of integration through OpenMI wrapped SOAP web-services and the DAL (data access layer) library provides the cross-platform interaction for operation with the distributed ASHM data storage system. Thus, this software architecture enables external control during runtime progress under observance of the data integrity condition.

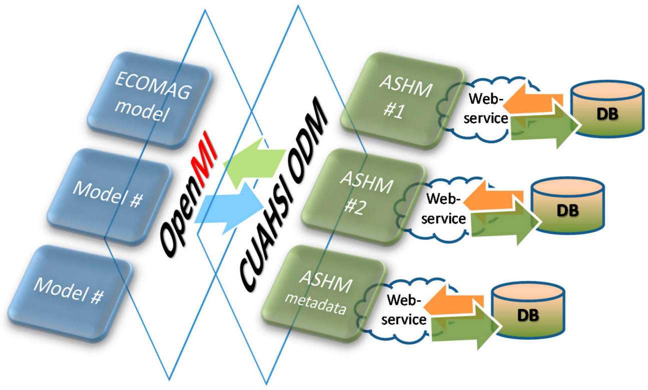

Figure 3. Scheme of two-level ECOMAG-AHMS integration.

The system was determined by connecting the input/output exchange items of the ECOMAG and ASMH models OpenMI components. Data exchange items for each model variable of both components use the same configuration of the meteorological stations and river gaging stations. Unique identification codes of the stations are used during the data transfer between components. The ECOMAG model uses three input items for precipitation, air temperature and dew point temperature and one output item to transfer the calculated streamflow discharges at the gaging stations to the ASMH. The information that is used to create real-time measurements of the components (assembly and classes) and fill it with data is contained in the OMI files stored as extensible markup language (XML) files that match the OpenMI XSD scheme.

Operational activity of the integrated forecasting system is controlled by the ECOMAG model which started daily from the so-called checkpoint—the date on which the model saves the status at the end of the operation. In the operation mode, the ECOMAG with the help of its active OpenMI connections requests the observation data and the meteorological elements forecast (daily rainfall, average values of saturation deficit and air temperature) to predict water discharge. ECOMAG transmits to the ASHM the physical description of the requested values including a set of spatial elements and time. According to the OpenMI standard at the level of the data Exchange Items (communication port), the description of the variables was made in accordance with the international SI system. When accessing the database web-service, the SI units were reduced to the terms of the ASHM database dictionaries.

The ASHM for each data Exchange Item made it possible to specify the “queue” of providers (reading) or consumers (record) of data with each of them related to the specific web-service (the database of the local ASHM instance). With a partial lack of data from the priority source, the serial search at other suppliers (the local ASHM instances) was performed. Using the OpenMI technology and SOAP, the ECOMAG output data was sent to several ASHM instances at once.

In order to configure the operational activity of the ASHM local instances, the terms of the metadata CUAHSI ODM dictionaries were used. The sampling from the database was organized by setting the observational data and prognostic information sources of origin (organization or individual) as a priority. Additionally, in the search for metadata, the method of measurement/calculation can be specified. In case of measurement unit inconsistency in the description of the OpenMI exchange item and the ASHM variable, the component performed the data aggregation. All the metadata required to customize the operation of the component was obtained via the ASHM web-service.

As a rule, in the database, for the same date and for the same point, there are several forecast values associated with different forecast release dates and lead times. The component returns values for which the difference between the date of the initial conditions actuality and the date of calculation actuality is minimal. The observation data at meteorological stations are combined with the forecast information in accordance with the suppliers (the ASHM instances) and sources (organizations) priorities specified in the configuration. In the absence of the required meteorological forecast data, ASHM makes an attempt to import them directly from the GRIB-files of WRF's calculated near-surface meteorological characteristics.

The forecast water discharge values were entered into the ECOMAG output ports, which buffered the calculation results and provided data on the local and channel stream tributaries at any point (or section) of the channel network. By default, any forecast in the ASHM database scheme was produced but in the degenerate case, it can have a unified implementation. The initial data of observations including the meteorological and hydrological forecast were visualized and disseminated to consumers by the ASHM means.

Since the ECOMAG model accepts only meteorological data, its operation does not depend on the possible damage of the gaging station equipment during flood events. However, the evaluation of system operational applicability was designed to test system reliability against an assumption of incomplete, delayed, duplicative, or unreliable weather (observation and forecasts) input data.

