



Final Report

Velika Morava Flood Forecasting and Warning System



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Mihailo Andelić

Final Report

Velika Morava Flood Forecasting and Warning System

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Client	The Ministry of Agriculture, Forestry and Water Management, Serbia
Contact	Republic Hydrometeorological Service of Serbia
Reference	SRB-DRM-C 3.5-2019-20
Keywords	Velika Morava, real-time hydrological forecasting, Delft-FEWS, hydrological modelling, HEC-HMS, WFlow,

Document control

Version	1.0
Date	21-04-2020
Project nr.	11204532-000
Document ID	11204532-000-ZWS-0041
Pages	43
Status	final

Author(s)

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Doc. version	Author	Reviewer	Approver	Publish
0.1, draft	Klaas-Jan van Heeringen	Peter Gijsbers	Nadine Slootjes	
1.0	Klaas-Jan van Heeringen 	Peter Gijsbers 	Gerard Blom 	

Executive Summary

It is with great pleasure to present the final report on the implementation of the Velika Morava Flood Forecasting and Warning project. The objective of the project was to build a well calibrated hydrological model that supports operational flood forecasting in the Velika Morava basin by the Republic Hydrometeorological Service of Serbia (RHMSS) in Belgrade.

The project was initiated at the project kick-off meeting, held on August 29, 2019, at the RHMSS. In accordance with the Terms of Reference (ToR), the principal objective of the project was to build well calibrated hydrological model that supports flood forecasting embedded in a real-time operational platform, without inclusion of a hydraulic model and training components. The Consultant has developed, calibrated and verified two hydrological models for the Velika Morava catchment - a semi-distributed HEC-HMS and a fully distributed Wflow_sbm model. These models are integrated in an independent Delft-FEWS client-server application hosted at the RHMSS in a Test and Production environment, fed with real-time observations from the RHMSS WISKI database, csv files and deterministic and ensemble Numerical Weather Prediction models.

During the inception phase, focus of the project was on collection and thorough analysis of available data, clarification of modelling approach and other technical and organizational issues that had to be clarified and included into a detailed inception report of the project. The inception phase ended up at the Inception Workshop – held on October 10, 2019, at the RHMSS in Belgrade. The workshop reviewed the findings and solutions presented in the report, clarified issues, endorsed the report, and agreed on the workplan to be executed during the remaining project period.

The period after the project inception workshop witnessed a number of activities, carried out by the Consultant and the RHMSS project team and also jointly in the period November 18-21, 2019, which eventually led to the delivery of the Velika Morava FFWS Pre-release 0.2 at the workshop held on Friday, November 22, 2019. In the period after this pre-release 0.2 workshop, significant tasks had been accomplished, focusing on additional analysis of the available data, preparation of data in the form adequate for model input, and in particular on calibration and verification of the HEC-HMS and the Wflow_sbm models.

These efforts have eventually resulted in delivery of the key project output - the Velika Morava FFWS Release 1.0 - during the joint working session that took place on December 19th, 2019, and the subsequent R 1.0 Delivery Workshop, held the following day, i.e. on December 20th, 2019, at the RHMSS in Belgrade. From the December Workshop onwards, the designated RHMSS team was able to operationally use and systematically test the system and its potential for real-time hydrological forecasting in the basin. Owing to a sustained effort of the whole RHMSS team, a number of suggestions for additional fine tuning and improvements of the Release 1.0 has been suggested and subsequently implemented in the final VM-FFWS Release 2.0 and as such accepted by the RHMSS, the Water Directorate of Ministry of Agriculture, Forestry and Water Management, and the World Bank.

It can be concluded that the project is a success. Nevertheless, there is always a potential for improvements. This report also describes the technical aspects of the identified potential improvements, covering topics including data (increase spatial distribution and data quality of both meteorological and fluvial gauges), improvements on the hydrological models and inclusion of hydraulic simulation models, training and support & maintenance.

The consultant is happy to put on record that it was a rewarding experience to work on the project, owing first of all, to an excellent cooperation and a sustained effort, throughout the project implementation period, of the RHMSS and its designated project team. The cooperative spirit of all involved in the project at national level and the pervading friendly working atmosphere had a significant impact on the project implementation and greatly contributed to its overall success.

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1 Introduction

1.1 Background

This report gives an overview of the implementation of the project for development of the Flood Forecasting and Warning System for the Velika Morava river basin (VM-FFWS).

This forecasting system is implemented for the Republic Hydrometeorological Service of Serbia (RHMSS). The project is part of the larger Serbia National Disaster Risk Management Program, which is financed by the Trust Fund provided by the European Commission on behalf of the European Union, administered by the World Bank and managed through the Water Directorate of the Ministry of Agriculture, Forestry and Water Management. The implementation project includes two components:

- Development of hydrological forecasting models
- Establishment of real-time forecasting platform for the integration of all components of the system

The system has been implemented during the period of August 2019 till March 2020 by Deltares, along with the Centar Građevinskog fakulteta d.o.o. Zagreb and Mihailo Anđelić as subcontractors. During the project implementation, all partners have maintained fruitful and mutually beneficial cooperation with the RHMSS, the Ministry, the World Bank and the independent advisor - Prof. Dr. Jasna Plavšić.

1.2 Structure of the report

This report aims at describing the main outputs of the project concerned with development of the VM-FFWS. It starts with explanation of the general concept and the use of operational forecasting, a discipline where hydrological and meteorological data, meteorological forecasts and related real-time and non-real time information are translated into the river flow and water level forecasts at the required hydrological profiles. Based on such forecasts, emergency response organizations are issuing timely alerts and warnings to people and water management decision makers of potential floods.

Chapter 2 explains in more details the technical background of the VM-FFWS.

The implementation of the project VM-FFWS is discussed in Chapter 3, including a description of the work carried out and completed and lists the project achievements and outputs.

Chapter 4 deals with the gap analysis and provides, based on the Consultant's experience, an insight on the ways and means for further improvement of the established VM-FFWS. Keeping in mind the importance of the subject, full details of the gap analysis are provided in a separate Annex A of the report.

Finally, Chapter 5 summarises main conclusions and recommendations on the way forward in the period following completion of the project.

1.3 The Velika Morava River Basin

The Velika-Morava river basin (38,200 km²) is the largest basin in Serbia, whilst 15% of the basin belongs to Montenegro and Bulgaria. The river basin (see Figure 1-1) encompasses three main hydrographical entities: the Južna (South) Morava River Basin, the Zapadna (West) Morava River Basin and an immediate catchment of the Velika (Great) Morava.

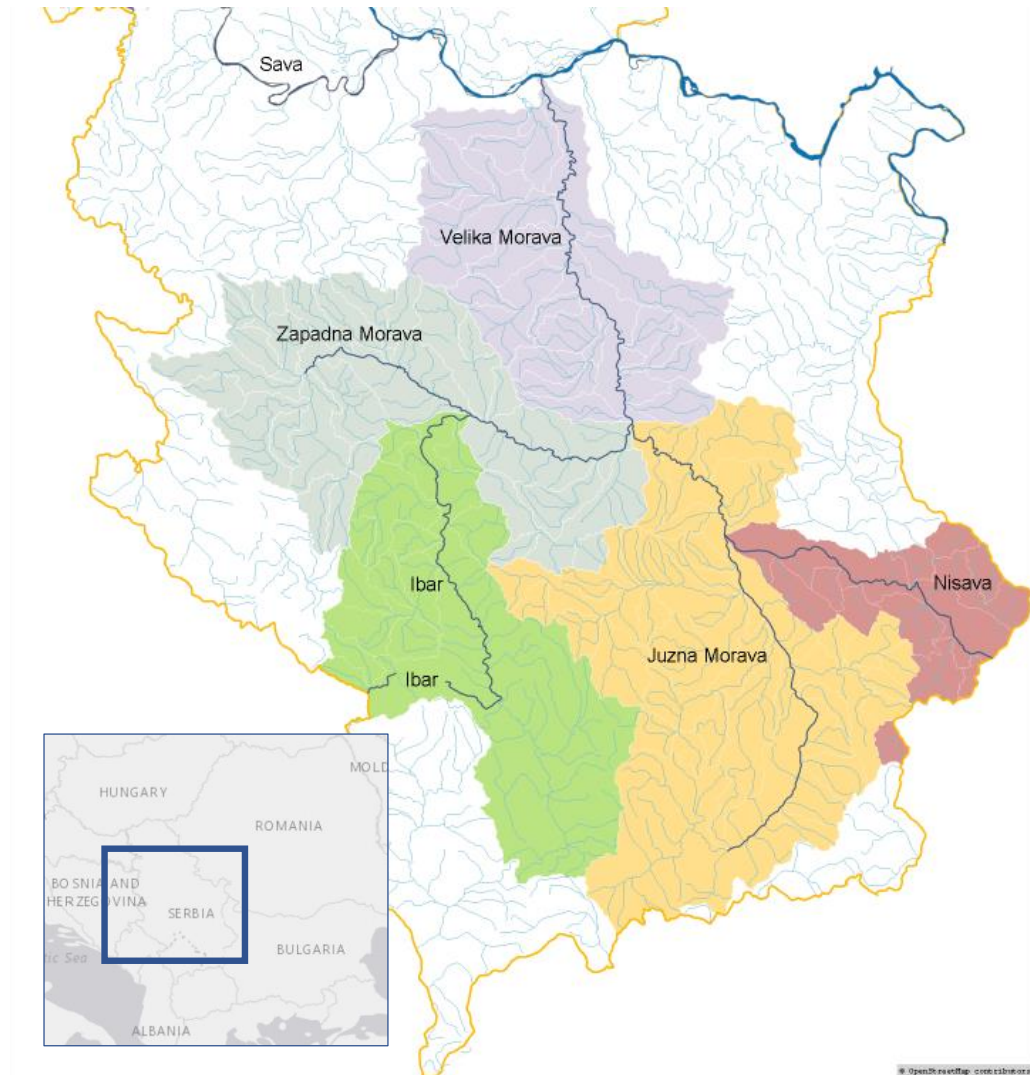


Figure 1-1 The Velika Morava river basin in Serbia.

It has a very heterogeneous river network while its topography is diverse, ranging from plains in the north, rolling hills and wide valleys along the north-south direction, and mountainous central, southwest, south and east parts of the basin. Besides the main streams (Južna, Zapadna and Velika Morava) there are a number of smaller watercourses in the VMRB with wide ranging hydrological regimes, including the torrential streams. The largest settlements, the most fertile land, infrastructure, industrial and other structures are located in the valleys of the Južna, Zapadna and Velika Morava rivers and their larger tributaries. They are endangered by flooding, consequences of the river channel deformations, and other adverse impacts of watercourses.

Extensive flood protection and river training works have been taken in the past in order to reduce the harmful water effects. However, significant areas in the valleys are still endangered by flooding, including both the areas which are not protected and those areas which can potentially be flooded (areas protected by levees which ensure a certain level of protection).

The levee system is not continuous so there are river sections along both main streams and tributaries without levees or with levees only along one riverbank. In general, larger settlements are protected from flooding while agricultural land is not. Levees along the main streams together with those along the tributaries form the flood protection retentions. There is, however, still the risk of flooding in the current situation due to a lower level of protection along the tributaries or unfinished system, so water can come from the hinterland.

The long-term mean flow at the Velika Morava river mouth is $235 \text{ m}^3/\text{s}$, which corresponds to about 0.53 mm/day . The flows range from about $40 \text{ m}^3/\text{s}$ (typical low flows) to $2350 \text{ m}^3/\text{s}$ (highest registered value at February 23, 1965, while $2150 \text{ m}^3/\text{s}$ during the May 2014 flood). The summer periods show a relatively long duration of low flows, while most of the high flows and subsequent flood hazard is caused by snow melt.

