Concept of flood early warning systems in Serbia

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Article history:
Received: September 20, 2022
Revision: September 22, 2022
Accepted: September 26, 2022

Abstract: The occurrence of high waters due to climate change is an increasingly common phenomenon, especially in watercourses where there are built-up flood protection systems. Also, recent high-water levels are already surpassing historically recorded flood events, thus putting at risk existing flood protection systems, which were designed according to superseded criteria defined by statistical data modelling. Reducing risks and strengthening resilience and preparedness for effective flood response is achieved by timely and reliable flood warning based on hydrological forecasts. The aim of this paper is to present the concept of a flood early warning system that relies on real-time measurements and simulation models to provide vigilance maps to key experts in flood management. This paper presents an example of the concept in the Kolubara River basin, as well as the implementation of the pilot system in the Tamnava River basin, the left tributary of the Kolubara River.

INTRODUCTION

We have witnessed major floods around the world during the last twenty years. The change in the frequency and intensity of rainfall, because of the increase in air temperatures and the accumulation of moisture in the air, leads to frequent floods. On many watercourses, the available time for undertaking flood protection measures from the moment of the warning is very short.

Floods on the territory of Serbia occurred in 2005 in the basin of Tamiš and Velika Morava rivers, in 2007 in the river basins of Vlasina, Nisava and others in Eastern Serbia, in 2009 in Eastern and Western Serbia, in 2010 in the Timok River basin, and in 2014 when the most of Serbia was flooded [1].

Although the practice of investing significant funds in flood protection structures is present in Serbia, it is practically impossible to protect all flood-prone areas, nor is it economically viable. In addition to the fact that flood protection structures do not protect all the areas, the problem is the occurrence of flood waves that are larger than designed. Due to climate change, the occurrence of high waters is more frequent, and the existing flood protection structures are exposed to higher loads than designed.

Flood risk reduction, strengthening resilience and preparedness for effective response to flood events can only be achieved if timely and reliable information on flood events can be provided. Hydrometeorological systems for flood early warning and flood warning are required to minimize damage and evacuate the population from flood-prone areas in time.

Modern flood early warning systems (FEWS) rely on real-time hydrometeorological measurements and probabilistic weather forecasts. River basin simulation models are then used to forecast water levels along rivers. If the simulated water levels are above a defined threshold, it is possible to issue alerts through the information dissemination system.

The development and implementation of FEWS should create conditions under which at the time of unfavorable meteorological conditions those responsible for the implementation of flood protection can undertake appropriate activities promptly and prevent or mitigate the harmful consequences of floods.

Although the development of the flood protection system in Serbia is in focus for decades, the development of FEWS started recently. It started when Serbia began to use the European early warning systems and continued with the development of new systems across the country.

Serbia is presently included in the European Flood Awareness System (EFAS) [2][3] and Flood Forecasting Warning System (Sava FFWS) [4]. EFAS is an interstate flood early warning and forecasting system that integrates individual national systems based on different platforms (e.g., Delft-FEWS5, INFLUX6). The Republic Hydrometeorological Institute (RHMI) has established operational systems of meteo-alarm and hydro-alarm (for the territory of Serbia) as part of this system. Sava FFWS is a joint platform of the countries in the Sava River basin for flood hazard forecasting and warning, based on the Delft-FEWS software package that integrates available hydrological and hydraulic models in the Sava River basin. The system user in Serbia is RHMI. Numerical models for weather forecasting provide air temperature and rainfall forecasts, and information on snow and soil moisture. Serbian RHMI manages also the recently developed forecast and early warning system for the Velika Morava Basin (VM-FFWS) [5], which is also based on Delft-FEWS software. VM-FFWS uses data on rainfall, temperature and water levels imported from telemetry systems, radar data on rainfall, and weather forecasts of various Serbian and European meteorological institutions.

This paper presents the concept of the FEWS for river basins in Serbia which have flood protection system in place. It describes the structure of FEWS for the Kolubara River basin and presents the development of the pilot FEWS for the Tamnava River, the left tributary of the Kolubara River.

CONCEPT OF THE FLOOD EARLY WARNING SYSTEM

The basic role of the flood early warning system is to issue a timely warning on the forthcoming flood event, needed for making decisions on population and infrastructure protection measures. The system should deliver timely notification to the authorities in charge of flood protection and the public about the current and predicted hydrological situation on profiles of the major watercourses in the river basin.

FEWS is comprised of many activities like the collection of meteorological and hydrological data, data transfer, control, and archiving, as well as use of data in mathematical models resulting in hydrological forecasts. The comparison of forecasted values and specific values of the flood protection system leads to the identification of the alert degree or the flood protection phase. If needed, the FEWS will send a prompt notification about the current and predicted hydrological situation to the flood protection authority and the public. Using precise information on the state of flood protection structures, the information received from EFWS will be used to make a decision on raising the level of preparedness, to undertake an effective response to a flood event or to mitigate the adverse consequences of floods.

The activities within an efficient FEWS must be automated to the greatest possible extent. The system efficiency is enabled by an organized and interconnected set of hardware and software components that belong to the following subsystems: (1) Monitoring System, (2) Data Management System, (3) Computation Management System, (4) User Interface, and (5) Dissemination System. The following figure shows the scheme of the aforementioned subsystems and their connections.

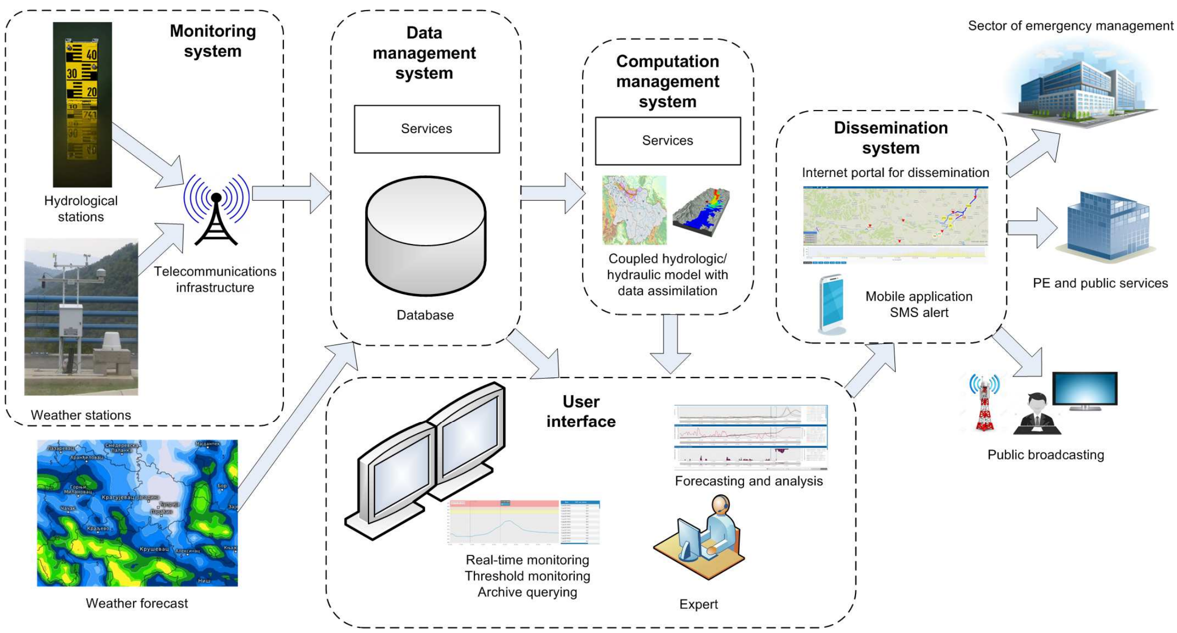

Figure 1. *Flood Early Warning System Scheme with Subsystems*

Monitoring System

The monitoring system consists of automatic meteorological and hydrological stations, together with telecommunications infrastructure. The role of the monitoring system is to promptly provide reliable data on meteorological and hydrological values in the basin area. This data can be used for decision-making according to the criteria defined in the operational flood protection plans, and for simulations in FEWS, by assimilation of measurements into the hydrological model.