The Inverse Distance Weighted interpolation method is used to interpolate the data between the weather station and the centroids of the model sub-basins. The algorithm ignores the stations that did not provide the data (signed as "missing" in the OpenMI input exchange item). The AHMS selects only the maximum QC valued data from the DB by default. Doubtful or duplicative values applied after quality control routines received high QC level but the compromised data values did not contaminate new model run results. To mitigate the possible data latency due to lineout, glitch, or other network equipment malfunction, model runs can be scheduled to preserve its initial state for subsequent re-runs given the latency time. Thus, if the renewed, corrected, or missing data are received during the latency time, it can be used by the model for forecast generation.

4. Results and Discussion

4.1. Forecasting Scheme Performance Assessment Methodology

The model spatial schematization of the river basin and its channel network was created using the ECOMAG-extension technology (as seen in Figure 4). The DEM SRTM with a resolution of 80 m $\times$ 80 m and specially developed for this basin [20] digital soil and landscape maps with a scale of 1:100,000 were used to schematize the basin and assign the model parameters. At the basin model schematization, about 800 partial catchments were selected with an average area of about 30 km^2.

The years with outstanding summer-autumn rainfall floods and with the availability of sufficiently complete archives of meteorological observations data were selected for calibrating and testing the model. According to these criteria, we selected 1989, 1990 and 1994 as the parameter calibration sample. 2013 and 2016 were used for verification purposes because the WRF forecasts were available for these years. Most of the ECOMAG model parameters were specified from the database of soils, vegetation and river basin characteristics. Some of the key parameters were determined by manually calibrating the model using the Nash-Sutcliffe efficiency (NSE) criterion [22,24,25] simultaneously in several basin monitoring points with various weighted averages and estimated integration for a group of stations. The weighted NSE value of the developed model for the calibration sample has exceeded 0.80.

For calibration and verification periods, the continuous data on daily discharges for 11 gaging stations distributed throughout the basin were collected (as seen in Figure 4b). During the calibration of the forecasting scheme, the forecasts were calculated by taking the observed meteorological data at the station locations, transformed into precipitation grades (weak, medium, strong and very strong), in which was based on the Primorsky Hydrometeorological Centre operational practice. Thus, a hydrological forecasting scheme was implemented by taking the perfect meteorological forecast from the stations. The most recent years with high rainfall floods were used for the forecast model testing for which the archives of the WRF model forecast fields with meteorological characteristics were available, as well as the data archives of the weather stations. The forecasts for these years were made by taking the observed precipitation grades and the modelled precipitation from the WRF model and verified against the observations.

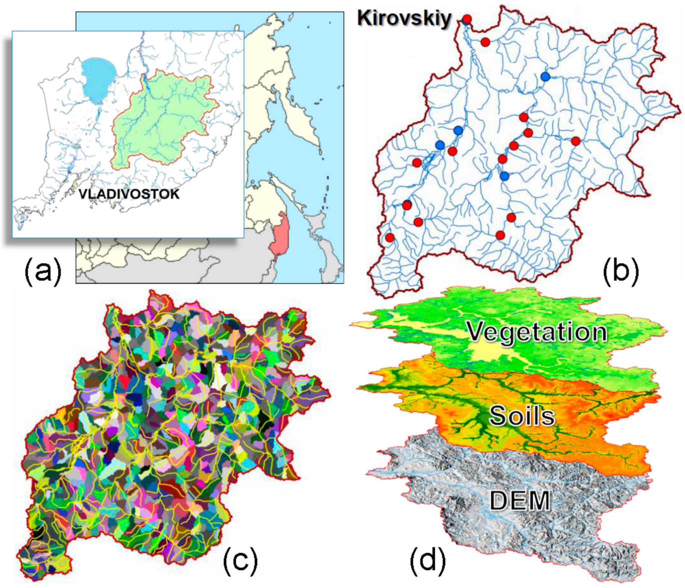

Figure 4. Upper Ussuri River Basin position (**a**) and information set; (**b**) observational network (red circles weather stations, blue circles hydrological gages); (**c**) ECOMAG model unit schematization and (**d**) DEM, soil and vegetation map coverages.

In the adopted scheme, the ECOMAG model calculated the streamflow forecast for a three-day lead-time based on the predicted data of the WRF atmosphere model with the same lead-time. The calculations were carried out only for the summer–autumn period (June–October) of each year. For the prior configuration of the model a few months before the forecast issue date, the calculation was made according to data behind meteorological observations. Then the forecast meteorological WRF information was used for calculating the lead time period.

