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Faculty of Geography
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DOCTORAL THESIS

- Summary-

Modeling a spatial decision support system for proactive flood control downstream of the Firiza reservoir dam in relation to upstream tributary floods

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CONTENTS

1. INTRODUCTION

Flooding is one of the most significant hydrological hazards, given its potential for lost lives and catastrophic socioeconomic impacts (Jonkman and Vrijling 2008). Over the past decade, the frequency of flooding has increased due to population growth and climate change worldwide (Wijayarathne et al. 2021; Zhang et al. 2018; Tol 2016; Pagano et al. 2014). In Romania, a country prone to floods (Figure 1), between 1960 and 2010, there were about 400 major floods, registering 237 victims (IGSU 2016). Flash flooding is responsible for more fatalities in the Romanian territory than any other convective storm-related phe- nomenon (Stancalie et al. 2008). Flash flooding can be triggered when a large amount of rain falls at a certain location in a short period of time. Torrential rain is key to the onset of flash flooding, but the drainage and topography of the surrounding area determine the scale and impact of the event (e.g., steep-sided valleys in the Carpathian Mountains, accentuated flooding by acting as funnels for the runoff) (Stancalie et al. 2008). During the past few years, significant urban floods such as the flash flood of 5 March 2001 in Baia Mare have increased the demand for flood mitigation measures in Romania aimed at minimizing dam- ages (Sabău et al. 2020).

Standard flood mitigation measures are divided into two main categories: structural and nonstructural measures (Wijayarathne et al. 2021; Thampapillai and Musgrave 1985). Flood forecasting and warning are recognized as the most important nonstructural flood damage reduction methods (Basawan 1980; Nafchi et al. 2021a). A flood forecasting system that can deliver accurate and reliable forecasts with appropriate lead time is a critical part of nonstructural flood management (Wijayarathne et al. 2021; Unduche et al. 2018; Nafchi et al. 2021b). According to the United Nations, flood damages can be reduced up to 35% if a flood is adequately forecasted in advance (Pilon 2002). Various flood forecasting systems with varying complexities are being used worldwide to predict floods in advance. Community Hydrologic Prediction System (CHPS) in the United States, European Flood Forecasting System (EFFS) in Europe, National Hydrological Forecasting and Modeling System (RONHFMS) and National Flash Flood Guidance system (RONFFG) in Romania (Ioana et al. 2020; Ramos 2016; Mătreață et al. 2013) are some of the examples. Hydrological and hydraulic models are critical parts of such flood forecasting systems (Teal and Allan 2017).

Hydrological and hydraulic modeling approaches were used to forecast river flows for real-time flood-control operation of river-reservoirs systems and flood extent over decades

(Wijayarathne et al. 2021; Wijayarathne and Coulibaly 2020; Awol 2020; Leach et al. 2018; Che and Mays 2015). These models represent different hydrological processes in the hydrologic cycle, such as precipitation, evapotranspiration (Talebmorad et al. 2020; Javadinejad et al. 2021), infiltration, interception and runoff, using a set of model parameters (Vanani et al. 2017; Derakhshannia et al. 2020; Ostad-Ali-Askari and Shayan 2021). Hydrological models calculate streamflow using inputs such as precipitation, temperature, soil moisture, and topography (Devia et al. 2015; Ostad-Ali-Askari and Shayannejad 2021; Shayannejad et al. 2022). Reservoir simulation and hydraulic models use the hydrological models' output for optimization of reservoir operations and inundation mapping (Aksoy et al. 2016; Nafchi et al. 2022). Among all meteorological inputs, precipitation is the primary forcing for hydrological models (Sabău et al. 2022; Ioana et al. 2020; Cho 2020; Devia et al. 2015; Ye et al. 2014). Therefore, the efficiency of flood forecasting systems where hydrological and hydraulic models are embedded is mainly determined by the accuracy and reliability of precipitation inputs (Wetterhall et al. 2011; Pappenberger and Buizza 2009; Ostad-Ali-Askari et al. 2017).