Automatic meteorological and hydrological stations are comprised of measuring equipment, dataloggers and telecommunications equipment. The process of converting the original physical values (air temperature, rainfall, water level, etc.) into a measurable electronic value is performed on the measuring equipment in several ways, depending on the specific conditions at the measurement location. Recommendations of the World Meteorological Organization [6, 7] should be used to define the precise specification of the measuring equipment. Key measurements, like the measurement of the water levels, should be done using two independent methods (for example, radar probe and bubbling system). Registered electronic values are then converted into digital values and recorded on the datalogger at time intervals defined by the FEWS requirements. Depending on the river basin characteristics (mountainous region, plain, etc.), data can be collected frequently (every 5, 10, 15 minutes) or every hour.

Telecommunications equipment is used to transmit recorded digital values to the data management system. At least two independent telecommunication channels should be provided to ensure redundancy if one channel fails (e.g., mobile network and radio link). By default, the power supply should be provided from two independent sources, as a main and a backup power supply (e.g., solar panel with battery). The use of video surveillance equipment and alarm systems is also planned as a measure against the risk of theft.

For the proper functioning of the system, it is necessary to obtain meteorological and hydrological values from the entire FEWS area. Meteorological and hydrological data are collected from automatic stations of the state observation network, but it often cannot provide sufficient measurement density, both spatial and temporal. Hence, a development of supplementary network of stations is often required to fulfil the FEWS needs. The supplementary network should meet the aforementioned prerequisites and should be aligned with the practice of the national hydro-meteorological service, in order to be used in parallel with the stations of the state network.

Data Management System

The data related processes on a dedicated data management system are of utmost importance for the FEWS operation. The effectiveness of data management system can significantly affect the timeline and accuracy of other processes, and thus it should be properly perceived and created following the recommendations of the World Meteorological Organization [8].

The first process in data management system is the reception of data from monitoring systems and other sources (weather forecast, etc.). Data reception can be done by calling stations in a predefined order or by stations reporting in a predefined time interval. Regardless of the data receiving method, the data management system will get measurement data files and associated information (error messages, telecommunication equipment status, etc.). Permanent storage of original files must be ensured, so that potential problems can be detected in case of the monitoring system and data transmission operation analysis.

The data formats provided by the monitoring system stations through the telecommunications infrastructure are often specific to the equipment manufacturer, and a problem of format inconsistencies within one or more observation networks always exists in practice. Therefore, the base of the data management system is a data model that describes every measurement on meteorological or hydrological station. In addition to the information on the location and the time of measurement, it is required to record as much metadata as possible about the measurement process itself (type of sensor, data processing at the measurement interval, etc.), the state of the measuring equipment (error codes, supply voltage, etc.), as well as the origin of the data (monitoring system, data exchange with other systems, etc.).

Upon receipt, the data is delivered into the data model applied in the data management system. This process is the Extract-Transform-Loading procedure (ETL), where generic file parsers are applied to find and extract information (Extract), fill the data model (Transform), and eventually store the data in the standard format of the data management system (Loading). All supporting information is recorded as metadata, in order to facilitate the interpretation of the value during its use.

Data storage is organized in the form of a relational database, which is based on the data model of the data management system. The database should contain current and archived measurements in the form of time series that with clear descriptions, allowing easy interpretation. Besides storing of the original data obtained through ETL processes, it is necessary to provide the data correction mechanism. This is achieved by the dual structure of the time series: the original data series are stored separately from corrected data. The result presented to users and automated software components is a combination of these two series. Each corrected value has accompanying metadata on the time when the correction was made, which user made the correction and why. Group changes are allowed to facilitate the correction process.

The data management system should also provide for the storage and search of data on characteristics of flood protection structures needed for the interpretation of simulation results. It is possible to store data on the geometry of embankments, regulated riverbeds, reservoirs, and other hydro-technical facilities, especially it they can affect the flood wave transformation. Recording of the history of changes on flood protection structures (embankment breach, damage to the embankment toe, etc.) is also necessary.

The database use should be managed through a dedicated layer for processing and technical quality assessment. Users and automated software components must not have direct access to the database, but their requests should be processed at the layer and translated into queries that are executed over the database. For the purposes of processing data from the database, the class of time series to be calculated on request, the so-called derived series, should be envisaged. This means that the values that are calculated based on the original values are not stored in the database but are calculated at the request of the user or automated software components. The derived values can be analytical formulas (calculation of absolute level based on gauge datum, discharge curve, etc.), aggregate (mean values, minima, and maxima at the desired interval, etc.) and multilayer, so-called composite, which are a combination of multiple series of the same size that can serve as redundancy. The best example is to combine a series from a radar sensor and a bubbling system in such a way that a value from one sensor (for example, bubbling) is preferred, so in the event that a value from that sensor is not available, a value from another series (in this case, radar) is read. The possibility of combining derived series into complex calculation trees should be provided, which is why it is necessary to provide caching mechanisms to improve performance. Possibility of setting up new series or modifying new ones, without adversely affecting the operation of the system should be also provided.

One of the mechanisms that needs to be implemented in early warning system is data quality control. Due to the imperfections of measurement methods, problems in the measuring equipment operation and possible errors in data transfer, the quality of the measured data cannot always be suitable for use in simulations and analyses. An example of a data quality problem may be the sudden jump (peak) of the water level value at the hydrological station. Very often, such changes in values are due to local phenomena (slowing down due to floating sediment, sewage spills, etc.), so they cannot be considered in analyses and simulations, because they do not apply to the entire river section where the measurement is implemented. If these data are not considered, together with possible data gaps that may occur for objective reasons (power supply interruptions, communication, etc.), they can create incomplete input data in the simulations. Since the models do not operate with incomplete input data, it is necessary to provide a fill-in mechanism. The best practice recommends that data from hydrological stations be interpolated for shorter periods, while missing data on rainfall are not filled in. Spatial interpolation functions are used in the preparation of input data for longer periods of rainfall missing data.

The security of the use of data accessed through the data management system must also be taken into account. The data can only be used by authenticated and authorized users, which is achieved by applying an access management layer. Authentication should be performed in a protected protocol, based on the user's name and password, or by integration into other authentication services (Active Domain, RADIUS, etc.). Through this layer, access rights are checked when accessing data through user tools, and it is necessary to leave the possibility for the system administrator to set rights and manage user accounts.

Computation Management System

The computation management system is a set of hardware/software components connected in a single unit with the aim of providing the infrastructure required for use of mathematical models. The system consists of mathematical models, server components for computation management as well as dedicated hardware for computations.

Mathematical models used in flood early warning system are hydrological and hydraulic models. The hydrological model simulates transformation of rainfall into a runoff, while the hydraulic model performs the transformation of runoff through the river network, thus obtaining discharges and levels along the modelled sections. The hydrological model and the hydraulic model are connected: the output nodes of the hydrological model represent the input nodes of the hydraulic model.