With respect to hydrological forecasting, the RHMSS of Serbia has a long-lasting history and professional experience at all rivers in the country – including large rivers (Danube, Sava, Tisa, Velika Morava and Drina) as well as many medium and small catchments. Concentrating on the Velika Morava River Basin, two models (MANS and HBV) have been used in some parts of the VMRB before the VM-FFWS has been implemented.

2 On Operational Forecasting

2.1 Role of flood forecasting in flood management

The need for flood forecasting and warning systems comes as consequence of the limitations of structural flood protection systems. Due to the existence of settlements in flood-prone areas and to the need to meet community safety and protection of assets, the provision of an adequate flood forecasting and warning service is a necessity in every country, including Serbia. Forecasting and warning services are, in most cases, provided by national state agencies and in the case of Serbia it is the responsibility of the Republic Hydrometeorological Service of Serbia (RHMS). Their main duty is to deliver reliable and timely information to the flood managers, civil protection agencies as well as to the general public. This should be accomplished with long enough forecast lead times to allow people to take measures to protect themselves from flooding or take appropriate actions.

As no preventive or flood defence measures can ever be completely effective, flood forecasting constitutes a crucial part of flood management. The reality of economic limits to the provision of a flood defence system, together with the possibility that the capacity of defence systems may be exceeded, or may fail, require that other measures should be in place.

This is the reason why flood forecasting forms a part of flood management planning and development strategies, which recognize that there are occupied flood plain areas where non-structural measures can be effective. Flood management requires a variable degree of response from the water management agency, local or municipal authorities, transport and communications operations and emergency services. Flood forecasting has to provide information to these users both for preparation and response: at the most extreme level, flood forecasting is part of the wider disaster management capacity, which devolves from the highest level of government in Serbia.

No less important is to note the vital role that the flood forecasting, and streamflow forecasting in general, play in management and optimal operation of reservoirs and river flow regulation.

2.2 Real-Time Hydrological Forecasting: A Short Overview

Hydrological forecasting is one of the many branches of geophysical science where the hydrometeorological data, meteorological forecasts and other related information are “translated” into forecasted river flows and water levels. In this process, in addition to the meteorological forecasts, all kind of other relevant data are used – such as observed water levels, rating curves, discharges, precipitation, air temperatures, snow depth and snow cover/pack, soil type, vegetation cover and topographic characteristics. The “translation” is being achieved by using (mostly conceptual, not physical) hydrological models that simulate the rainfall-runoff processes in the catchment (including snowmelt), and hydraulic models to simulate the dynamic hydraulic behaviour of water flow in the rivers and flood plains.

Hydrological forecasting has already been applied and widely used for many years, and rightly so because the forecasting and warning systems have been shown to reduce impacts and save lives. Therefore, these systems are becoming an increasingly important tool for flood risk and water managers and emergency response services in the whole world.

However, the distinct advantage the hydrologists have nowadays over their predecessors is the advancement of science and technology. Better scientific understanding of physical phenomena and processes allows introduction of better and more realistic models, improve measurements of hydrological and meteorological variables, and improve prediction of model inputs, including the use of meteorological ensemble forecasts. Dramatic advancements in affordable technology have made the application of modern hydro & meteo science and hydraulics to flood forecasting possible mainly due to the following three factors: (1) the availability of very fast computers, with significantly more memory and data storage capability than was available even just 10 years ago; (2) proliferation of inexpensive modern sensors for measurement of hydrological and meteorological variables as well as widespread availability of high-resolution GIS-based data sets from remote-sensing sites, which are needed for model parameter estimation and calibration; and (3) highly reliable telecommunications systems for data transmission from ground-based and satellite data collection platforms (DCPs). In addition, the expansion of the Internet and the proliferation of mobile phones have had a dramatic impact on the distribution of flood warnings.

2.3 The Velika Morava FFWS

2.3.1 Introduction

The Flood Forecasting and Warning System for the Velika Morava, developed within the project, is fully hosted and operated by the RHMSS. The startup splash screen of the VM-FFWS is shown in Figure 2-1.



Figure 2-1 Velika Morava Forecasting System startup screen

The system is built by using the Delft-FEWS software. This software platform enables integration of many data sources and to connect these data to hydrological models. This is illustrated in Figure 2-2. The figure shows the various data sources on the left upper side, being imported into the database of the VM-FFWS. The VM-FFWS includes two types of hydrological models i.e. the fully-distributed Wflow_sbm and the semi-distributed HEC-HMS, which have been selected and agreed upon as most suitable for operational use keeping in mind main features of the VMRB and available input data. Proper data validation and preparation is performed by the FFWS to make sure it provides the best possible model input as well as to retrieve and present model results in adequate user-friendly form. All imported and produced data is also archived within the system, such that later analysis is possible.

The FFWS application is a so-called client-server application. That means that all tasks are automatically running at a server, hosted by RHMSS and sharing all data in a central database. The forecasters use a so-called “Operator Client” (OC) application, that connects to the central database and visualizes all data, next to giving control to all kind of versatile functionalities.

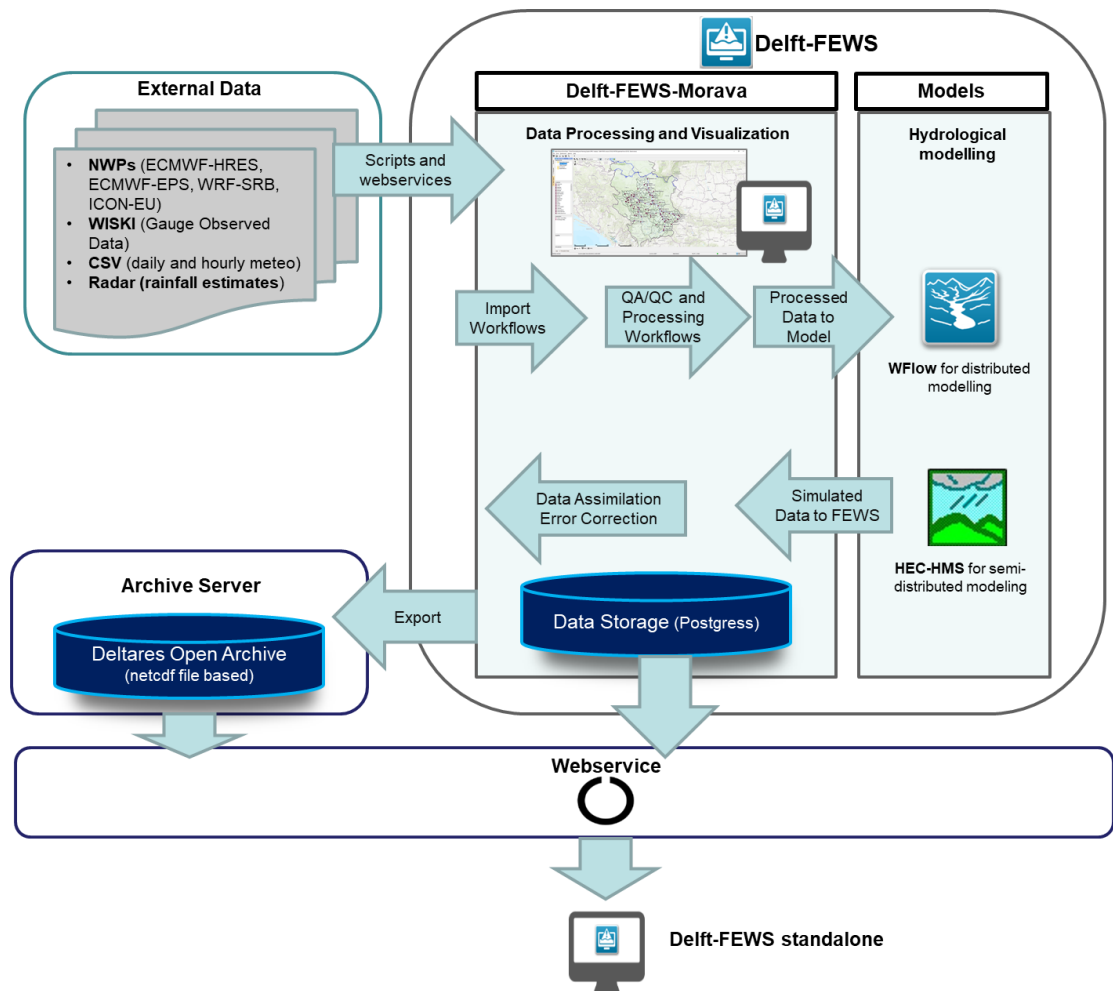


Figure 2-2 Conceptual modelling framework for the Velika Morava River Basin using the Delft-FEWS platform

2.3.2 Data used in the VM-FFWS

The VM-FFWS collects data from the next sources:

- hydrological telemetry data available from the WISKI hydrological information system of the RHMS (water levels and discharges)
- meteorological telemetry data from:
 - WISKI (precipitation and air temperatures)
 - PMS – principal meteorological stations (precipitation and air temperatures)
 - AWS – automatic weather stations (precipitation and air temperatures)
 - ARG – automatic rain gauges (precipitation only)
 - Ordinary daily rain-gauge stations (precipitation only)
- Radar images (in hdf5 format)
- Numerical Weather Predictions (NWP) products
 - ECMWF deterministic high-resolution forecasts
 - ECMWF ensemble forecasts
 - ICON-EU deterministic forecasts
 - NMM-WRF deterministic forecasts
- Copernicus satellite images on Snow Water Equivalent

The details of the various NWP product are listed in Table 2-1, showing the timesteps, lead times update frequency and available parameters in the FFWS.

Table 2-1 NWP products

NWP product	Time step (hr)	Lead time (hr)	Parameters	Remarks
ECMWF-HRES deterministic	0-90: 1 93-144: 3 150-240: 6	240	<ul style="list-style-type: none"> Precipitation Convective Precipitation Air Temperature Snow melt 	The model is named 'high-resolution deterministic' model. Products at 0 and 12 hrs (UTC)
ECMWF EPS	0-90: 1 93-144: 3 150-240: 6	240	<ul style="list-style-type: none"> Precipitation Air Temperature 	The ensemble has 51 members Products at 0 and 12 hrs (UTC)
WRF Serbia	3	72	<ul style="list-style-type: none"> Precipitation Convective Precipitation Air Temperature Soil Moisture Snow Cover Depth Snow melt 	Products at 0 and 12 hrs (UTC)
ICON-EU	0-78: 1 81-120: 3	120	<ul style="list-style-type: none"> Precipitation Air Temperature Snow Water Equivalent 	Products with full forecast at 0, 6, 12 and 24 hrs (UTC).

All data is imported automatically, validated through various validation rules (like exceeding extreme values) and processed where applicable. Data processing is for example applied to derive catchment average precipitation.