When using physically based models for a short-term hydrological forecast, it is reasonable to use the post-processing (statistical adjustment) to the output modelling data, which can significantly improve the quality of practical forecasts. We used the correcting relationships in the form of a multidimensional linear regression of the form [26]

$$Qf_i = f(Qm_i, Qo_{i-\tau}, Qm_{i-\tau}) \tag{1}$$

where Qo, Qm and Qf are the actual, model and forecast discharges respectively; i is the number of the current day, τ is the forecast lead-time. In the Russian practice of operational monitoring for the short-term forecasting effectiveness, a criterion in the form of the ratio of the forecast mean square error S to the mean square deviation of river discharge during the lead-time period σ_Δ is used [27]

$$\frac{S}{\sigma_\Delta} = \sqrt{\frac{\sum\limits_{i=1}^{n} (Qf_i - Qo_i)^2}{\sum\limits_{i=1}^{n} (Qo_i - Qo_{i-\tau})^2}} \tag{2}$$

where n is the duration of the period at which the forecast is evaluated. The S/σ_Δ ratio values less than 0.8 show satisfactory quality of the forecast while the values less than 0.5 show good quality.

4.2. Short-Term Forecasts Verification for Extreme Rain Flood Events

Table 1 presents the forecast performance results assessment for two years—1989 and 2013—that were selected as the most extreme events observed. The values of S/σ_Δ (see Table 1) show the satisfactory quality of the forecast without correction of the 2–3-day lead time for most hydrological stations including the outlet station of the basin. The correction procedure, in most cases, significantly improved the quality of forecasting and allowed for satisfactory forecasting methods for almost all forecast points and lead times (as seen in Figure 5). We emphasize that the forecasts were issued simultaneously for multiple gaging stations within a unified spatially-distributed modeling framework. The model calibration was also carried out within the unified framework by using the data from multiple gauging stations and weight-average convergence measurements.

Table 1. Estimates of the quality of short-term forecasts of flow S/σ_Δ in forecasting points *.

River-Gaging Station	Area (km^2)	Applying the Statistical Correction	Calibration Sample (1989)						Verification Sample (2013)		
			Forecast with Precipitation Grades						Forecast with WRF Data		
			Lead Time (Day)								
			1	2	3	1	2	3	1	2	3
Ussuri–Kirovskiy	24400	without	1.64	0.95	**0.70**	1.10	**0.64**	**0.49**	1.09	**0.63**	**0.49**
		with	1.31	0.81	**0.59**	**0.71**	**0.59**	**0.46**	**0.71**	**0.59**	**0.47**
Ussuri–Koksharovka	9340	without	1.82	1.16	1.09	0.93	**0.59**	**0.50**	0.91	**0.57**	**0.51**
		with	1.16	**0.67**	**0.57**	**0.75**	**0.61**	**0.55**	**0.77**	**0.61**	**0.55**
Arsenyevka-Yakovlevka	5312	without	1.56	0.96	**0.77**	0.93	**0.61**	**0.52**	0.93	**0.61**	**0.54**
		with	0.99	**0.69**	**0.72**	1.06	0.88	**0.62**	0.93	**0.61**	**0.52**
Ussuri–Novomikhaylovka	5170	without	1.25	0.99	0.93	1.68	1.08	0.93	1.63	1.00	0.90
		with	**0.75**	**0.57**	**0.55**	0.86	0.82	**0.77**	0.91	0.81	**0.75**
Pavlovka–Antonovka	2670	without	1.84	1.05	0.90	1.09	0.82	**0.78**	0.98	0.83	1.06
		with	**0.64**	**0.49**	**0.44**	**0.51**	**0.38**	**0.32**	**0.60**	**0.43**	**0.36**
Arsenyevka–Anuchino	2480	without	0.92	**0.75**	**0.77**	**0.74**	**0.52**	**0.49**	**0.71**	**0.53**	**0.54**
		with	**0.71**	**0.48**	**0.43**	**0.54**	**0.46**	**0.41**	**0.54**	**0.45**	**0.41**
Ussuri–Verkhnyaya Breevka	1730	without	1.54	1.20	1.04	1.24	0.88	0.82	1.07	**0.76**	0.83
		with	0.87	**0.78**	**0.72**	**0.70**	**0.67**	**0.63**	0.86	**0.63**	**0.58**
Izvilinka–Izvilinka	1160	without	1.44	1.17	1.04	1.56	1.14	1.07	1.37	0.96	1.02
		with	**0.77**	**0.71**	**0.68**	**0.71**	**0.70**	**0.69**	0.89	**0.68**	**0.65**
Krylovka–Krylovka	1070	without	1.90	1.02	0.82	1.45	0.92	**0.76**	1.41	0.91	**0.62**
		with	**0.73**	**0.51**	**0.68**	1.11	0.84	**0.69**	1.20	0.85	**0.70**
Arsenyevka–Vinogradovka	940	without	**0.68**	**0.63**	**0.61**	**0.79**	**0.62**	**0.59**	0.81	**0.73**	**0.63**
		with	**0.49**	**0.42**	**0.42**	**0.66**	**0.52**	**0.50**	**0.70**	**0.56**	**0.52**
Muraveyka–Grodekovo	761	without	1.08	**0.73**	**0.64**	1.26	0.90	**0.79**	0.96	**0.71**	**0.72**
		with	**0.53**	**0.45**	**0.44**	**0.49**	**0.51**	**0.52**	**0.48**	**0.41**	**0.40**