It is recommended to use conceptual continuous hydrological models [9]. Such models are relatively simple to understand by users and can perform simulations with a temporal discretization of 1 hour or less, which is required in flood early warning systems. Given that flood early warning systems are developed in basins where a flood protection system already exists, such basins are usually covered by the state observation network, so data is expected to be available for model calibration. It is recommended to use a 1D hydraulic model in selecting a hydraulic model, due to the speed of simulation. Although 2D models can provide more detailed information needed for flood protection, there are still no models that can perform simulations for a complete hydrographic network of a larger basin in a reasonable amount of time.

The most important values used in flood early warning systems for making adequate decisions are current and forecasted levels and discharges along river sections in the subject basin. These values are obtained via mathematical models by two processes: (1) process of reconstruction of the hydrological state of the system (2) process of multi-day forecast of hydrological values (levels and discharges) based on the meteorological forecast and the previously reconstructed initial state of the system.

The reconstruction process aims to find an adequate initial state of mathematical models based on which the forecasting process continues. The reconstruction process uses the observed meteorological values as inputs to the model, and then the hydrological values resulting from the model are compared with the observed values. Corrections to the initial state of the models are generated using assimilation methods. Corrected states are further used in the simulation of the forecast.

After the initial state has been provided, the model is then run with the forecasted inputs. The result of this process are forecasted hydrological values, i.e., levels and discharges along river courses that are further compared with defined alertness levels. Based on this comparison, the phase of flood protection can be declared.

To effectively use the described processes in early warning systems, it is necessary to provide automatic execution of simulations. The processes of reconstruction and forecast are implemented to be executed on arrival of an up-to-date meteorological forecast into the system (usually at 12-hour intervals). In the period After the reconstruction and forecast simulations, and before the arrival of the new forecast, simulations are made where the forecasted values are replaced by values collected from the observation network. These simulations allow the operator to gain knowledge of the real state of the system during the period between two forecasts.

The aforementioned simulations can also be run at the user's request via user applications. In this case, the user can opt to run computations with alternative forecasts as well as with forecasts with altered initial state of mathematical models, which enables further analysis of the situation in the basin, primarily regarding the sensitivity analysis of the forecast.

For the user to view the forecast quickly and efficiently, a post-processing of the results must be performed after the forecast simulation has been performed. Based on the simulated cross-sections levels, as well as the characteristics of the protective structures, information on criteria violation along all sections of the watercourse within the model is obtained. This serves to make the decision on the declaration of flood protection phases. In addition to the level exceedance, it is also necessary to perform checks of the level duration as there is a risk of embankment soddening in the event of long-term high-water presence.

The complexity of the presented processes used in flood early warning system implies the need for implementation of dedicated High-Performance Computing (HPC) hardware. Although resources can be leased on cloud platforms, with flood early warning systems, reliability comes first, so access to resources via the Internet is an additional level of risk that can be avoided by acquiring own hardware.

User Interface

Regarding the use of data available in flood early warning system, the following functionalities are required to be provided to the users through user software tools: generation of flexible numerical and graphical presentations of measured values, spatial presentations, and reports for printing. The implementations of real-time and archival data display can be further separated during the implementation of subject functionalities.

Real-time data monitoring consists of examining ongoing measurements to gain knowledge of meteorological and hydrological state of the basin, as well as the state of the measuring equipment. The first functionality is implemented by forming dedicated spatial presentations with value visualization at measuring stations with the aim to interpret spatial relationships of rainfall, air temperature, etc. In doing so, it is necessary to interpret the current values of measured levels at hydrological stations according to the criteria defining flood defense phases (threshold monitoring). The second functionality is implemented by dedicated numerical and graphical value presentations related to measuring equipment (supply voltage, battery voltage, signal strength, etc.), to detect possible changes in the behavior of measuring and telecommunication equipment.

A review of archival data implies access to data stored in the data management system during the entire period of system operation. Measured values should be displayed for a user-defined period, and data search mechanisms should be provided. When performing data search, user should be able to search by measurement location and by metadata related to individual measurements. Data search should also be enabled on flood protection structures. User should be able to view respective changes in time.

A special user tool should serve to monitor the operation of the model and warnings indicating possible flooding. The functionalities of this tool should provide a numerical and graphical presentation of input data (meteorological forecast, model state), and level forecast values, but also a comparison of archival data with simulated values. In systems with hydrotechnical facilities that may affect the flood wave propagation (e.g., reservoirs), the expert should be provided with an option to test possible scenarios of facility management through this tool, aimed at checking variants of the event development in the basin. Also, this tool should provide spatial presentations of alerts, so that the expert can review the results of simulation during the forecast period and assess whether it is necessary to forward the information to the dissemination system.

Dissemination System

In flood early warning system, the dissemination system serves to inform users about the following critical issues: where and when a flood can occur, what is the possible volume of the flood, and how long can it last? Therefore, the information should be presented in a clear and comprehensible manner to users who do not necessarily have to be experts in modeling and simulations.

The dissemination system may include multiple ways of delivering information to the user. Most often, bulletins are made based on measured and forecast values of meteorological and hydrological values, with indications of the place and time of occurrence of potentially hazardous levels in river courses. Also, a dedicated internet portal for authorized users is often created with an interactive overview of the simulation results. It is particularly important to provide vigilance maps on the portal so that areas with an increased risk can be viewed for each day of the forecast. The internet portal can also be open to the public, but it is important to consider the psychological effect of announcements and warnings. In fact, too frequent false flood warnings can reduce confidence in the system, while in the case of extreme forecasts, panic spreads inadvertently by direct delivery of information to the public. An additional possibility to provide information are SMS messages and mobile applications.

DEVELOPMENT OF THE KOLUBARA RIVER BASIN FLOOD EARLY WARNING SYSTEM

Description of the Kolubara River Basin

The Kolubara River Basin is in the northwestern part of Serbia. It is bordered on three sides by the middle and low mountains of the Valjevo and Šumadija regions. On the fourth, northern side, it is bordered by slightly wavy foothills spreading into the Pannonian Plain. The basin area is 3,638 km^2. The length of the basin in the north-south stretch is about 66 km, and the width is about 81 km. The elevation of the basin is from about 76 m above sea level at the mouth to the Sava River, up to 1,346 m above sea level on Povlen. The average elevation of the basin is about 206 m above sea level. The general slope of the basin area stretches southwest-northeast.

The Kolubara River and its tributaries sprout in hills and mountain areas, flowing through slightly rolling, hilly areas in the middle, while the rest of the river basin is mostly flat. The basin is dominated by the lowland, while the low (up to 1,000 m) and medium-high mountains are located only in the source part of the Kolubara River basin and its tributary the Ljig River.