In watershed-scale hydrologic modeling, the required inputs of watershed characteristics (i.e., elevation, land use, soil, etc.) and precipitation data are readily available on various public websites, including the National Oceanic and Atmospheric Administration (NOAA), the National Weather Service (NWS) and the Advanced Hydrologic Predictions Service (AHPS) in the USA, which provide remotely sensed rainfall data such as the Weather Surveillance Radar–1988 Doppler (WSR-88D) which uses Next Generation Weather Radar (NEXRAD) radar-based quantitative precipitation estimations (QPEs) for weather and flash flood forecasts, etc. (NOAA 2020a, NOAA 2020b; Cho 2020). NEXRAD provides great opportunities to simulate hydrologic model processes enabling the use of grid-based spatially distributed precipitation instead of point-based rain gauge observations for non- uniform landscapes and storm events using a more realistic representation of their spatial distribution (Cho 2020; Kull and Feldman 1998; Peters and Easton 1996).

After the severe floods of the 1970s, Romania began to heavily invest in flood protection infrastructure creating a flood management system. Currently, the delays in maintenance work, as well as the incidence of structurally unsafe dams, are two of the major problems faced by the water management system in Romania (World Bank 2018).

As Romania is a territory with a high population density (often urban) living downstream of the important reservoirs with complex functions (Figure 1) and developed mainly based on proximity to water supplies while ensuring protection against floods; the need for global implementation of a decision support system (DSS) is highly important. The next step for Romania will be the implementation of an integrated water management system (IWMS) Until now, a series of studies have been carried out regarding the development of decision support systems (DSS) for different basins in Romania; however, to date none of them has been translated into practice (Adler et al. 2006; Popescu et al. 2012; Rata et al. 2016).