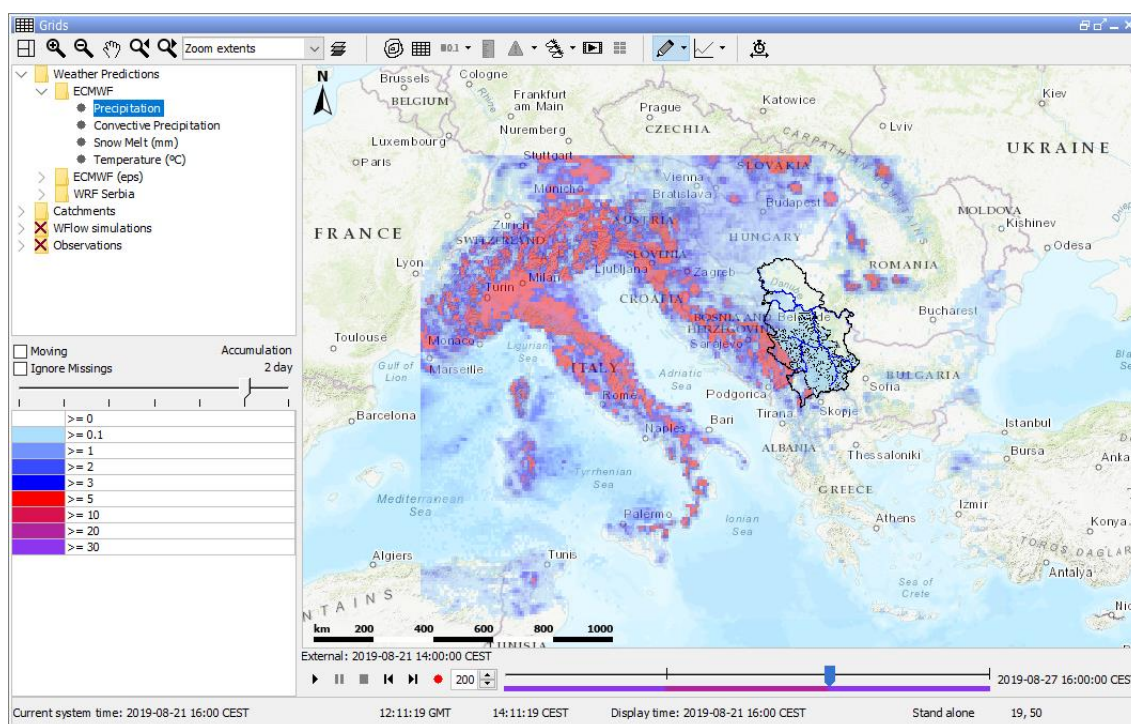


Figure 2-3 Precipitation forecast grid from ECMWF visualized in the Spatial Display of Delft-FEWS

2.3.3 Hydrological models

2.3.3.1 Semi-distributed HEC-HMS model

The selected semi-distributed model for this project is the Hydrologic Modelling System (HEC-HMS). The HEC-HMS software is designed to simulate the complete hydrologic processes of dendritic watershed systems. The software includes many traditional procedures for hydrologic analysis, such as event infiltration, unit hydrographs and hydrologic routing. It also includes procedures necessary for continuous simulation, including potential evapotranspiration, snowmelt, soil moisture accounting and reservoir operation.

The spatial resolution of the semi-distributed model match to the forecast locations. Also, the heterogeneity of the sub-catchments is considered. The sub-catchments are of such a size that the area within the sub-catchment can be described by a single parameterization.

The temporal resolution is an hourly time step. For the purpose of flood forecasting, an hourly timestep is often used since that time step matches well with observed processes in the field. This decision is evaluated by the consultant and agreed upon in cooperation with RHMSS project team after the first test-runs.

For a detailed description, set-up, calibration and verification of the HEC-HMS model of the Velika Morava river basin, please be referred to the separate report on the HMS model: "HEC-HMS Hydrological Modelling Report R2.0".

2.3.3.2 Distributed Wflow_sbm model

The distributed Wflow is an open source framework for setting up hydrological models. The framework includes different hydrological model concepts, such as the Wflow_hbv or the Wflow_sbm concept. For the Velika-Morava catchment the Wflow_sbm model concept is used. This model concept is more physically based then for example Wflow_hbv, therefore making it easier to translate the available geographical datasets into model parameter datasets. The Wflow_sbm allows for continuous simulation of catchment runoff and includes the soil moisture accounting component.

The model has been setup in LAT/LON coordinates to optimally make use of available global datasets. Model coordinates are therefore in WGS84 (EPSG:4326) and the model resolution is 0.0041666° (approximately 500 meters). The model runs also at an hourly timestep.

For a detailed description of the model, please be referred to the separate report on the Wflow-model "Wflow model for the Velika-Morava basin".

2.3.3.3 Modelling of reservoirs

Streamflow regimes in the Velika Morava River Basin may be influenced by the reservoirs located in the upstream river sections. The reservoirs in the Zapadna and Južna Morava basins that may influence river flow in the downstream sections were identified by the RHMSS and specially addressed in the model setup.

After identification of adequate hydro measurement stations, it has jointly been decided by the consultant and the RHMSS to exclude any upstream reservoir and replace any computed timeseries at these hydro stations by observations, using extrapolation or a default value to fill any data gaps.

2.3.3.4 Model calibration and validation

The HEC-HSM model skill was assessed at each forecasting station by a comparison of discharges, cumulative runoff volume and discharge bias between calculations and observations as well as by calculation of Nash-Sutcliffe Efficiencies (NSE) for discharges and analysis of timing of the peak discharge. The calibration of the model was performed for four hydrological years 2014 to 2017 and model verification for three hydrological years 2011 to 2013. The model skill in the calibration period was very good (average NSE=0.637 on 13 forecasting stations, low bias in value and timing of the peak discharge) and also very good for year 2013 in the verification period (average NSE₂₀₁₃=0.741 on 13 forecasting stations). A long-term performance in the calibration period was also very good (average NSE=0.709 for 6 stations for a 4-year simulation). A lower model performance was evident in smaller catchments (like Guča), for hydrological years with lower quality of input meteorological data (2011, 2012) and for some stations in the downstream river reaches (overestimation of flood flows in river sections with wide floodplains). As floods in the Morava River basin are usually generated by snow melt, the HEC-HMS model performance can further be improved by improving the quality of input meteorological data (hourly precipitation and air temperature observations in winter period) and introduction of hydraulic modelling in the downstream river reaches.

The wflow_sbm model skill was assessed and presented in the form of hydrographs and performance indicators like NSE, KGE and RSME. The overall skill of the wflow_sbm model is reasonably good based on the calculated skill scores. The difference between stations and especially between years can, however, be large. The average NSE value for all stations for the year 2013-2014 is 0.71 and for the year 2014-2015 0.68. However, for the year 2012-2013 the NSE score is -0.3.

Looking at the results from basin to basin it can be observed that mainly Zapadna Morava has a very good skill (NSE values around 0.7-0.8). Lower scores are obtained for Juzna Morava. The reason for the good performance in Zapadna Morava and lower performance in Juzna Morava could be partly explained by the quality of the input data. Since especially for Juzna Morava, large part of the basin is not covered by meteorological stations, the input data for the model (rainfall, air temperature) might not be correct.

Although the skill scores give a good impression of the skill of the model, also the visual inspection of the hydrographs and the accumulated volume need to be considered. Based on the analysis, some general conclusions can be drawn. For example, the wflow_sbm model seems to be mainly overestimating the peaks rather than underestimating. Due to the fact that the model was mainly calibrated on the 2014 event, the model is quite fast reacting, although most of this behaviour was corrected afterwards when the model was run for the longer period. The timing of the peaks, however, seem to be very well captured in the model, except for some snow events. The correct timing of snow melt and snow depth are strongly related to the quality of the air temperature input data. It was shown that the results can differ strongly when using different input data.

Based on the analysis of both models it can be concluded that their performance is the same for the same basins and same years. Based on the operational test, however, it seems currently the wflow_sbm model is performing slightly better than the HEC-HMS model. This could be due to the fact the HEC-HMS model is slightly more sensitive to a change in input data (mainly air temperature data), which is different from calibration/validation period compared to the operational data. In an operational setting, however, the wflow_sbm model is rather slow and cannot be used for e.g. ensemble forecasts in the current setup of the live system. Therefore, it is advised to use both models in parallel and examine their results; if there are large deviations between results of the two models for the deterministic run (i.e. with exclusion of the meteorological ensemble forecasts as model input) the decision to use one or the other model should be based on a thorough analysis of current hydrological conditions in the basin.

General recommendations on which model performs better per individual forecasting location are yet hard to make. This should rather come from the forecasters' experience after using the system for some time in the operational setting.

2.3.4 IT and hardware

The VM-FFWS is based on hydrological models which are run in a data integration platform that is configured using the Delft-FEWS software. Delft-FEWS is a fully scalable system that can be run as a self-contained, manually-driven, stand-alone system operating on a normal laptop or desktop computer but can also be deployed as a fully automated distributed client-server application. The client server application allows further scalability through running time-consuming tasks in parallel and distributing tasks across multiple servers. This client-server setup is the recommended mode for operational forecasting in a multi user RHMSS environment. It was confirmed during the inception phase that two independent client-server systems will be installed. One Test environment, and one Production environment. The architecture of Delft-FEWS is captured in Figure 2-4.

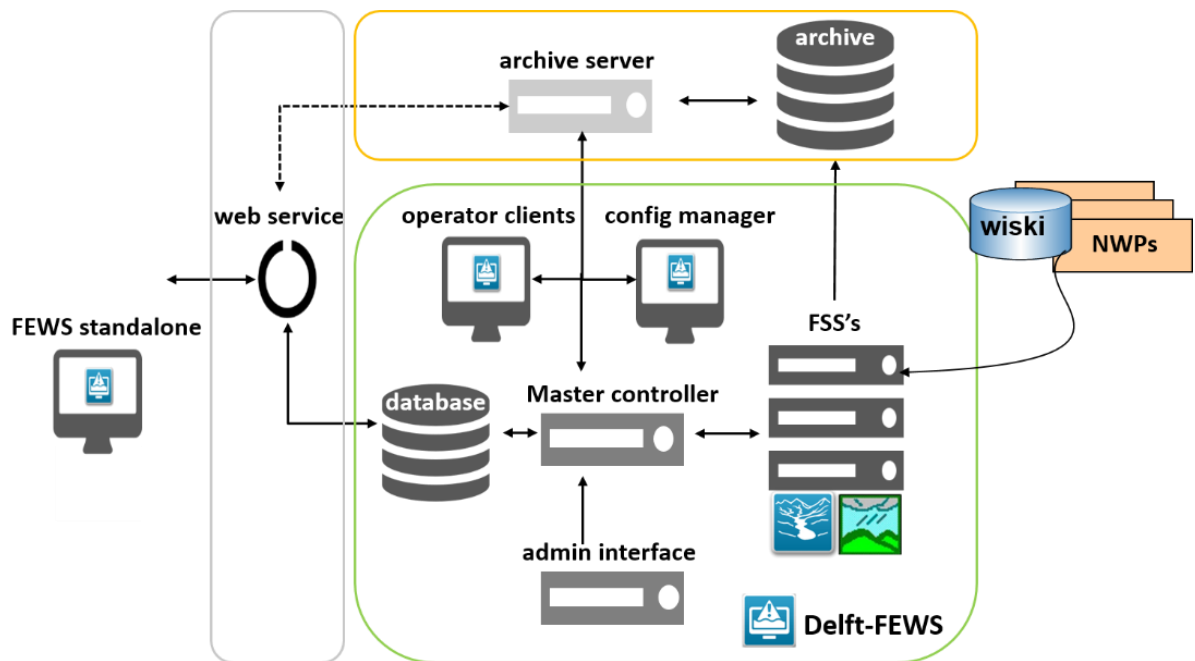


Figure 2-4 Overview of overall system architecture Delft-FEWS implementation

In general, a Delft-FEWS system consists of different components:

- 1 Green frame: the required core of a Delft-FEWS client-server operational system.
- 2 Yellow frame: Open Archive connected to the Delft-FEWS operational system.
- 3 Grey frame: PI Webservice for exchanging data with external applications, in this case a standalone application reading data from the archive.

The hardware and operating system requirements for an operational Delft-FEWS client-server system are listed below and are similar for both the TEST and Production environments unless stated otherwise. Details can also be found at the [Delft-FEWS WIKI pages](#).

The servers, installed by RHMSS, for running the testing and production systems have been illustrated in Figure 2-5. Note that both systems share the Archive, Database and Master Controller servers. The production system has 4 computational servers, while the testing system has only 2. The Delft-FEWS software version 2019.02 is installed.