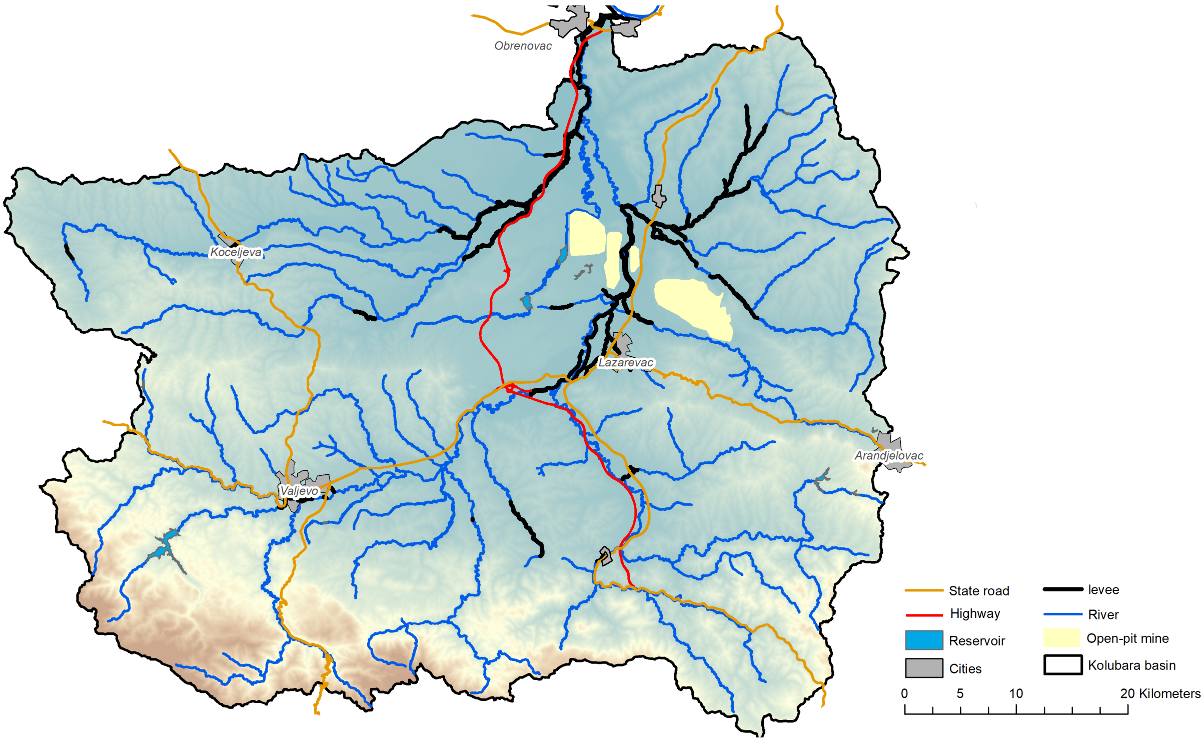

Figure 2. *Kolubara River Basin with Linear Flood protection Systems*

Flooding threatens about 31,000 ha of the highest quality land, many settlements, important economic facilities, natural resources, and roads.

The Kolubara River basin is predisposed to the formation of flood waves of torrential character due to its geomorphological and hydrological characteristics. The unfavorable water regime is the result of hydrometeorological, topographic-geological and hydraulic conditions in the basin. The unfavorable weather and spatial distribution of rainfall and sharp slopes of tributaries along with the unfavorable arrangement of the hydrographic network of watercourses regularly cause rapid and concentrated water affluence on the relatively short section of the central valley of Kolubara.

Improvements in flood protection in the Kolubara basin were implemented after the floods in May 2014. The consequences of this catastrophic flooding, which included human casualties, highlighted the need to improve protection. Due to the expected lengthy period of implementation of protective measures, it was necessary to adopt a strategic concept, implementation phases and priorities.

After the floods in 2014, the Public Water Management Company (PWMC) Srbijavode initiated the development of expertise and reconstruction of the flood wave, and then the development of the Study on the improvement of protection against the harmful effect of waters in the Kolubara River basin (hereinafter: the Study on the improvement of protection), prepared by the Jaroslav Černi Water Institute (completed in 2018).

The Study on the Improvement of Protection provides an assessment of the area's flood risk for the relevant hydrological parameters. It was adopted based on the analysis of the flood event from 2014 and flood damage, the results of hydrological-hydraulic simulations and the analysis of the existing state of the flood protection system. A considerable risk of new floods and damage to the entire basin has been highlighted, which is a consequence of the permanent occupation of natural retention areas in the immediate Kolubara riverbank and tributaries, the unfavorable position of riverbank settlements, and the unfavorable contact of watercourses with the capital transportation infrastructure.

The results of the Study of Improvement of Protection confirmed that the protection of Obrenovac is the priority. In the present conditions there is a high risk of penetration of high waters towards the settlements even at significantly lower inflows than those recorded in 2014. This is a consequence of the elimination of existing retention areas by construction of transportation infrastructure in the floodplain zone. as well as the elimination of required retention areas by reconstruction of protective embankments in the zone of surface coal mines.

After the adoption of the results of the improvement study, PWMC Srbijavode started the implementation of the hydrometeorological flood early warning system called FEWS Kolubara. The main user of this system is PWMC Srbijavode.

Given the importance and complexity of the system, it is planned to develop the system in several phases. The first phase of development was initiated in 2019. The implementation included the development of the Feasibility Study with the concept of development and implementation. The study defines the conceptual solution of the complete system, all required functionalities of dedicated software components, selection of the optimal number and optimal sites for the creation of the observation network, technical characteristics of recording stations, technical characteristics of measuring, telecommunication, and computer equipment, as well as the plan and organization of development. In addition to the preparation of the study, an early warning system was established in the first phase of development on the pilot basin of the Tamnava River, the left tributary of Kolubara River. The following chapters present the structure of the future FEWS Kolubara and the implementation of the system in the pilot basin of the Tamnava River.

Structure of the FEWS Kolubara

The FEWS Kolubara is formed as an organized set of dedicated software components and data, which relies on the respective observation network, telecommunication infrastructure and computer equipment, serving purposefully trained technical persons and other users. The following chart shows the structure of the planned system.

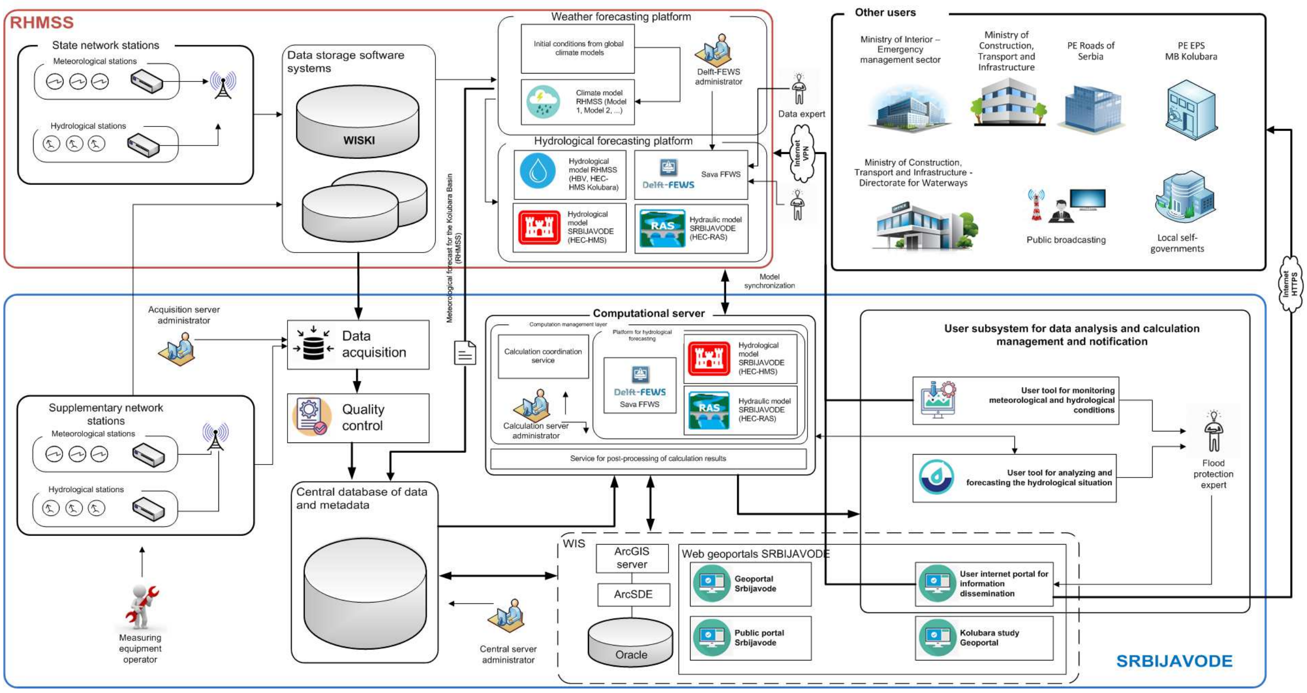

Figure 3. *Scheme of Flood Early Warning System Kolubara*

The observation network of the FEWS Kolubara consists of existing and future rainfall/meteorological and hydrological stations of to the state observation network (stations established and maintained by RHMI) and a supplementary observation network developed by PWMC Srbijavode. The Feasibility Study included the selection of the optimal number and sites and a list of locations for the establishment of a supplementary observation network. The construction of 17 meteorological and 9 hydrological stations is planned. The telecommunications infrastructure conceptual solution has been defined in the Study in such a way that it respects all available standards used by RHMI including technical possibilities for data transmission based on selected locations. Data transmission is planned through mobile network and radio systems.