* Satisfactory S/σ_Δ values are shown in bold, good S/σ_Δ values are shown in underline bold (see Section 4.1 for explanation).

We also emphasize that the WRF-based hydrological forecast's quality is quite comparable to the quality of the "perfect" hydrological forecast (based on the precipitation grades forecasts described above). Regardless of significant errors in precipitation amounts at station locations that are common to the WRF model, the mentioned forecast's quality is achieved by the dense WRF model grid coverage as compared to the scarce weather station network.

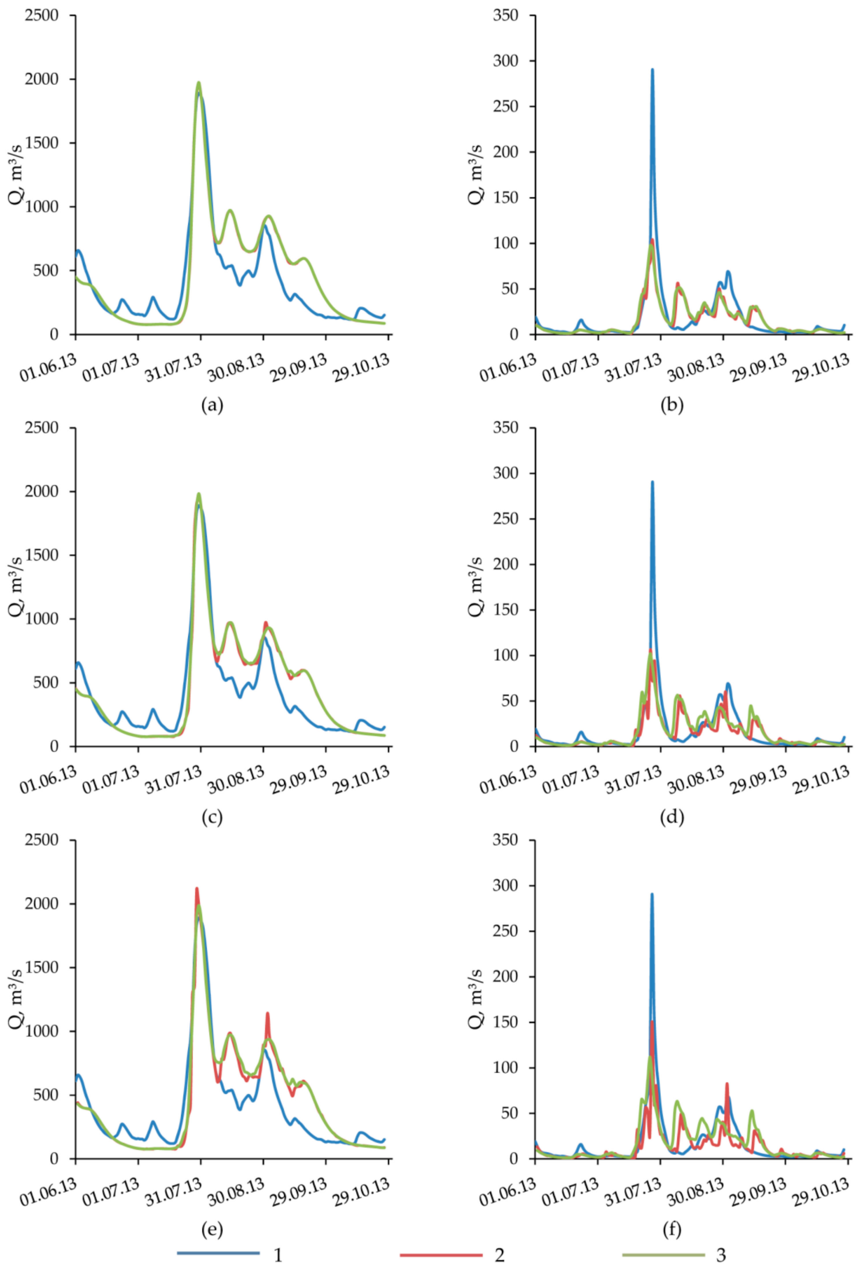

Figure 5. Examples of observed (1) and forecasted (2—with precipitation gradations, 3—with WRF data) runoff hydrographs of 2013 year in gaging stations Ussuri-Kirovskiy (**a**,**c**,**e**) and Krylovka- Krylovka (**b**,**d**,**f**) with lead time at 1, 2 and 3 days, accordingly.

5. Conclusions

The article presents the technical solution that combines information resources, technologies and software components to create the automated system for the Ussuri River streamflow forecast based on the use of modern information infrastructure, physically-based hydrological modeling and standards of inter-model and cross-platform integration.

Both the operability of individual components and technology, as well as the possible short-term forecast of rainfall floods in a medium-sized river basin within the monsoon climate zone were tested. The estimates obtained on the limited data of preliminary hydrological monitoring and forecast system tests gave a satisfactory reproduction of the complex space-time structure of the runoff generation during extreme rainfall floods. This also offered opportunities for forecasting ungauged points as well.

The technologies used can solve the task of developing the operational streamflow forecast for the Ussuri River in an automated mode. The use of modern standards in the field of data transfer and storage software allows the creation of multi-level integration schemes of any complexity, using any (open and commercial) models on the ASHM platform. This can lead to the production of data pre- and post-processing stacks at minimum costs of the back-code writing. This approach has a high degree of reliability, scalability and cost-effectiveness while preserving the freedom to choose the software implementation media.

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References

1. Pagano, T.C.; Wood, A.W.; Ramos, M.-H.; Cloke, H.L.; Pappenberger, F.; Clark, M.P.; Cranston, M.; Kavetski, D.; Mathevet, T.; Sorooshian, S.; et al. Challenges of operational river forecasting. *J. Hydrometeorol.* **2014**, *15*, 1692–1707. [CrossRef]