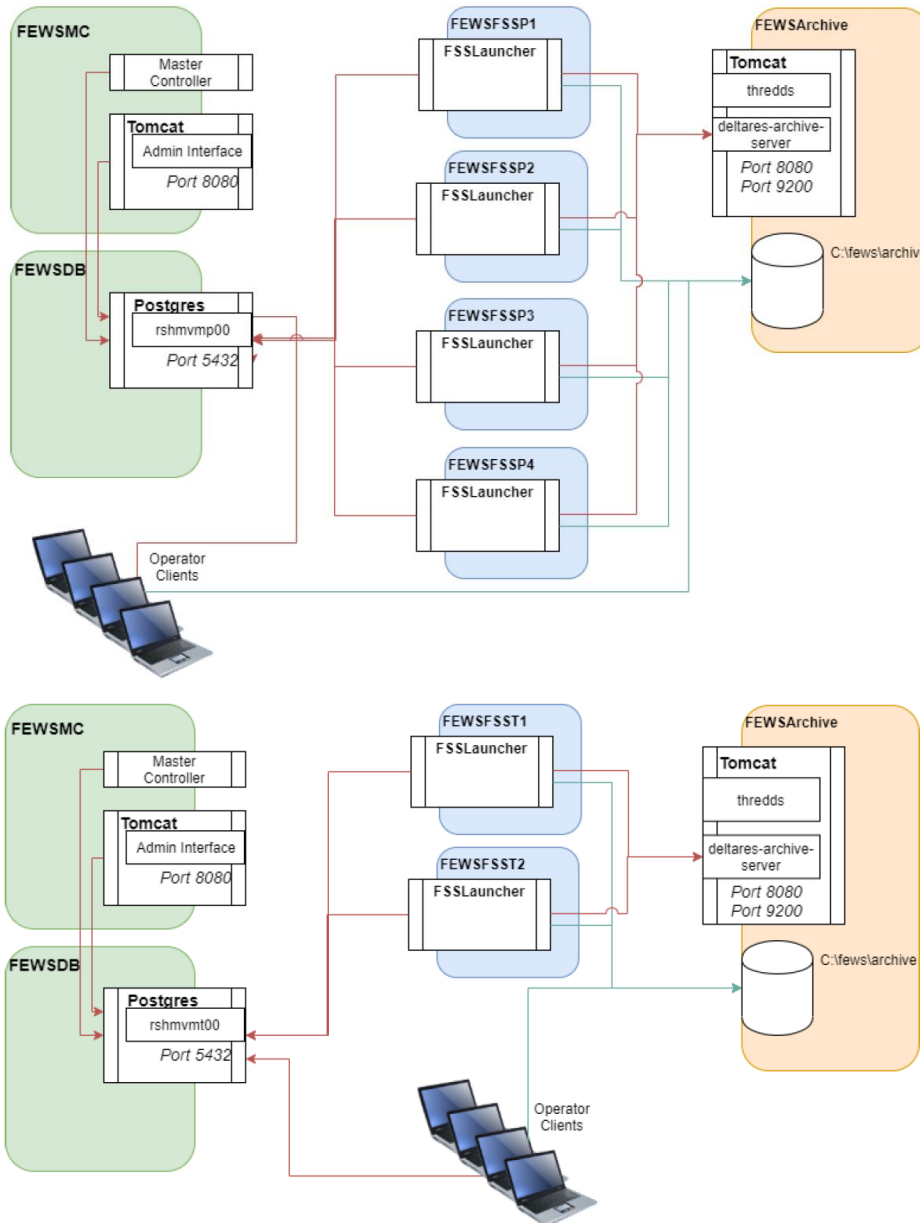


Figure 2-5 IT server schematic of the production (upper scheme) and testing (lower scheme) system

2.3.5 Dissemination of forecasting results

As mentioned already, the operational forecaster on duty is using the FFWS application to daily prepare the forecasts as they have to be disseminated. The forecaster uses the FFWS to check the availability of relevant data, performance of the models and decides which model results fit best to the current conditions and should be used as official forecast. Note that the forecaster has two hydrological models and various meteorological models and as a result of that, many different forecasts are produced. Especially during the snow melt season, the start of melting is a quite sensitive and challenging choice. If wanted, the forecaster can make additional forecasts by using scenarios or changed/corrected model input data.

The forecasting results contain forecasted river flows and water levels derived from rating curves. These results are checked with crossing of warning levels, which may result in additional alerts to be sent out by the RHMSS.

3 Implementation Project and Completed Activities

3.1 Setup of the project

Implementation of the project started with the kick-off meeting, held on August 29, 2019 at the premises of RHMSS. The Inception Phase of the project lasted till the October 10, 2019. As already mentioned in the introduction chapter, the project comprises two main components:

- Development of hydrological forecasting models HEC-HMS and Wflow_sbm.
- Establishment of real-time forecasting platform for the integration of all components of the system

During implementation of the Velika-Morava flood forecasting system a step-wise approach is followed before the final system is released, according to the release schedule given in Table 3-1. As such, the VM-FFWS could be built and extended step by step, while RHMSS staff could interact, experience and feedback already with very early development versions of the VM-FFWS.

Table 3-1 Release Schedule

Release	Due	Description
pre-release 0.1	Oct 10, 2019	Standalone Delft-FEWS application with data and GIS information implemented
pre-release 0.2	Nov 22, 2019	Client-server Delft-FEWS application with real-time data and pre-processing algorithms implemented, on RHMSS TEST environment
release 1.0	Dec 19, 2019	Client-server Delft-FEWS application with HEC-HMS and Wflow_sbm models implemented, ready for Acceptance Testing, on RHMSS TEST and Production environment
release 2.0	March 2020	Final Client-server Delft-FEWS application, on RHMSS Production environment

To ensure good synergy and communication with the Consultant in the course of project implementation, the RHMSS has established a Working Group with designated specialists for implementation of the project, including their respective roles. As mentioned in the introduction of the report, an independent advisor, Prof. Dr. Jasna Plavšić, was assigned to the RHMSS team to assist in evaluating the project results and advise on the way forward in resolving inherent technical issues.

To establish and maintain good working relations and permanent communication throughout the project duration, the following communication channels have been used: occasional meetings, phone, e-mail, designated Deltares ftp server and on-line skype or GoToMeeting discussions.

These efforts have eventually resulted in delivery of the key project output - the Velika Morava FFWS Release 1.0 - during the joint working session that took place on December 19th, 2019, and the subsequent R 1.0 Delivery Workshop, held the following day, i.e. on December 20th, 2019, at the RHMSS in Belgrade. From that moment onwards, the RHMSS was able to operationally use the system for their hydrological forecasting. Testing of the system by RHMSS was structured through dedicated testing scripts. Owing to a sustained effort of the whole RHMSS team, a number of suggestions for additional fine tuning and improvements of the Release 1.0 has been suggested and subsequently implemented in the final VM-FFWS Release 2.0 (installation date March 30, 2020) and as such accepted by the RHMSS, the Water Directorate of Ministry of Agriculture, Forestry and Water Management, and the World Bank.



Figure 3-1 Group picture of the attendants of the project's kick-off meeting, held on August 29, 2019



Figure 3-2 Picture of one of the sessions during the working week of Nov 18, 2019

3.2 List of Products and Reports

During the implementation project, the reports and products have been delivered as listed in Table 3-2.

Table 3-2 List of products and reports

Date	Title	Description
Sept 3, 2019	Minutes from the project kick-off meeting	Minutes from the project kick-off meeting, including appendixes: 1. List of participants 2. Final kick-off workshop agenda. 3. Workshop presentations 4. Questionnaire on models and required input datasets.
Sept 18, 2019	FFWS Morava - IT Specs.docx	Memo with required specifications for IT
Oct 14, 2019	Minutes from the project Inception Workshop	Minutes from the project Inception Workshop and pre-release 0.1, including appendixes: 1. List of participants 2. Adopted inception workshop agenda. 3. Workshop presentations
Nov 6, 2019	IT reports	IT AdminManual-201902.pdf IT Morava-prod.pdf IT Morava-test.pdf
Nov 18-22, 2019	Notes working sessions week of November 18	Minutes from the various working sessions in the week prior to the release 0.2
Nov 22, 2019	Minutes – V. Morava FFWS 0.2 Delivery Workshop	Minutes from the Pre-release 0.2 workshop, including appendixes: 1. Notes of the joint 4-day working session 2. List of participants 3. Workshop Agenda 4. Workshop presentations
Dec 20, 2019	FFWS Morava - proposal for reservoir modelling R1.0.pdf	Discussion document to come to approach for reservoir modelling
Dec 24, 2019	Minutes – V. Morava FFWS R-1.0 Workshop preliminary	Minutes from the Release 1.0 workshop, including appendixes: 1. Notes of one-day working session held on December 19 2. List of participants (available, attached) 3. Workshop Agenda 4. Workshop presentations
Jan 8, 2020	Minutes webinar Jan 8	Minutes are sent in form of e-mail
Jan 15, 2020	Minutes webinar Jan 15	Minutes are sent in form of e-mail
Jan 29, 2020	Minutes webinar Jan 29	Minutes are sent in form of e-mail
Febr 6, 2020	Minutes webinar Febr 5	Minutes are sent in form of e-mail
Febr 12, 2020	FFWS Morava - proposal additional trainings.docx	Proposal for additional trainings, as action from the Release 1 workshop
March 4, 2020	Minutes webinar Febr 19, Febr 26	Minutes are sent in form of e-mail
March 13, 2020	Minutes webinar March 11	Minutes are sent in form of e-mail
March 31, 2020	HEC-HMS Hydrological Modelling Report 2.0	
March 31, 2020	Wflow_sbm modelling report	
March 31, 2020	FFWS Configuration report	
March 31, 2020	FFWS User Manual	
March 31, 2020	Final Report	

4 Gap Analysis

4.1 Introduction

As per the project ToR, the principal objective of the project was to build hydrological models that support flood forecasting embedded into a real-time operational forecasting platform. The Consultant has developed, calibrated and verified a semi-distributed HEC-HMS model, as well as a fully distributed Wflow_sbm hydrological model for the Velika Morava catchment. These models are integrated in an independent Delft-FEWS client-server application hosted at the RHMSS in a Test and Production environment, fed with all the available real-time observations from the RHMSS WISKI database, csv files and deterministic and ensemble Numerical Weather Prediction models.

Based on analysis and a thorough testing of the VM-FFWS system during the project implementation, new insight and experience have been gained regarding the system performance and its shortcomings, thus providing input for consideration of its future improvements. The detailed gap analysis in Appendix A describes the technical aspects of the identified potential improvements, covering the following key components: meteorological and hydrological data, hydrological and in particular hydraulic simulation models, training and support & maintenance. The focus of the analysis is primarily on the processes and data leading towards as accurate as possible forecasts and warnings. The rules and procedures for dissemination of forecasts and warnings are beyond the scope of the project and hence not part of this analysis.

4.2 Results of the Gap Analysis

As described in detail in appendix A, several topics for additional features and/or knowledge have been identified. These topics have been summarized in Table 4-1. The complete details are in the appendix.

Note that the budget estimations are an indication. Next to that, the possible costs for activities which have to be done by RHMSS cannot be estimated.