Data management is performed through a set of dedicated software components developed according to the principles of service-oriented architecture, using the following components: database and associated services, data acquisition from various sources, data quality automatic validation and evaluation, as well as archiving of meteorological and hydrological observation data of the basin, including all relevant data.

A functional connection is planned within the FEWS Kolubara between the central database and the Water Management Information System (WMIS). This connection is based on the geometric data exchange (data on the boundaries of sub-basins, hydrographic network, water management facilities, meteorological and hydrological stations) between the WMIS and the central database of the FEWS Kolubara.

The most significant functionalities of the FEWS Kolubara rely on the hydrological and hydraulic model of the Kolubara River basin. For the purposes of the FEWS Kolubara, the following were selected: HEC-HMS hydrological model and HEC-RAS hydraulic model. The selection of the model was made after a detailed examination of the FEWS Kolubara objectives, as well as the characteristics of various hydrological-hydraulic modeling schemes in accordance with the standardized model development process for flood forecasting.

According to the concept, the coupled hydrological-hydraulic model of the Kolubara River basin should be implemented on the computational server in the PWMC Srbijavode. The computational server should consist of both mathematical models and corresponding computational services including the role of detailed hydraulic simulations based on the hydrological forecast. The later stages of development are planned to implement the computational platform also in one part of the RHMI platform that is already in operation with the earlier models of the Kolubara River basin.

User tools should be developed as graphically oriented web and GIS-based applications. Users of the FEWS Kolubara will access data, mathematical models, and all available information. Data access will be controlled and defined by access rights granted in accordance with the organization of the FEWS Kolubara and all other participants in the organization of flood protection.

Administrator tools will enable the following: maintenance of software components for data management (databases, data processing and access services, etc.), maintenance of mathematical models and computation services, management of user access rights, etc.

Computer equipment includes the required dedicated computer resources (servers, workstations, displays, etc.) with the appropriate system software and database server. They will provide for the monitoring, management, and administration of the system.

Trained technical staff will serve as the technical persons who will be able to use and maintain all software, hardware, and communication elements of the FEWS Kolubara through training and joint work activities.

Tamnava River Basin Pilot

The development of the system so far has included the development of the coupled hydrological-hydraulic model of the Tamnava River, the implementation of the data management system and the computation management system, the user interface, and the user web portal for data dissemination. As part of the first phase, the monitoring system on the Tamnava River basin was also improved.

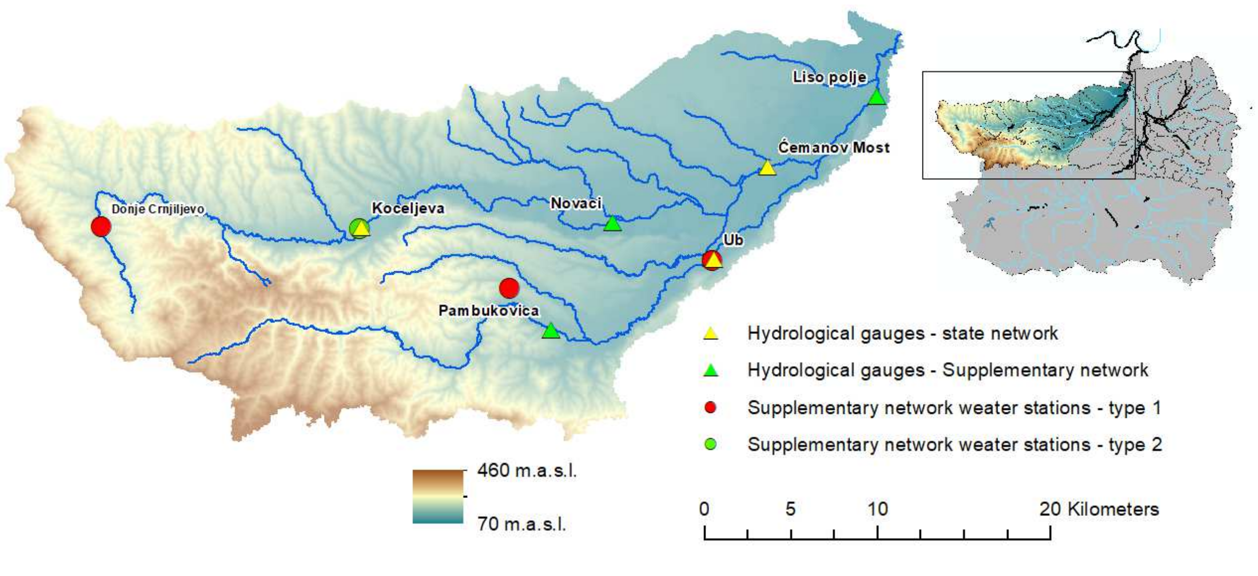

Figure 4. *Observation Network on the Tamnava River Pilot Basin*

The monitoring system on the Tamnava pilot basin includes stations from the state and a supplementary network. During the first phase, the system was improved by installing 3 hydrological and 4 rainfall stations. Two hydrological stations are located on the Tamnava River: Liso Polje and Novaci, while the hydrological station Pambukovica is located on the Ub River. Hydrological stations are equipped with a bubble system and a depth measurement radar system. The rainfall stations Donje Crniljevo, Pambukovica and Ub are fitted with automatic rain meters, while the rainfall station Koceljeva, in addition to the automatic rain meter, is also fitted with a disdrometer and a sensor for measuring air temperature and humidity. The equipment is secured with an alarm system and video surveillance.

Figure 5. *Hydrological and meteorological stations of the state and supplementary network in the Kolubara River basin*

The system for data management within the FEWS Kolubara consists of acquisition and the central server. The acquisition server aims to download, validate, and prepare the data collected within the observation network, both state and supplementary, for sending to the central server. Also, the weather forecast data is downloaded to the acquisition server. The number of data values transmitted daily within the observation network of the Tamnava pilot basin is over 25000. The central server is in charge of managing the database and consists of software components that coordinate, distribute, synchronize, and store data, as well as managing access to data and services. Data from the central database server are used by the computation server and the user system.

All functionalities related to the computations are centralized on the computation server. The computation server consists of a hydrological forecasting platform with associated models, a service for coordination of computations and a service for post-processing the computation results. Automated operation is provided through a hydrological forecasting platform that enables the execution of hydrological computations for assimilation and forecasting purposes, contains the model files required for the execution of the subject computations and contains a module for the automatic launch of forecasts, which manages the processes of starting and refreshing forecasts in the background, without user intervention.