2. Molteni, F.; Buizza, R.; Palmer, T.N.; Petroliagis, T. The ECMWF ensemble prediction system: Methodology and validation. *Q. J. R. Meteorol. Soc.* **1996**, *122*, 73–119. [CrossRef]
3. Barnier, B.; Siefridt, L.; Marchesiello, P. Thermal forcing for a global ocean circulation model using a three-year climatology of ECMWF analyses. *J. Mar. Syst.* **1995**, *6*, 363–380. [CrossRef]
4. Skamarock, W.C.; Klemp, J.B.; Dudhia, J.; Gill, D.O.; Barker, D.M.; Wang, W.; Powers, J.G. *A Description of the Advanced Research WRF Version 2*; NCAR Technical Note NCAR/TN-468+STR; National Center for Atmospheric Research: Boulder, CO, USA, 2007.
5. Takenaka, H.; Nakajima, T.Y.; Higurashi, A.; Higuchi, A.; Takamura, T.; Pinker, R.T.; Nakajima, T. Estimation of solar radiation using a neural network based on radiative transfer. *J. Geophys. Res.* **2011**, *111*. [CrossRef]
6. Li, Z.C.; Chen, D.H. The development and application of the operational ensemble prediction system at national meteorological center. *J. Appl. Meteorol. Sci.* **2002**, *13*, 1–15.
7. Ahlgrimm, M.; Forbes, R.M.; Morcrette, J.-J.; Neggers, R.A.J. ARM's impact on numerical weather prediction at ECMWF. *Meteorol. Monogr.* **2016**, *57*, 28.1–28.13. [CrossRef]
8. Jasper, K.; Gurtz, J.; Lang, H. Advanced flood forecasting in Alpine watersheds by coupling meteorological observations and forecasts with a distributed hydrological model. *J. Hydrol.* **2002**, *267*, 40–52. [CrossRef]
9. Yucel, I.; Onen, A.; Yilmaz, K.K.; Gochis, D.J. Calibration and evaluation of a flood forecasting system: Utility of numerical weather prediction model, data assimilation and satellite-based rainfall. *J. Hydrol.* **2015**, *523*, 49–66. [CrossRef]
10. Bugaets, A.N. Using the OpenMI standard for developing integrated systems of hydrological modeling. *Russ. Meteorol. Hydrol.* **2014**, *39*, 498–506. [CrossRef]
11. Clematis, A.; D'Agostino, D.; Danovaro, E.; Galizia, A.; Quarati, A.; Parodi, A.; Rebora, N.; Bedrina, T.; Kranzlmueller, D.; Schiffers, M.; et al. DRIHM: Distributed Research Infrastructure for Hydro-Meteorology. In Proceedings of the 2012 7th International Conference on System of Systems Engineering (SoSE), Genova, Italy, 16–19 July 2012.
12. Goodall, J.L.; Robinson, B.F.; Castronova, A.M. Modeling water resource systems using a service-oriented computing paradigm. *Environ. Model. Softw.* **2011**, *26*, 573–582. [CrossRef]
13. Werner, M.; Schellekens, J.; Gijsbers, P.; van Dijk, M.; van den Akker, O.; Heynert, K. The Delft-FEWS flow forecasting system. *Environ. Model. Softw.* **2013**, *40*, 65–77. [CrossRef]
14. Bugaets, A.N.; Gartsman, B.I.; Krasnopeev, S.A.; Bugaets, N.D. An experience of updated hydrological network data processing using the CUAHSI HIS ODM data management system. *Russ. Meteorol. Hydrol.* **2013**, *38*, 359–366. [CrossRef]