Table 4-1 Summary of Gap Analysis recommendations

Topic	Recommendations (see details in Appendix A)	Budget estimate
1. Hydrological and Meteorological Data	<ol style="list-style-type: none">1.1. Improve density and spatial coverage of rainfall network1.2. Improve quality of the network (robustness)1.3. Improve water level recordings1.4. Improve rating curves at hydrological stations1.5. Improve temporal resolution to hourly values1.6. Increase the number of hydrological stations1.7. Provide information about real-time reservoir releases1.8. Secure that the hydrological stations are (i) located close downstream of the selected reservoirs; and (ii) provide real-time river flow data.1.9. Enhance the data on snow processes	p.m.
2. Hydrological modelling	<ol style="list-style-type: none">2.1. Improve air temperature data (for snow melt & accumulation)2.2. Include snow water equivalent (for comparison with model results)2.3. Include soil moisture data (for comparison with model results)2.4. Update hydrological model parameters after installation of the additional precipitation and air temperature gauges2.5. Update reservoir modelling	€ 50k

Topic	3.1. Recommendations	Budget estimate
3. Hydraulic modelling	3.2. Terrain surveys of the river cross-sections. 3.3. Topographic surveys of adjacent overbanks and river structures/bridges. 3.4. Develop and add hydraulic model, either one for the entire river network, or limited to the downstream river reaches and sections at the forecast locations of the hydrological model. Recommended river reaches are from Miločaj and Korvingrad downstream to Ljubičevski most.	€ 30k + additional data surveys
4. Flood Forecasting Platform	4.1. Model State Updating 4.2. Predictive uncertainties. 4.3. Dissemination and report preparations.	€ 55k
5. Training and Capacity Building	5.1. FFWS user training 5.2. FFWS Configuration training 5.3. FFWS Admin training 5.4. HEC-HMS modelling training 5.5. Wflow_sbm modelling training	€ 10-60k
6. Support and Maintenance	6.1. Support and Maintenance contract on Delft-FEWS software and the VM_FFWS configuration and operation	€ 20-25k

5 Conclusions and Recommendations

5.1 Conclusions

The project – Development of Flood Forecasting Model for the Velika Morava River Basin (VM-FFWS project) – was initiated at the project kick-off meeting, held on August 29, 2019, at the Republic Hydrometeorological Service of Serbia (RHMSS) in Belgrade.

During the inception phase, focus of the project was on collection and thorough analysis of available data, clarification of modelling approach and other technical and organizational issues that had to be clarified and included into a detailed inception report of the project. The inception phase ended up at the Inception Workshop – held on October 10, 2019, at the RHMSS in Belgrade. The workshop reviewed the findings and solutions presented in the report, clarified issues, endorsed the report, and agreed on the workplan to be executed during the remaining project period.

The period after the project inception workshop witnessed a number of activities, carried out by the Consultant and the RHMSS project team and also jointly in the period November 18-21, 2019, which eventually led to the delivery of the Velika Morava FFWS Pre-release 0.2 (Morava FFWS PR02) at the workshop held on Friday, November 22, 2019.

In the period after November 22, 2019, significant tasks had been accomplished, focusing on additional analysis of the available data, preparation of data in the form adequate for model input, and in particular on calibration and verification of the HEC-HMS and the Wflow_sbm models.

These efforts have eventually resulted in delivery of the key project output – the Velika Morava FFWS Release 1.0 – during the joint working session that took place on December 19th, 2019, and the subsequent R 1.0 Delivery Workshop, held the following day, i.e. on December 20th, 2019, at the RHMSS in Belgrade.

From the December Workshop onwards, the designated RHMSS team was able to operationally use and systematically test the system and its potential for real-time hydrological forecasting in the Velika Morava River Basin (VMRB). Owing to a sustained effort of the whole RHMSS team, a number of suggestions for additional fine tuning and improvements of the Release 1.0 has been suggested and subsequently implemented in the final VM-FFWS Release 2.0 (installed March 2020) and as such accepted by the RHMSS, the Water Directorate of Ministry of Agriculture, Forestry and Water Management, and the World Bank.

5.2 Recommendations

A Gap Analysis has been performed to identify potential improvements and to come up with recommendations for future use, maintenance and further development of the system. These recommendations are as follows:

1. Operational use

It is recommended to use the VM-FFWS for real-time hydrological forecasting in the basin and to build up experience in general with the forecasting performance of the models at each of the forecasting locations.

2. Hydrological and Meteorological Data

The current system suffers sometimes from a lack of adequate good quality data. Therefore, it is strongly recommended to improve the hydrological and meteorological monitoring network in the WBRB. Regarding the hydrological data, there is in particular a need for additional discharge measurements, especially at the locations immediately downstream of the significant reservoirs.

As there is evident a poor quality of hydrological data at hydrological stations Miločaj, Kratovska stena and Niš in the operation period since September 2019, it is recommended to improve water level recordings and rating curves at these stations. From a meteorological point of view, there is a need for a much denser network of hourly automatic rain and air temperature gauges. Since the runoff in the Velika Morava basin is highly sensitive to snow melt it is particularly recommended to improve air temperature data (for snow melt & accumulation) in winter period, include snow water equivalent (for comparison with model results) and include soil moisture data (for comparison with model results). This will also improve the quality of the input data into the hydrological model and, consequently, the accuracy and reliability of the model results.

3. Hydrological modelling

Some forecasting stations show problems in the winter flood peak and recession which is the result of inadequate snow modelling and inadequate input data. For the improvement of current HEC-HMS and Wflow_sbm operational performance the more adequate input precipitation and air temperature data in winter period is recommended together with the implementation of data validation (such as spatial homogeneity checks with neighbouring stations). Hydrological model parameters should be updated after the installation of additional precipitation and air temperature gauges. The reservoir operational modelling should be updated after the collection of reservoir operation rules and discharge data.

4. Hydraulic modelling

The current hydrological models can at times overestimate the peak flow values which is the case in the downstream reaches of the Južna, Zapadna and Velika Morava rivers during flood events. The flow in rivers is currently routed in a simpler manner by using hydrological routing methods (Muskingum method, kinematic wave, etc.) which are not able to account for lateral flow dispersion in wide floodplains of downstream reaches. For the improvement of the forecasting system it is recommended to develop hydraulic models on the Zapadna Morava river downstream from Miločaj, on the Južna Morava downstream from Korvingrad and on the entire Velika Morava river. Information on river bed, adjacent overbanks and river structures/bridges should be initially collected on the basis of surveys of the river cross-sections and topographic surveys.

5. Flood Forecasting Platform

On the operational use of hydrological models, it is always important to ensure that the model meets the current conditions. During the last years, new computational techniques offer possibility to apply so-called Model State Updating, which improves the model performance significantly, especially for relatively unknown processes like snow melting.

On the other side, one can handle this unknown aspect also by identifying the so-called predictive uncertainties: in that case the forecasting error is estimated based on historical analysis. This technique is also very useful for communicating forecast results.

That brings to the last recommendation, where currently no “products” are provided by the VM-FFWS: the system could easily support dissemination of forecasts through reports on the web etc.

6. Training and Capacity Building

Given the limited training opportunities during the project implementation phase, usage of the system with respect to forecast accuracy, data analysis, efficiency, maintenance and sustainability can be optimized by facilitating dedicated courses to different user groups. It is strongly recommended to bring the hydrological forecasting to a higher level through various trainings.

7. Support and Maintenance

It is recommended to come to a Support and Maintenance contract on the Delft-FEWS software, the FFWS configuration and also the modelling software HEC-HMS and Wflow and the hydrological models.

The FFWS will then be regularly updated for using the latest software versions and (security) patches. Next to that, the RHMSS will be supported in small developments and other possible questions.

5.3 Concluding Remarks

It is with great pleasure to put on record that it was indeed a rewarding experience for the Consultant to work on implementation of the Velika Morava Flood Forecasting and Warning project, owing first of all, to an excellent cooperation and a sustained effort, throughout the project implementation period, of the RHMSS and its designated project team. The cooperative spirit of all involved in the project at national level and the pervading friendly working atmosphere had a significant impact on the project implementation and greatly contributed to its overall success.

It is with a great regret that, due to the unprecedented life-threatening circumstances created by coronavirus in the whole world, it was not possible to hand over the final project outputs, the VM_FFWS Release 2.0 and the accompanying reports, at the concluding Delivery Workshop at the RHMSS in Belgrade, as originally planned. Instead it will be arranged through a teleconference, but the Consultant stands ready, once the pandemic is over, to continue assisting the RHMSS colleagues in using and improving further the established VM_FFWS.

At this moment, the most important is to save lives and get over the coronavirus pandemic in Europe and the whole world.

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A Detailed Gap Analysis

A.1 Introduction

A.1.1 Scope of the Gap Analysis

This appendix describes the gap analysis of the project 'Flood Forecasting and Warning System for the Velika Morava River Basin in Serbia' (FFWS Velika Morava).

As per the project ToR, the principal objective of the project was to build a hydrological model that supports flood forecasting embedded in a real-time operational platform. The Consultant has developed, calibrated and verified a semi-distributed HEC-HMS model, as well as a fully distributed Wflow_sbm hydrological model for the Velika Morava catchment. These models are integrated in an independent Delft-FEWS client-server application hosted at the RHMSS in a Test and Production environment, fed with real-time observations from the RHMSS WISKI database, csv files and deterministic and ensemble Numerical Weather Prediction models.

The Delft-FEWS open data and model platform is essentially a sophisticated collection of software modules designed for building a hydrological forecasting system customized to suit the specific user requirements. The target user group of the FFWS Velika Morava are the dedicated RHMSS specialists responsible for flood forecasting in the Velika Morava catchment.

Based on the ToR analysis and a thorough testing of the system during the project implementation, new insight and experience have been gained regarding the system performance and its shortcomings, providing input for consideration of its future improvements. The gap analysis describes the technical aspects of the identified potential improvements, covering the following key components: meteorological and hydrological data, hydrological and in particular hydraulic simulation models, training and support & maintenance. The focus of the analysis is primarily on the processes and data leading towards as accurate as possible forecasts and warnings. The rules and procedures for dissemination of forecasts and warnings are beyond the scope of the project and hence not part of this analysis.

A.1.2 Characteristics of a mature forecasting system

The FFWS Velika Morava as delivered represents a good framework which integrates in one platform the available data and hydrological models for the Velika Morava basin. As such, it provides a versatile and flexible system which enables easy integration of new (or improved) models and/or new data (for example new measurement locations, weather predictions, radar data, etc.) whenever they become available in the future.

There is always necessity and room for improvement of any forecasting system in the world, and the FFWS Velika Morava developed within this project is no exception. When it comes to early warning systems, sustainable maintenance of the system is essential as measurement locations, rating curves etc will change and models will improve in future. These changes should be implemented in the system accordingly. Depending on requirements of the end users, different modules of the system can always be further refined or improved. Perfect is the enemy of good – but let's consider what makes the given forecasting system a good and mature system.

The WMO (2011) issued a separate manual on flood forecasting and warning. As stated in this publication, there are no hard and fast rules regarding the provision of lead time (timeliness) for warnings.

Lead times are dependent not only on the appropriate action related to the flood warning, but also to the type and accuracy of information available. In the FFWS Velika Morava the meteo forecasts are used as input to the hydrological, which form the basis for the flood warning based on hydrological forecast that discharge/water level will exceed the established threshold value. As such, the accuracy of the forecasts and its performance with respect to correct, false and missed alarms depends on three main aspects:

- 1 Accuracy of meteorological forecast;
- 2 Accuracy of hydrological/hydraulic model and thus flood forecast.
- 3 Availability of timely and accurate reservoir releases

A.1.3 Roadmap towards more accurate forecasts within the V. Morava FFWS

As stated above, the FFWS Velika Morava as delivered within the project represents a good framework for integrating available data and models for the Velika Morava basin. Flood early warning represents a chain: starting from observed meteorological and hydrological data proceeding towards hydrological forecasting variables through use of hydrological and potentially hydraulic models and setting up the correct threshold levels in order to retrieve operational warnings. As an early warning is an operational system, it needs to be operational 24/7/365. Retrieving accurate warnings (high performance skills), preferably for a long lead-time, sets requirements on forecast accuracy but also on computational times, characteristics, quality and stability of the models included in the system.

As discussed during the Release 1.0 workshop, further expansion and improvement of the FFWS Velika Morava should be focused on the following components:

- Inclusion of an adequate hydraulic model into the system;
- In-depth training of the RHMSS specialists on major aspects of use and further enhancements of the installed system;
- Ingestion of additional real-time data, from the new telemetry stations that are currently being implemented by the RHMSS and expected to become operational in the near future;
- Further expansion of real-time monitoring network, with particular emphasis on stations with sensors for measurement of precipitation in both the warm and the cold season, air temperature, and on establishing new hydrological stations close downstream of all the significant reservoirs in the basin;
- Recalibration and update of the two hydrological models after the expansion of precipitation and air temperature gauges.