There are two processes for the preparation of the hydrological forecast: the process of computing the forecast, which takes place automatically at every 12 hours on the arrival of new meteorological forecasts, and the process of data updating, which is performed automatically every hour with the arrival of new measurements. The first step in computing the forecast is the reconstruction process, by which the assimilated initial state of the coupled model is obtained. This state, together with the latest meteorological forecast (rainfall and temperatures) is the input for the coupled hydrological – hydraulic calculation. The results are forecast levels and discharges. An updated forecast is then formed every hour – this is a forecast where the forecast rainfall is replaced with the measured rainfall.

The mathematical model in the Tamnava pilot basin is a coupled hydrological-hydraulic model and consists of a hydrological model which transforms the forecasted rainfall into runoff from the sub-basins and a hydraulics model, whose role is to transform the runoff along the Tamnava and Ub rivers. The purpose of the model is to forecast water levels along the Tamnava and Ub rivers based on rainfall and temperature forecasts in the basin. Since the basin is subject to torrential flooding, the hydrological model was formed with a time step of 1 hour to allow for a timely reaction to warnings. The hydrological model was developed with the software package HEC-HMS (Hydrologic Engineering Center – Hydrologic Modelling System) and consists of 18 sub-basins with a total area of 724 km^2. The following figure shows the delineation of the Tamnava basin, based on the position of hydrological stations of the state and supplementary network, the position of the embankments and the tributaries of the Tamnava River. The results of the hydrological model are hydrographs generated from the sub-basins, which are the input data to the hydraulic model on the profiles where the boundary conditions are set. The one-dimensional hydraulic model was formed in the software package HEC-RAS (Hydrologic Engineering Center's River Analysis System). The model covers the Tamnava and Ub rivers. The total length of the modeled courses is 93.5 km.

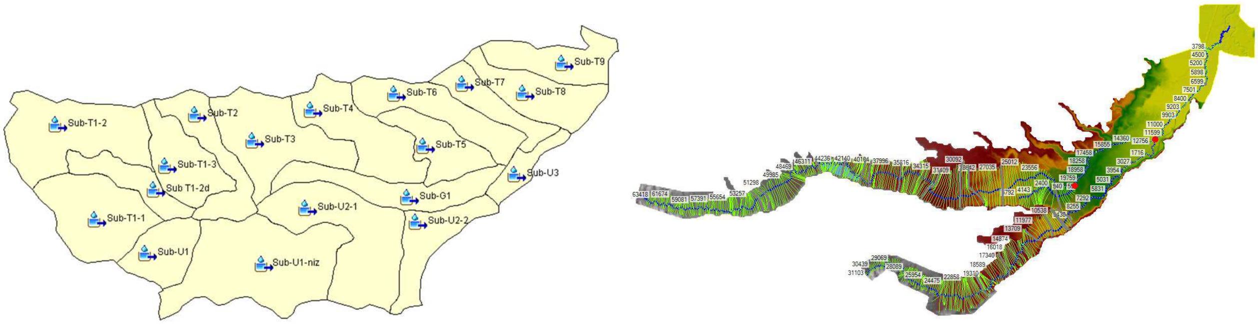

Figure 6. *Delineation of the Tamnava basin and display of the hydraulic model profile*

The simulation within a single sub-basin of the hydrological model can be divided into two parts. The first part deals with the vertical water balance. The simulation of the vertical water balance can be described as a series of reservoirs, where each reservoir is one layer of soil, and the water exchange takes place between layers. The hydrological model is designed to perform continuous simulations, and continuity is reflected through the change in the model state (the volume of water in the reservoirs) during the simulation. Modules that participate in the simulation of vertical balance are the evapotranspiration module, snow process simulation module, vegetation reservoir module and soil reservoir module. The second part refers to the simulation of direct and base runoff of the sub-basin, i.e., to the identification of the shape of the output hydrograph. The modules in charge of this part are the module for the transformation of effective rainfall and the module for base discharge.

In the 1D hydraulic model, in addition to the main river reaches, parallel reaches and systems of connected reservoirs were added to better simulate flooding of inundations. The configuration and parameters of additional elements were obtained based on the results of 2D hydraulic model, which was formed for this purpose. The approach with additional elements instead of 2D flow areas was chosen due to the speed of simulations required in the operational use of the model.

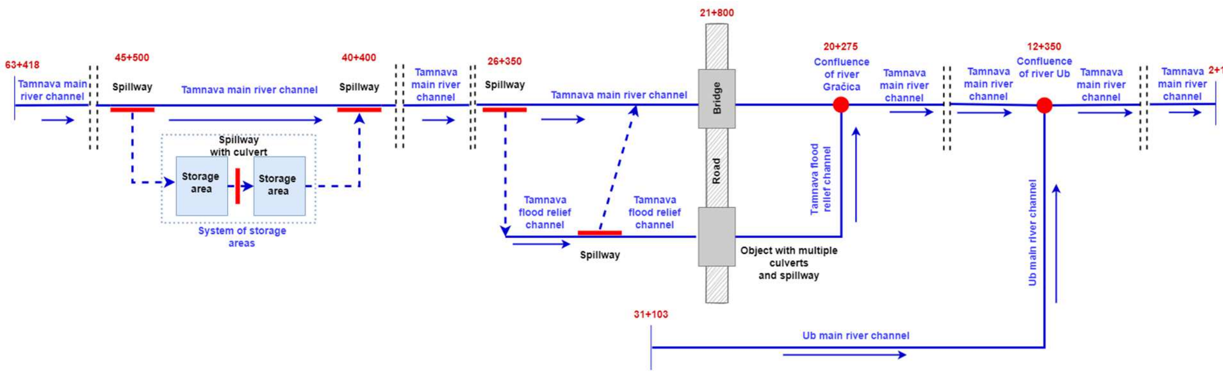

Figure 7. *Scheme of the hydraulic model formed for the Tamnava basin*

As part of the development of the FEWS Kolubara so far, user tools have been developed to enable access to data, mathematical models, and all other available information. Tools have been developed to monitor the meteorological and hydrological conditions in the Tamnava River Basin and to analyze and forecast the hydrological situation in the Tamnava River Basin.

The user tool for monitoring the meteorological and hydrological status provides the required information on the measured time series on the profiles of the measuring points (discharges, water levels, rainfall, and temperatures), as well as the assessment of the mentioned values according to the applicable criteria for declaring the flood protection phase. This data is available in "real-time" (close to real-time, with a delay of a few minutes) and in the form of an archive, for historical review.

Figure 8. *Tool for meteorological and hydrological status monitoring: rainfall station display*

Through this tool users can see data on hydrological, meteorological and rainfall stations (position of stations, measured values at stations, data on changes at stations, etc.) and graphic layers (hydrographic network, topographic maps, position of large water protection facilities). Graphic layers aim to provide users with a tool that has an intuitive way of viewing measured time series by querying the position of measuring points in the basin.