15. Motovilov, Y.G.; Gottschalk, L.; Engeland, K.; Rodhe, A. Validation of a distributed hydrological model against spatial observations. *Agric. For. Meteorol.* **1999**, *98*, 257–277. [CrossRef]
16. Gonchukov, L.V.; Lamash, B.E. The numerical prediction of hazardous weather phenomena in the north of Primorsky Krai. *Vestn. FEB RAS* **2010**, *6*, 17–23.
17. Gregersen, J.B.; Gijsbers, P.J.A.; Westen, S.J.P. OpenMI: Open modelling interface. *J. Hydroinform.* **2007**, *9*, 175–191. [CrossRef]
18. The Far East. *The Surface Water Resources*; Hydrometeorological publishing: Leningrad, Russia, 1972.
19. *The USSR Geological Map*; The state scientific and technical PH publishing of the geology and protection of subsurface resources literature: Moscow, Russia, 1960. (In Russian)
20. Bugaets, A.N.; Pschenichnikova, N.F.; Tereshkina, A.A.; Krasnopeev, S.M.; Gartsman, B.I.; Golodnaya, O.M.; Oznobikhin, V.I. Digital soil map of the Ussuri River basin. *Eurasian Soil Sci.* **2017**, *50*, 907–916. [CrossRef]
21. The Far East. *Physiographic Description*; Soviet Academy of Sciences: Moscow, Russia, 1961.
22. Motovilov, Y.G.; Bugaets, A.N.; Gartsman, B.I.; Fingert, E.; Kalugin, A.S.; Moreido, V.M.; Suchilina, Z. Sensitivity of hydrological response of a monsoon-dominated river basin to spatial resolution of precipitation and land surface data. In Proceedings of the EGU General Assembly Conference, Vienna, Austria, 23–28 April 2017.
23. Horsburgh, J.S.; Tarboton, D.G.; Maidment, D.R.; Zaslavsky, I. A relational model for environmental and water resources data. *Water Resour. Res.* **2008**, *44*, W05406. [CrossRef]
24. Gelfan, A.N.; Motovilov, Y.G.; Moreido, V.M. Ensemble seasonal forecast of extreme water inflow into a large reservoir. *Proc. Int. Assoc. Hydrol. Sci.* **2015**, *369*, 115–120. [CrossRef]
25. Nash, J.E.; Sutcliffe, J.V. River flow forecasting through conceptual models part I—A discussion of principles. *J. Hydrol.* **1970**, *10*, 282–290. [CrossRef]
26. Gartsman, B.I.; Gubareva, T.S. Forecast of the rainfall flood hydrograph on the Far East rivers. *Russ. Meteorol. Hydrol.* **2007**, *32*, 328–335. [CrossRef]
27. Forecasts of the Surface Water Regimes. In *Forecasting Service Manuals*; Hydrometeorological Publishing: Leningrad, Russia, 1962.