These, and some other enhancements of the V. Morava FFWS, will be described in more detail in the following chapters.

A.2 Hydrological and Meteorological Data

A.2.1 Current Status

The HEC-HMS and Wflow_sbm models are calibrated and verified using available historical hydrological and meteorological time series for discharge, precipitation and air temperature, and thereafter forced by generated/forecasted precipitation and air temperature data. Accuracy of the generated/forecasted precipitation and air temperatures strongly depend on hourly and/or daily values, real-time measured at the meteorological stations in the basin. Real-time meteorological and hydrological data as well as NWP products, radar and other data within the V. Morava FFWS are retrieved from (amongst others) the WISKI database at RHMSS or imported as files.

A.2.1.1. Hydrological data

There are 94 hydrological gauges within the system, of which 45 currently report real-time hourly data for water level and 42 for discharge. See Figure A- 1 below, where locations with light or dark red crosses represent stations without current active data feed to the WISKI database.

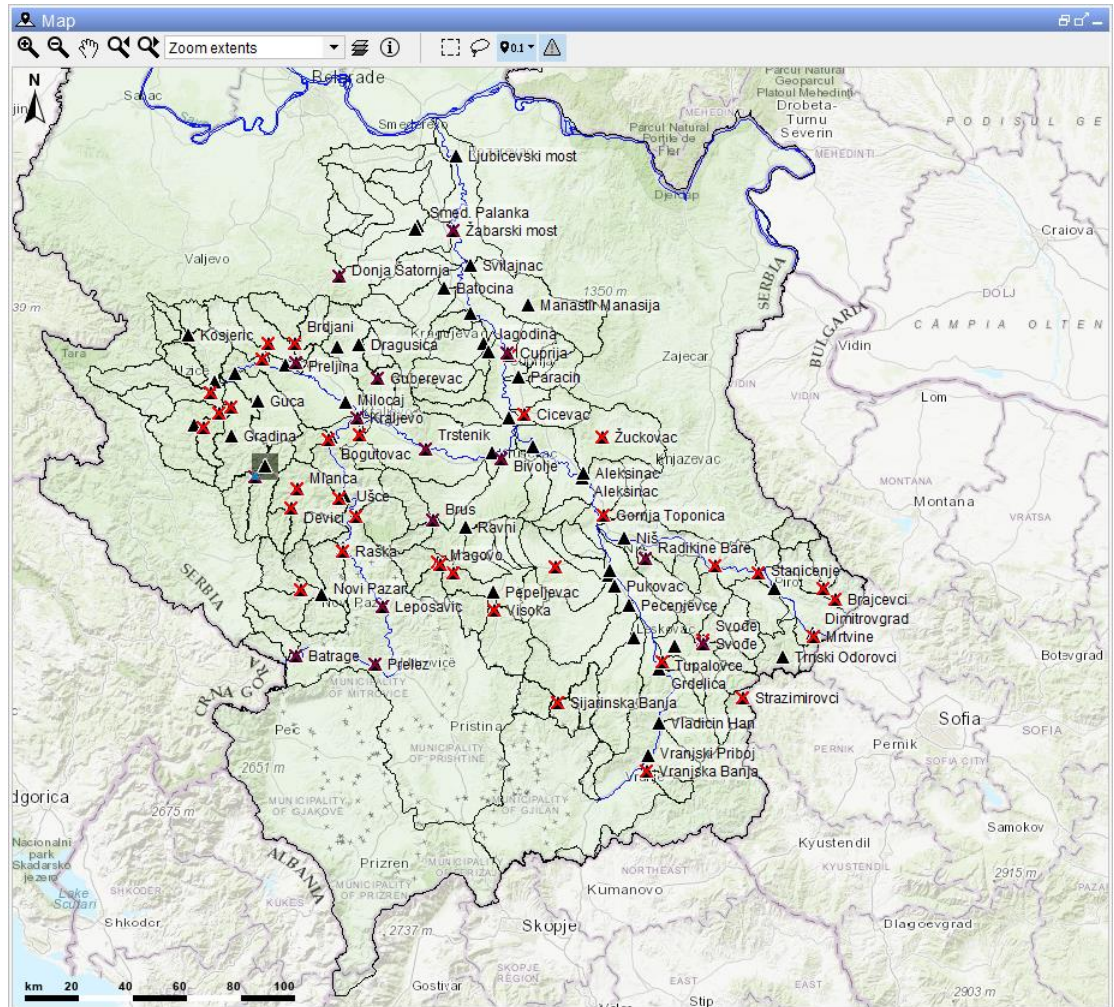


Figure A- 1 Overview of hydro gauges as available currently in the Delft-FEWS Velika Morava system. The icons without the red cross represent stations that retrieve real-time data from the WISKI database

The following forecasting locations also have an inactive data feed for their observations: Bela Palanka, Cuprija and Prokuplje.

The reservoir modelling in the system for the 11 selected reservoirs is only moderately satisfactory due to the limited reservoir data availability but could be improved if the reservoir operating rules are known, or if, at the very least, the hydrological stations located downstream of the reservoirs have an active data feed. See for more details the memo on modelling of reservoirs.

A.2.1.2. Meteorological data

Meteorological gauge data is retrieved from WISKI and several csv files. See Table A-1 for an overview.

Table A- 1 Overview status of meteorological station data feeds

Source	Nr of locations	Type	Parameters	Status
Meteo - wiski	8	Wiski	P,T	OK
Meteo – PMS	13	CSV	P,T	OK, but precipitation stations not heated and therefore unreliable in winter
Meteo – AWS	8	CSV	P,T	Only 4 active precipitation stations, not heated and therefore unreliable in winter
Meteo – ARG	3	CSV	P	Only 1 active precipitation station, but not heated and therefore unreliable in winter
Meteo – Daily	234	CSV	P	120 active precipitation stations

The availability of hourly and daily real-time data is also visible in the two maps below. Absence of observations in the Ibar sub-catchment is clearly visible.

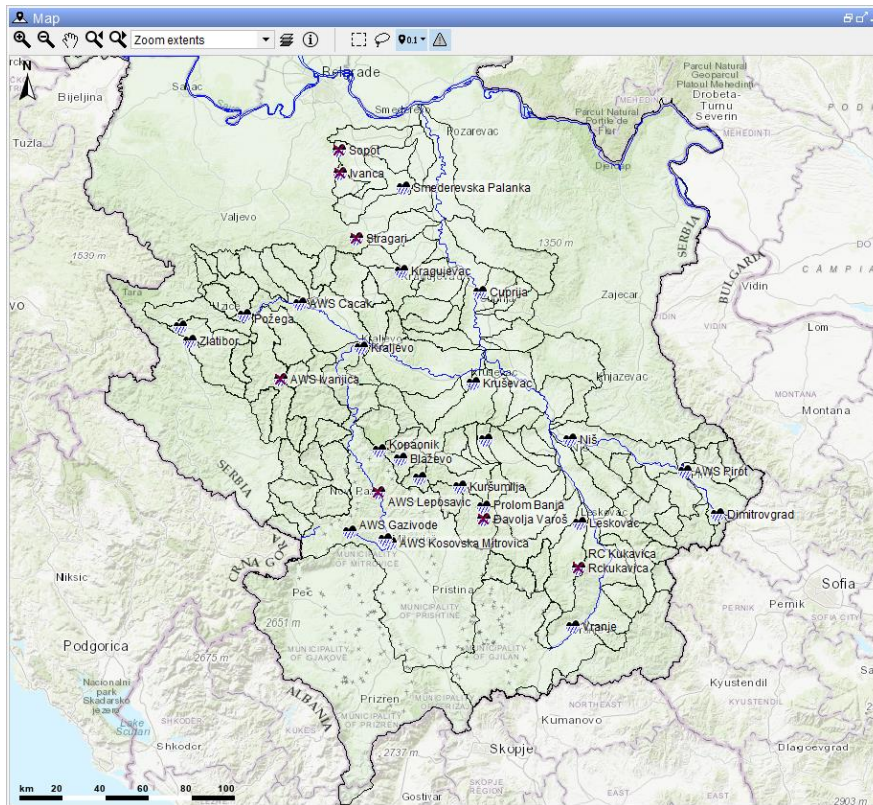


Figure A- 2 hourly observed meteorological data, where dark-red crosses indicate stations without active data feed

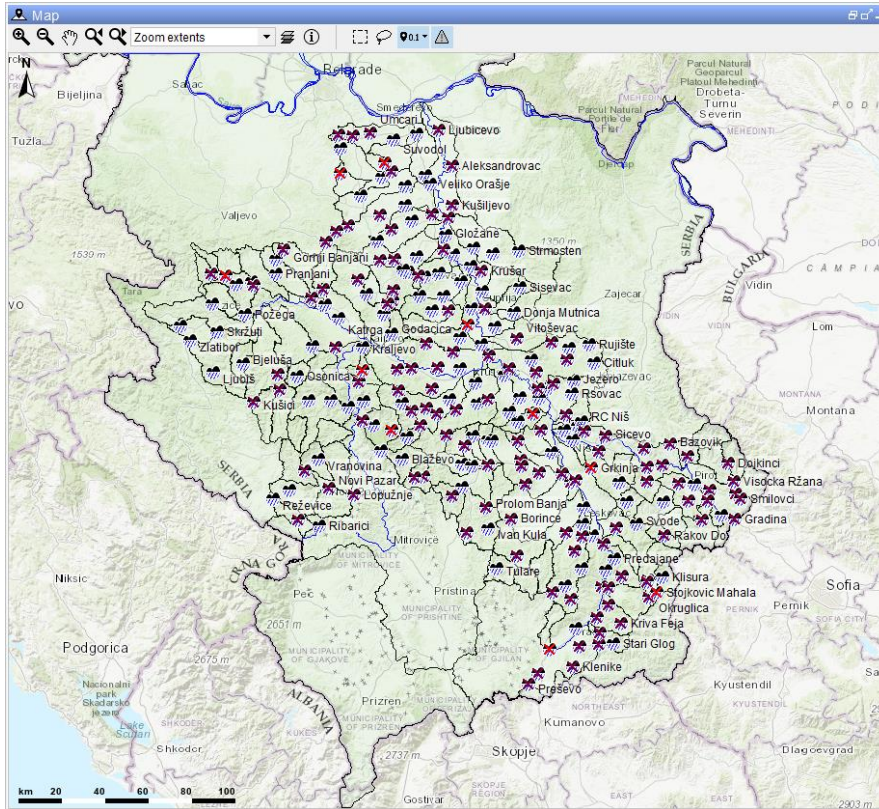


Figure A- 3 daily observed meteorological data, where dark-red crosses indicate stations without active data feed

There are 8 stations available in WISKI that have hourly precipitation data. Of these locations, Blaževo, Donja Bresnica, Lukovska banja, Šljivovica and Prolom Banja currently also include air temperature data. Furthermore, there are 13 Principal Meteorological Stations (PMS) and 8 AWS stations that retrieve real-time hourly data from a CSV file format data feed. However, these stations are not equipped with heater, and precipitation values in the winter season cannot be trusted, as concluded in the Inception Report. See, for example, the graphs for station Vranje where daily and hourly observed precipitation records are compared for monthly accumulations. The blue bars in the graphs represent monthly accumulated daily observations. The selected bold black lined bars represent monthly accumulated hourly observations