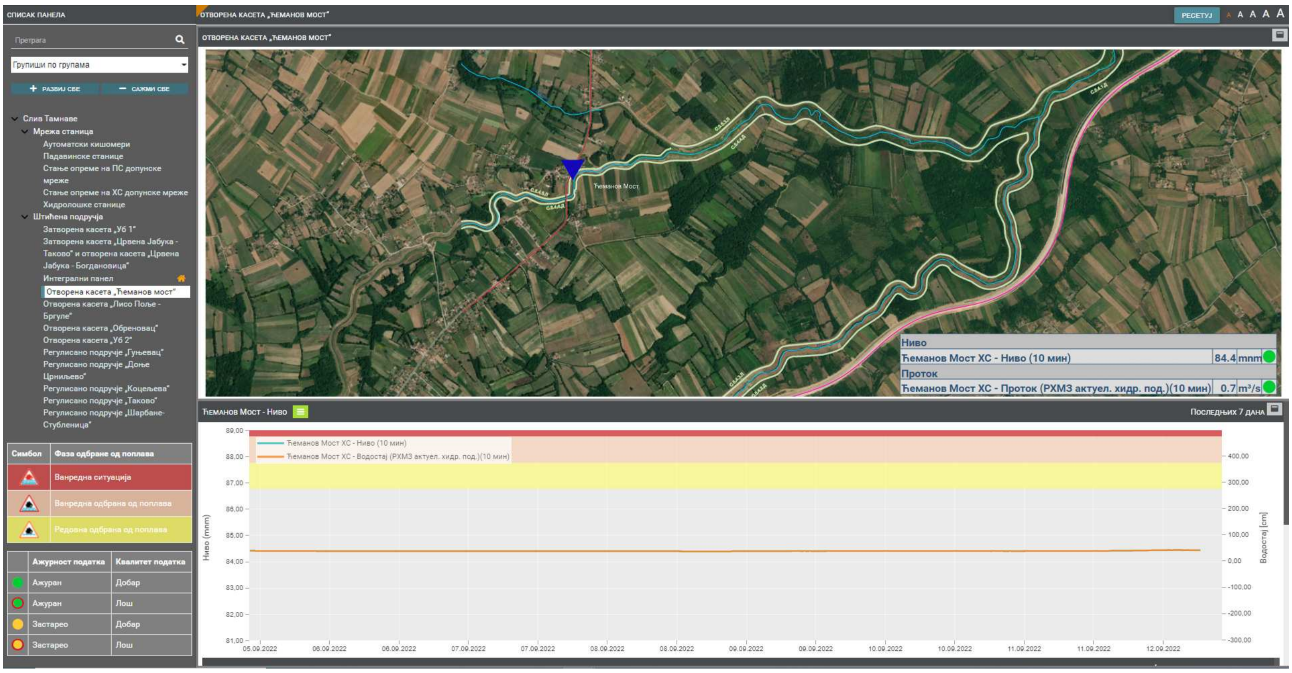

Figure 9. *Tool for meteorological and hydrological status monitoring: protective facilities display*

The user tool for the analysis and forecast of hydrological-hydraulic values is used for a detailed overview of current executed reconstructions and forecasts. In addition to displaying the results of the forecasts that are executed automatically, the tool provides the ability to enter information about the current state of flood protection facilities, as well as the ability to interactively analyze the available results. There are two operating modes within the tool: basic and advanced. The basic operating mode is automated, and the only available option is to view forecasts, simulation results, and warnings. Within the advanced mode, manipulation of input data for simulation is allowed, as well as individual execution of hydrological-hydraulic simulations with forecasts from other sources or arbitrary set of data, as well as comparison of different forecast scenarios that have been created.

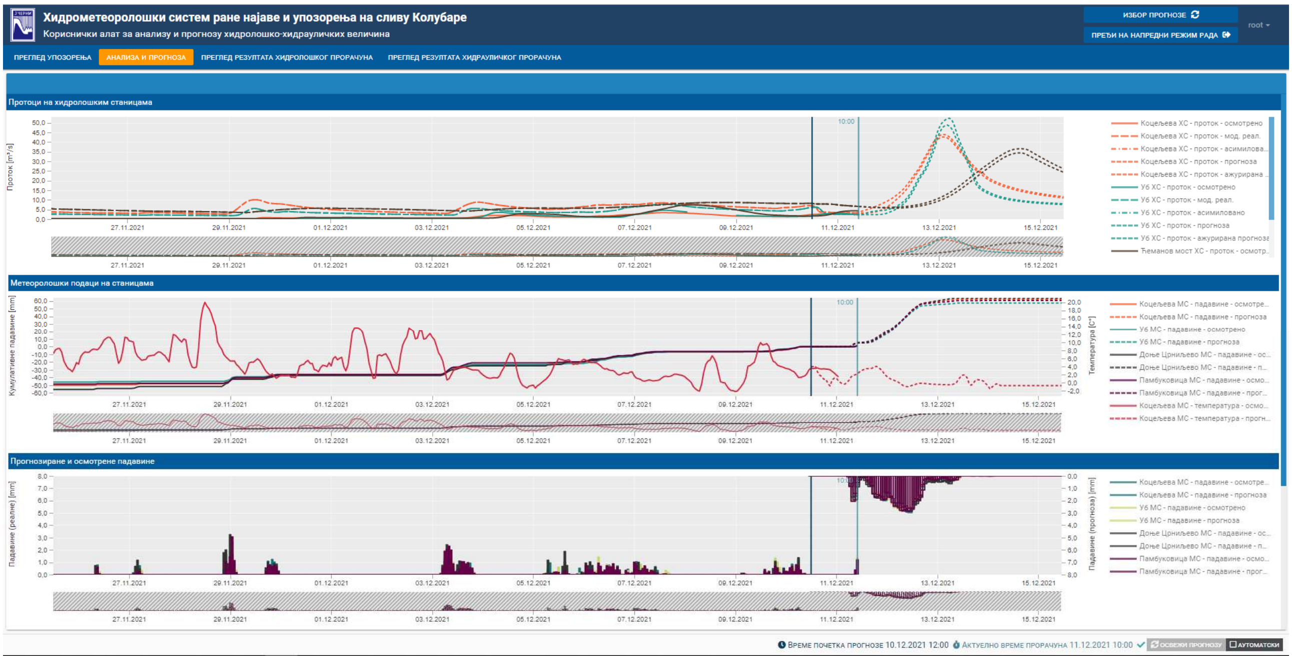

Figure 10. *Hydrological situation analysis and forecast tool*

Based on the results of hydraulic simulations in the post-processing stage, the user checks the effects of computed levels on the state of the system, i.e., whether the forecast water level at a site reaches the level of the embankment toe, or, if the forecast level has already exceeded the level of the embankment toe, whether it reaches up to 1 m below the embankment top at the most endangered site. The user who is analyzing the effects on the flood protection facilities system can use the existing state in the system, but also make changes (embankment subsidence, damage, etc.) in order to assess the possible effects of the forecast water levels. To facilitate the decision on the possible declaration of an emergency defense or a state of emergency, the tool allows for the computation of the duration of level above the embankment toe on each profile.

The user portal for information dissemination provides the information required for making decisions on the implementation of flood protection measures and works. The portal provides information on current and forecasted water levels and discharges, current and forecasted meteorological values, criteria for declaring regular and emergency flood defenses, and state of emergency.

The portal continuously displays in real time the results of the hydrological and hydraulic model based on the meteorological forecast, together with the current discharge and level values. Measurement points of meteorological stations enable the display of current measured parameters (rainfall, temperature, snow cover depth) and meteorological forecasts (rainfall and temperatures). The portal provides two views, graphical (situation with the presented watercourses and flood protection system) and numerical.

The graphic presentation of the user portal shows the situation of the basin of the displayed hydrographic network, the network of hydrological and meteorological stations in the system, as well as water facilities for flood protection. Water facilities where a certain level of alertness has been introduced, i.e., declared regular or extraordinary flood defenses or a state of emergency, are shown in distinct colors and by dotted symbols.

The portal supports the display of longitudinal watercourse profiles where the characteristics of the defense systems (thalweg, riverbank, level of the embankment top) are shown, as well as current and forecasted level lines. Criteria for declaring regular and emergency flood defense, criteria for declaring an emergency situation, and alertness levels on the longitudinal profile of the watercourse are shown with dotted lines.