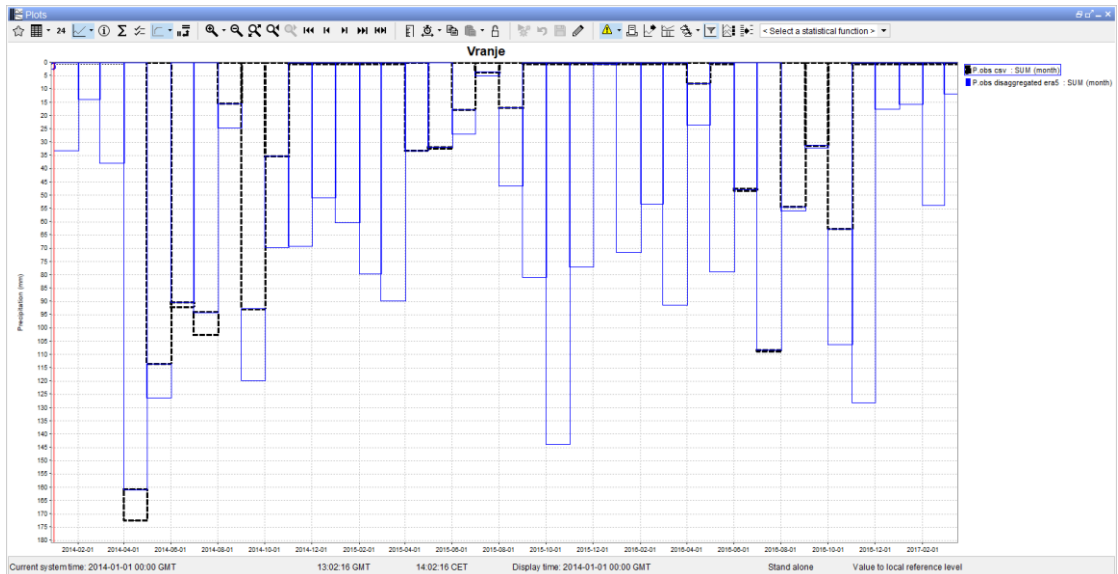


Figure A- 4 comparison for meteorological station Vranje where daily and hourly observed precipitation records are compared for monthly accumulations. The blue bars in the graphs represent monthly accumulated daily observations. The selected bold black lined bars represent monthly accumulated data

In the model pre-processing, the daily precipitation observations are disaggregated to hourly values. From the 234 available stations, 120 of them have an active data feed.

A.2.2 Gap Analysis and recommendations

Adequate network density and improved quantity and quality of the observed meteorological and hydrological data lead to better hydrological forecasts. As stated in the previous chapter, roughly half of the hydrological and meteorological stations in the Velika Morava basin actually report real-time data available to RHMS, of which most of the hourly precipitation stations are not heated and therefore report unreliable precipitation data in the winter season.

To fill the gap, the following recommendations are made:

- Improve density of the hourly and daily in-situ rainfall observing network (especially in the Ibar sub-catchments);
- Improve quality of the network by using robust equipment, including heaters, with telemetry connection to the RHMS central systems that feed the WISKI database;
- Improve temporal resolution of the observing network such that all stations eventually measure and log hourly instead of daily values;
- Increase the number of hydrological stations with an active data feed, especially the three forecasting locations indicated above (Bela Palanka, Cuprija and Prokuplje);
- Include real-time data for the stations located downstream of selected reservoirs: Batrage, Šengolj, Bivolje, Vranjska Banja, Dragušica and Borač;
- For the selected 11 reservoirs, provide information about real-time reservoir releases or reservoir operating rules for improved reservoir modelling and better performance of the V. Morava FFWS;
- At the very least, secure that the hydrological stations are (i) located close downstream of the selected reservoirs; and (ii) provide real-time river flow data.

Since the two selected models are sensitive to snow melt (see Chapter A.3), recommendations are also made related to improvement of the air temperature observing network, which is in particular important during winter season:

- Improve air temperature data (for snow melt & accumulation);
- Include snow water equivalent (for comparison with model results);
- Include soil moisture data (for comparison with model results).

Note that all the above-mentioned recommendations mainly refer to securing better and more reliable data. It is of interest to be stressed that even though the most important actions have to be taken outside of the Velika Morava FFWS, they will have a significant impact on the system performance, i.e. on accuracy and reliability of hydrological forecasts and warnings in the Velika Morava river basin.

Since the actions are mostly outside of the Velika Morava FFWS, an estimate of the costs for the amount of work cannot be provided here.

A.3 Hydrological modelling

A.3.1 Current status

The current HEC-HMS and Wflow_sbm modelling results are promising, even though there is no doubt they could further be improved providing more adequate data are available. Several statistical measures are derived from the 2010-2018 calibration period, as can be seen in the associated modelling reports. However, there is always room for improvement. Some stations show problems in the winter flood peak recession, conceivably as a result of the inadequate snow modelling (see Figure A-5), which strongly relates to the input data. In the case of the Nisava river basin, it is also possible that the problems arise due to: (a) the karst phenomena present in the catchment ; (b) the HPP Pirost operation; and (c) the unaccounted for water extraction in the Bulgarian part of the catchment.

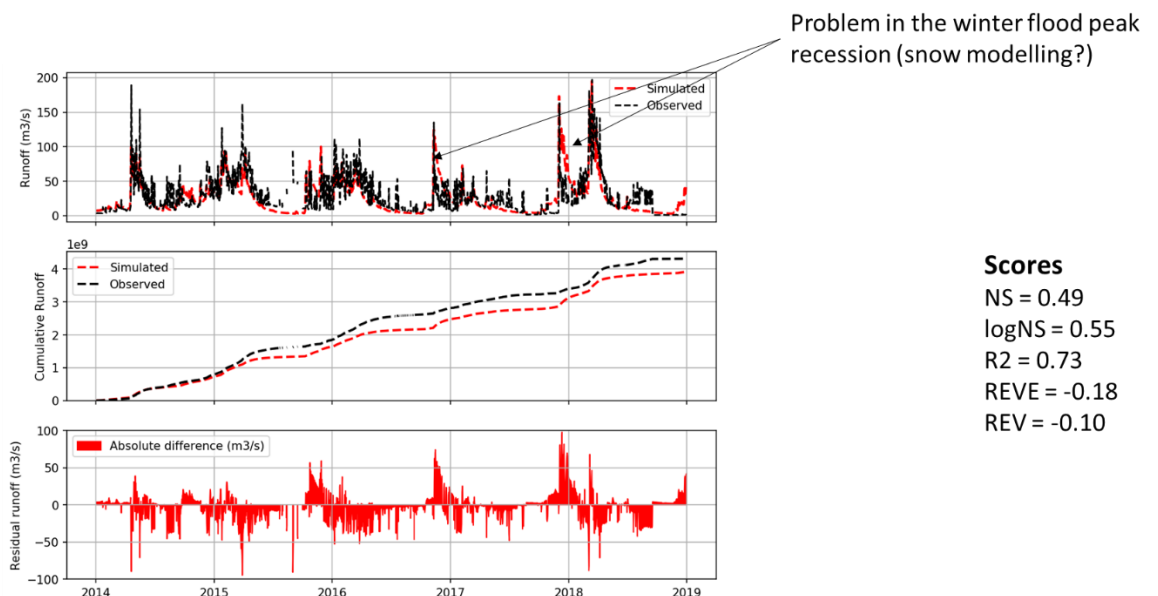


Figure A- 5 Flow calibration results for Nisava location Bela Palanka, indicating problems in winter flood peak recession likely due to snow modelling

Another sensitive element we learned is concerned with sensitivity of the initial model states. Spinning up the model carefully from dry states at the end of the summer season is important.

The current model adapters do not facilitate manual or automatic state updating using real-time hydrological observations at gauge stations.

A.3.2 Gap Analysis and recommendations

Since the models are sensitive to snow melt, recommendations are also made related to improvement of the air temperature observing network in case of snow conditions.

Other recommendations are:

- Based on the forecasters' experience in operational use of the system, analyse at each individual forecasting location what follow up actions, procedures or measures should be taken to fine-tune the system and improve further accuracy and reliability of real-time forecasts in the VMRB;
- Update reservoir modelling;
- Allow state or parameter interaction (manual data assimilation) to improve hydrological model state of for example snow water equivalent and soil moisture;
- Apply automatic data assimilation to improve hydrological model state. However, this should be balanced with the increase of computation times;
- Balance computation times and model quality. For ensemble runs, computational time of the hydrological models needs to be limited
- Improve data validation (especially rainfall) to improve input dataset for the hydrological models. This data validation should include spatial homogeneity checks with neighbouring stations. We have seen several issues with stations reporting precipitation data of reasonable amounts that actually did not exist at all
- Update hydrological model parameters after the installation of additional precipitation and air temperature gauges. Best insight into the VM_FFWS performance and capabilities can be gained through operational real-time use of the system by the RHMSS forecasters.

A rough estimate on the amount of work is set to 50,000 euro and would require 4 months to be implemented.

A.4 Hydraulic Model

A.4.1 Current Status

As stipulated in the project ToR, the current FFWS Velika Morava includes a hydrological model that translates precipitation into overland and base flow that are eventually discharged into the rivers. The flow in rivers in hydrological models is currently routed in a simpler manner using hydrological routing methods (Muskingum, kinematic wave, etc.). These methods are not able to account for lateral flow dispersion, as evident in the downstream reaches of the Južna, Zapadna and Velika Morava rivers. For this reason, the current hydrological models can at times overestimate peak flow values during flood periods, which is a direct consequence of the lateral flow dispersion in the low-laying downstream river reaches, characterized with wide floodplains. The forecasted river discharge is converted to water level at the forecasting locations using rating curves, and sometimes, due to use of simplified hydrological river flow routing method, can also overestimate water levels

A.4.2 Gap Analysis and recommendations

An improvement to the modelling chain within the V. Morava FFWS is to add a hydraulic model, either one for the entire river network, or limited to the downstream river reaches and sections at the forecast locations of the hydrological model.

There are several benefits of using a hydraulic model:

- A feature to check and validate the stage-discharge curve at gauging stations, especially for stations with limited discharge measurements at high and peak flows.
- Provides information on forecasted water levels (besides discharge) in the flood forecasting model at every cross section.
- Provides information on potential flood extent, i.e. flooded areas.
- Provide much better calculation of the peak flood attenuation and retention.

Introduction of the hydraulic models would need to include the information on river bed, adjacent overbanks and river structures/bridges and would be developed on the basis of surveys of the river cross-sections and topographic surveys. Calibration and verification of the hydraulic models will need to be based on comparison between computed and measured water levels at the hydrological stations.

For the improvement of the forecasting system it is recommended to develop hydraulic models on the following reaches:

- Zapadna Morava river
 - From Miločaj downstream to the confluence with the Južna Morava river
 - Approx. length 200 km
- Južna Morava river
 - From Korvingrad downstream to the confluence with the Zapadna Morava river
 - Approx. length 200 km
- Velika Morava
 - Entire river, from confluence of the Zapadna and the Južna Morava rivers to Ljubičevski most

A rough estimate on the amount of work is set to EUR 30.000,- which exclude costs for additional data surveys.

A.5 Flood Forecasting Platform

A.5.1 Current status

The FFWS Velika Morava uses the Delft-FEWS platform as its core. Delft-FEWS facilitates the real-time data management, processing, model execution, visualization and archiving functionality. Forecasters can interact with the data in FEWS, for example editing observations or adjusting precipitation and air temperature input to the models.

A.5.2 Gap Analysis and recommendations

A.5.2.1. Model State Updating

Currently there is no functionality configured to update parameters or initial states of the hydrological models, based on simulations drifting away from discharge observations. In several other Delft-FEWS applications, state updating is facilitated through either manual state updating modifiers, or automatic data assimilation based on Ensemble Kalman Filtering techniques. Both methods aim to improve the initial state of the model based on in-situ observations, therefore improving the accuracy of the forecasts.

Automatic model state updating can be implemented in Delft-FEWS using the open-source OpenDA platform. Manual state updating can be implemented through time series modifiers, where time series represent the actual state of the model in terms of, for example, snow water equivalent, soil moisture etc.

Delft-FEWS can export these time series to the model, which requires the model adapter to convert the information to native model file adjustments. For a lumped or semi-distributed model, the manual state updating through timeseries is possible from a practical point of view, for gridded distributed models like Wflow_sbm though the manual state updating should be limited to applying similar multiplication factors to all grid cells

A rough estimate on the amount of work is set to EUR 30.000,-.

A.5.2.2. Predictive uncertainties.

To reduce the uncertainty in the forecasted streamflow, we propose to use of meteorological forecast ensembles combined with a method called predictive uncertainty. The meteorological uncertainties are captured by an ensemble of weather forecasts, in this case the ECMWF Ensembles. Individual members are routed through the hydrological model, generating an ensemble of streamflow realizations. The statistical predictive uncertainty approach is used to dress a confidence band around the ARMA corrected streamflow ensemble traces. This band is a result of adding an estimate of model uncertainty to each individual streamflow ensemble member, where the estimate is based on an historical hindcast analysis in which daily streamflow forecasts are generated using perfect meteorological boundary conditions. In this way an estimate of the 'total uncertainty is produced that captures both the meteorological and hydrological uncertainties. The effort for adding this feature to the forecasting system includes the following activities:

- historical telemetry data collection and validation;
- running the hindcasts, typically over a period of some 5-10 years;
- performing the statistical analysis to derive the uncertainties;
- building the operational model for applying the uncertainties to the operational forecasts.

A rough estimate on the amount of work is set to € 15.000,-

A.5.2.3. Dissemination and report preparations.

Delft-FEWS offers sophisticated dissemination and report generation functionality that could be used to improve RHMSS's forecasting business. Examples are the use of web services, automatic emails, status reports or hydrology reports. The forecasts can be disseminated in the same way as of the Sava FFWS, so through the (rather basic) web viewer next to CSV files and webservices (providing for example in WaterML2 format). In case a more dedicated web viewer is required, that will be possible. In that case, we will build a similar web viewer as for Sava FFWS but extend that viewer with features like zooming in the graphs and status maps.

A rough estimate on the amount of work is set to € 10.000,-

A.6 Training and Capacity Building

A.6.1 Current status

Sustainability and capacity building are crucial features of any real-time flow forecasting system. Congruent to the project ToR, no explicit training courses were scoped and conducted during the project implementation. However, knowledge transfer was facilitated to some extent through the on-site visits, webinars and phone/email communication. Although the RHMSS specialists have some experience in using or maintaining Delft-FEWS systems, their skills in usage and maintenance of the system could further be optimized by providing dedicated courses to different user groups.

For the Velika Morava project we distinguish four target groups of users:

- 1 Modelers: people involved in modelling;
- 2 Daily operators: people who are responsible for creating and analyzing the forecasts, and the dissemination of warnings in the real-time system;
- 3 Configurators: people who configure the Delft-FEWS configuration to adapt or extend the system;
- 4 System administrators: people who maintain the system and solve IT related problems.

For ensuring a sustainable future use, maintenance and development of the system, it is strongly recommended to enhance current skills of the RHMSS users; raising their level of expertise and know-how is considered of vital importance for both short- and long-term sustainability of the V.Morava FFWS.

A.6.2 Recommendations

Given the limited training opportunities during the project implementation phase, usage of the system with respect to forecast accuracy, data analysis, efficiency, maintenance and sustainability can be optimized by facilitating dedicated courses to different user groups.

Goal of the training events is to impart to the attendees a solid understanding of the modelling concepts, schematization, limitations and obviously the usage of the FFWS. For the workshop and training the Delft-FEWS application in real-time mode (the Water Coach) will be used; this is an advanced training module of the Delft-FEWS system. Experience, in for example the Sava-FFWS, show that the FEWS Water Coach is a very efficient tool to train users in working with the system during a flood event under time critical conditions.

The following training sessions are recommended and – where possible - indicated with a priority and possibility for adding more topics.

A.6.2.1. Training in the FFWS usage and maintenance

- **FFWS user training**

The System Use training is designed to focus on enhancing the experience in using the Delft-FEWS system through each step of the forecasting process.

1st priority (1 day):

- How to import, validate, and edit data from WISKI and CSV data sources.
- How data can be visually assessed and modified prior to forecasting.
- Running HEC-HMS and Wflow_sbm from the Delft-FEWS interface.

2nd priority (1 day):

- Forecasting with the use of modifiers to influence the model run, both for model parameters and forcing meteorological data.
- Dissemination of forecasts

- **FFWS configuration training**

The System Configuration component will focus on how the FEWS is controlled, teaching participants the following components, among others.

1st priority (2 days):

- Use of xml files and schemas to control configuration.
- Configuration files of Delft-FEWS, overview and principles.
- Control of displays (spatial and graphical), with exercises.
- Layout of forecasting process, with exercise.
- Configuration of data import process, adding new imports (gridded and scalar)

2nd priority (1 day):

- Integrating HEC-HMS and Wflow_sbm models.
- Controlling modifiers of model runs.

- FFWS admin training (2 days)

In the System IT Admin training the installation, monitoring and maintenance of the Delft-FEWS back-end components are explained to RHMSS system administrators.

A.6.2.2. Training in understanding the hydrological models

- HEC-HMS model training

During this training the RHMSS staff will be trained on the next topics.

1st priority (2 days):

- General HMS modelling concepts.
- Specific modelling of the Velika Morava

2nd priority (2 days):

- More on specific modelling of the Velika Morava
- How to extend and/or improve the model

- Wflow_sbm model training

During this training the RHMSS staff will be trained on the next topics.

1st priority (2 days):

- General Wflow_sbm modelling concepts.
- Specific modelling of the Velika Morava

2nd priority (2 days):

- More on specific modelling of the Velika Morava
- How to extend and/or improve the model

The training sessions will be built on top of the existing User Manuals through a combination of class-room lectures and hands-on exercises.

All training courses will be conducted on-site at the RHMSS premises.

A.6.3 Budget and planning

The training sessions can be arranged directly after finalization of the implementation of the FFWS. It is actually recommended to plan the training events as soon as possible, to ensure smooth and uninterrupted operational forecasting processes within the Velika Morava FFWS. The training sessions will be planned in detail in cooperation with the RHMSS.

All prices are full totals, including training materials, travel expenses and DSA where applicable, but excluding any taxes.

The costs per training are listed in the table below. Any training can be selected, except that the 2nd priority course can only be selected when the respective 1st priority one is completed.

Moreover, the 2nd priority courses are assumed to be organized and conducted in the same week, subsequent to and immediately after the respective 1st priority course.

Table A- 2

Training	1 st priority	2 nd priority	Full training
1. User Training	€ 9 150	€ 4 750	€ 13 900
2. Configuration training	€ 9 150	€ 4 750	€ 13 900
3. Admin training	€ 3 950	€ 3 050	€ 7 000
4. HEC-HMS training	€ 6 350	€ 2 850	€ 9 200
5. Wflow_sbm training	€ 9 150	€ 4 750	€ 13 900
Totals	€ 37 750	€ 20 150	€ 57 900

A.7 Support and Maintenance

A.7.1 Current status

Implementation of the project on development of the real-time operational Velika Morava FFWS is reaching its completion date. It is paramount that an operational forecasting system with its many components should be monitored and maintained well during operations for reliability, accuracy and sustainability purposes. At this moment, there is no formal agreement in place between the RHMSS and the Deltares to support the FFWS Velika Morava and the RHMSS specialists when the implementation contract expires.

Note that a similar support and maintenance contract is setup for the Sava FFWS and planned to become active from March 2020 onwards.

A.7.2 Gap Analysis and recommendations

It is recommended that the RHMSS enter into a Support and Maintenance contract with the Deltares to provide longer term support services. User support covers issues related to operational forecasting within the Delft-FEWS platform. A Support and Maintenance typically includes one new release of the Delft-FEWS software per annum and a certain number of hours of support time. The RHMSS requested software enhancements and upgrades would normally be delivered in the Annual Release. Further detail on each component is provided in greater detail in this section.

Configuration and IT Support

Deltares offers a qualified knowledgeable support team, sufficient to support RHMSS implemented functionality. Our combined Help Desk support is available from 9:00 – 18:00 Central European Time, weekdays excluding holidays. Issues may be reported to the Help Desk by email or by phone. The support contact information may be updated by mutual consent via email exchange. In order to provide support, Deltares team members will need remote login access to the RHMSS systems and will need to be able to exchange data with RHMSS freely and without delay. This access is currently already facilitated.

Upon receipt by the Support Team of notice from RHMSS through the Help Desk of an error, defect, malfunction or nonconformity, in the covered software the Deltares team shall respond within timeframes based on the priority of the issue.

Table A- 3

Category	Description	Response time	Resolution time
1 - Fatal	No useful work can be done: The Delft-FEWS software is inoperable and no work around exists	4 hr	< 24 hr
2 - Significant Impact	Critical functionality is degraded: Errors that result in a lack of application functionality and or cause intermittent or unpredictable system failure, including degraded system performance	Next business day	24 hr
3 - Medium Impact	No loss of functionality: Minor bugs causing inconvenience, but a workaround exists.	3 days	To be agreed with RHSS
4 – Low Impact	Adaptations to already delivered features and functionality	5 days	Next release

The support hours may also be used for specialized services. Such services could include specific user and technical expert (IT) coaching as well as new software enhancements. Remote user and technical expert coaching will be arranged via GoToMeeting using a single web link and/or phone number. On-site user and technical expert training is described in Chapter A.6.

When an operational problem demands a Corrective Fix (bug fix) in the Delft-FEWS code, that cannot wait until the next FEWS stable build release, RHSS can ask Deltares to provide a FEWS Patch. A FEWS Patch will only include Corrective Fixes, no new software enhancements. Corrective Fixes refer only to those delivered initially in a Patch and subsequently integrated into a Stable Build. Other Corrective Fixes which are identified as moderate or lower urgency, and thus do not require a Patch, are to be addressed in the next annual stable release.

Annual Releases

As part of the Support and Maintenance agreement, the RHSS is eligible to receive a new stable release annually. Deltares conducts coordinated beta testing across multiple agencies to ensure the software is acceptable for operations.

A Delft-FEWS stable build release generally consists of:

- Functionality requested by multiple other clients
- All accumulated corrective fixes previously provided as part of a Delft-FEWS patch.
- Corrective fixes to existing Delft-FEWS functions which were not urgent enough to be provided as a Delft-FEWS patch. The number of corrective fixes to be included in a Stable build will be agreed between Deltares and RHSS and depends on any potential budgetary limitations to RHSS.
- Software enhancements requested by /to improve overall Delft-FEWS usability
- General release notes and RHSS specific release notes
- Remote Installation and updated system administration document, or update instructions.
- Configuration Update document which describes new configuration options required for new or changed software features

Software Enhancements

Software enhancements can be requested by RHMSS. The new development requirements will be discussed with RHMSS in detail and documents describing the requirements for the new functionality will be exchanged by e-mail. Before new features will be implemented, they will be discussed in detail in a meeting by our technical Delft-FEWS steering group. The outcome of this meeting is a common proposed implementation approach. RHMSS can then review the proposed implementation approach and decide whether or not to proceed with development. RHMSS will communicate approval to Deltares in writing. These enhancements will be identified and resourced as an add-on to the proposed standard maintenance and support.

Requested software enhancements may at times be introduced prior to the Annual release by means of a software patch. The decision for this and timing of these upgrades will be determined in consultation with the RHMSS and the technical Delft-FEWS steering group.

Budget Estimate

The yearly required budget for Support and Maintenance is estimated at € 20.000,-.

As it is recommended to add a yearly on-site visit of 1 week to the budget estimate which makes the total at € 25.000,-.

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