Also, the portal supports the possibility of displaying transverse watercourse profiles in the system where the current water level is marked, with the possibility of selecting the display of the forecast water level in accordance with the available meteorological forecast. An overview of the current and forecast water level is possible on any cross-sectional profile along the watercourse. As an additional criterion, cross-sectional profiles of hydrological stations include the discharge duration above the embankment toe as an indicator of the sodding of flood protection facilities in protected areas. Cross-sectional profiles of hydrological stations also show water levels at which regular and emergency flood defenses and emergency situations are declared.

The management center for the FEWS Kolubara consists of a control room and a server room. The operator station and user workstations are in the control room. The operator station is intended for monitoring the system via a video wall, while more detailed analyses are performed through user workstations. The server room contains FEWS Kolubara servers where server system components and databases are executed. A redundant system with identical data and models was formed, which is available in case of failure of the primary system.

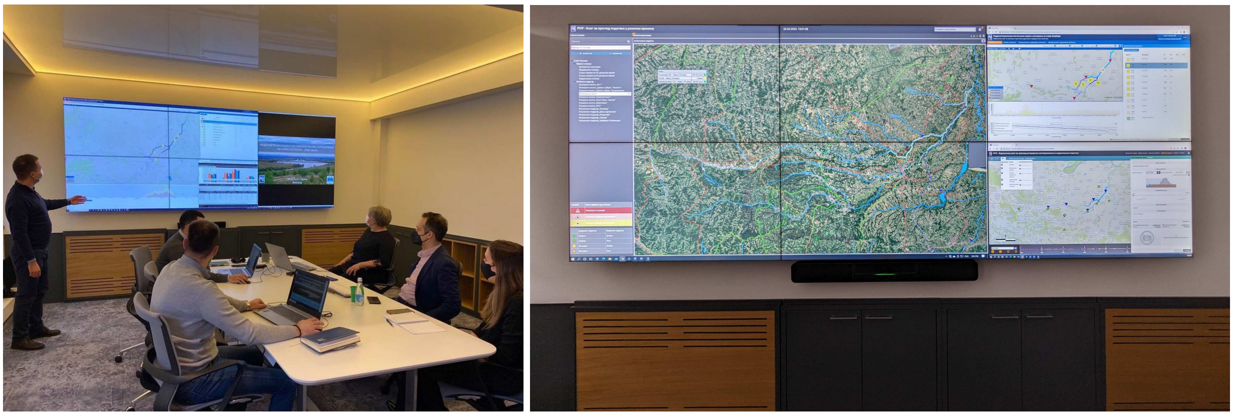

Figure 11. *Control Centre at PWMC Srbijavode*

CONCLUSION

The concept of the hydrometeorological system of early flood warning presented in this paper provides an effective platform for implementation in all areas of Serbia under the authority of public companies (more than 250 watercourses). Tamnava pilot basin implementation has shown that all system elements can be developed and successfully implemented within an integrated platform in a public water management company. Experiences from the implementation of the pilot basin should be transferred to future implementations of the presented system. As observed, data collected from the supplementary network can add to improve the calibration of the model, so this was also considered in the next implementation stages.

Several possible directions of research are set for further development and improvement of the presented concept and individual elements. One possibility is to improve the monitoring system, using radar images in order to improve the assessment of the spatial distribution of rainfall. The application of image recognition methods for the purpose of determining the effects of flooding may also be taken into consideration since all stations are equipped with video surveillance. The video surveillance footage can be used to detect water spills at the sites of the hydrological stations, to better interpret the recorded measurements [10].

In the segment of computations and meteorological forecasting products, accuracy can be improved for the near future period (next 6 hours) using nowcasting forecasts. Although the greatest benefit of such forecasts is an early warning in urban areas [11], it is also possible to use such forecasts for smaller basins with rapid wave propagation. The hydrological forecast could be improved in the next few hours, which is enough to implement some population and property protection measures.

Assimilation methods can be improved by applying data from remote-sensing data sets [12], aimed at improving the up-to-date state serving as the base for the hydrological forecast. Satellite images of snow cover and estimates of snow water equivalent [13] may also be used in basins where the snow cover impact on the flood waves occurrence cannot be ignored. Any improvement of the up-to-date state provides for a more accurate hydrological forecast, and therefore an assessment of the flood wave effects on protective water facilities.

The possibility of applying the presented system for the flood defense measures analysis (for example, analysis based on the simulation of the 2D hydraulic model) in cooperation with water management companies will be examined, which would go beyond the basic purpose of the early warning system but would significantly improve the efficiency of measures and increase the importance of systems implemented by users who manage and participate in flood defense.

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Editors

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Publisher

Jaroslav Černi Water Institute
Jaroslava Černog 80, 11226 Belgrade, Serbia
www. jcerni.rs, office@jcerni.rs

For the Publisher

Prof. dr Dejan Divac, Director General

Editors

Prof. dr Dejan Divac

dr Nikola Milivojević

Prof. dr Srđan Kostić

Cover page design

Tanja Jeremić

Printing

M&G Marketing, Belgrade

Circulation

1000 copies

PREFACE

Institute of Hydrology was established in 1947 within the Serbian Academy of Sciences. The Hydraulics Laboratory was established that same year within the Federal Ministry of Electricity, a predecessor of the later Hydropower Institute created in 1950. These two institutions were soon merged under the auspices of the Serbian Academy of Sciences into the Hydrotechnical Institute Eng. Jaroslav Černi. This Institute merged with the Serbian Water Management Institute in 1959 to create today's Jaroslav Černi Water Institute.

Over the past decades, the Institute has been the backbone of scientific research in the field of water in Serbia and the former Yugoslavia. The international scientific conference Contemporary Water Management: Challenges and Research Directions is organized to celebrate 75 years of the Institute's long and successful history. The Scientific Board selected 26 papers to provide readers with the best view of the current research results, as well as the further scientific research directions and potential challenges in the future. Selected papers are classified into six conference topics according to the corresponding research field, although one should note that most of the presented works is multidisciplinary, which is after all a characteristic of a modern problem-solving approach in the field of water. Hence, the chosen conference topics and corresponding papers represent only one possible way of classification of the presented works.

We wish to express our gratitude to the International Scientific Board and the Organizing Committee of this international conference for their efforts in selecting the papers, reviewing, and organizing the conference. We also wish to express our gratitude to all the authors of selected papers for the time they spent presenting the results of their research in a way suitable for this conference, and for contributing to the celebration of 75 years since the establishment of the Jaroslav Černi Water Institute. Respecting the importance of jubilee and wishing to express gratitude to previous generations of scientific workers, the Honorary Committee was also formed.

Following the path of previous generations, the Institute's present and future staff remain privileged, and under duty and obligation to continue and improve the scientific and research work of the Institute in the years and decades to come.

Belgrade, October 2022

Editors

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556(082)
626/628(082)

INTERNATIONAL Scientific Conference in the honour of 75 years of the Jaroslav Černi Water Institute (2022 ; Belgrade)
Contemporary Water Management : challenges and research directions :
proceedings of the International Scientific Conference in the honour of 75 years of the Jaroslav Černi Water Institute, October, 19-20, 2022, Belgrade, Serbia / editors Dejan Divac, Nikola Milivojević, Srđan Kostić. - Belgrade : Jaroslav Černi Water Institute, 2022 (Belgrade : M&G Marketing). - 430 str. : ilustr. ; 30 cm

Tiraž 1.000. - Bibliografija uz svaki rad.

ISBN 978-86-82565-55-0

a) Хидрологија - Зборници b) Хидротехника - Зборници

COBISS.SR-ID 76403977

9 788682 565550