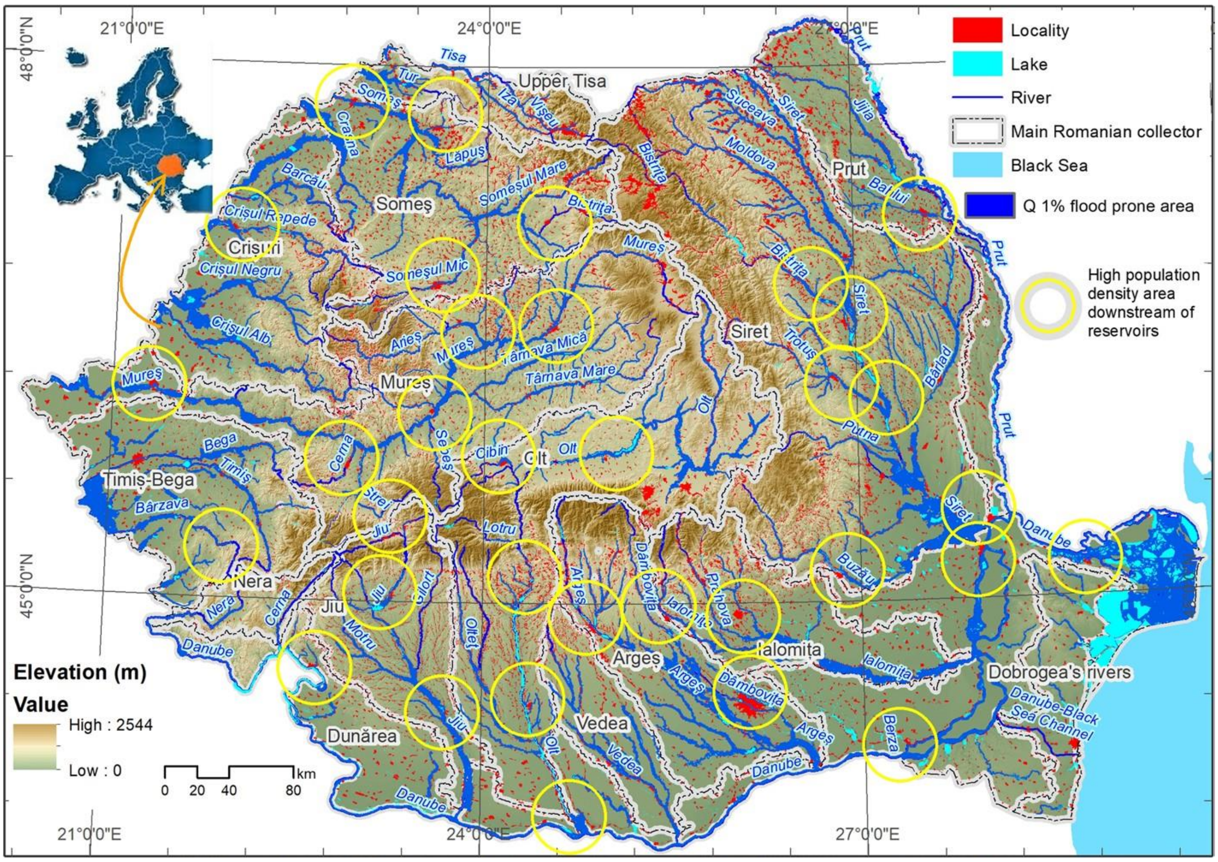

Figure 1. Location of the main Romanian urban agglomerations downstream of reservoirs with complex functions, reported to 1% probability of liquid flow, Flood Prone Areas (source of FPA: Romanian Waters National Administration, 2021; data sources: Digital Elevation Model over Europe, 2018 (adapted from Sabău et al., 2022b)

1.1. Research aim and objectives

This study aims to develop and adapt new methodologies to serve as the foundation of a new distributed hydrological model, an essential component of a decision support system (DSS) integrating GIS with hydraulic and hydrological applications. The main objectives are as follows: (1) to investigate the ability of hydrological modelling integrating quantitative precipitation forecasts (QPFs) and ensemble precipitation forecasts (EPFs) for stream flow forecasting and (2) to demonstrate the suitability of stream flow prediction for reservoir optimization using HEC-ResSim and associated hydraulic model inputs. For this purpose, a physically based distributed hydrological model was developed and used for analyzing two precipitation forecast scenarios. A methodology for developing the semi- distributed model and the application of gridded precipitation within HEC-HMS model outside of the regions covered by the hydrologic rainfall analysis projection (HRAP) and the standard hydrologic grid (SHG) grid systems is proposed. The process of adapting the methodologies for precipitation processing, loss and runoff transformation parameters for a Romanian basin is described. The model was calibrated using observed flows from Firiza gauging station, between 21 July–4 August 2017, 7–21 March 2018 for both wet and dry periods. Medium-range EPFs were used for determining the reservoir inflow 10-days in advance of reservoir inflow forecast. The optimization of reservoir release was examined in different scenarios of optimization using the 10-day inflow forecasts. The results of each forecast alternative were compared with measured values and were used as inflows for reservoir operations and inundation mapping scenarios. The methodology developed was applied for Strâmtori Dam (NW Romania), to highlight challenges and possible solutions for reservoir operation during a major flood event that occurred in 2001. The advantages of using the new methodology adapted to the Romanian context for the optimization of reservoirs in Romania is presented.

2. THE CURRENT STATE OF NATIONAL AND INTERNATIONAL RESEARCH

Conventionally, the areal rainfall is estimated by employing averaging methods (e.g., Thiessen polygon, etc.) to data obtained from (point) gauges. This method has been widely used for simulating the rainfall–runoff process in a watershed as it involves a relatively simple procedure compared to the complicated data processing associated with radar-based data.

However, due to precipitation heterogeneity across a broad spectrum of spatiotemporal scales, rain gauge observations most often represent only the local conditions and can result in potential errors when interpolated to larger scales, especially in areas characterized by complex terrain (Cho 2020; Michaelides 2019; Javadinejad et al. 2019). Thus, the spatial distribution of precipitation is not properly represented even if in situ rain gauge data exist, as rainfall can show extreme heterogeneity at watershed scale, with portions of watershed experiencing torrential rain while other areas record no precipitation during many precipitation events. The use of rain gauge data also causes difficulties relative to accurate simulation of rainfall–runoff processes and the calibration of watershed scale hydrologic models, as additional assumptions or parameters need to be employed for matching the observed and simulated runoff flows (Cho 2020; Cho et al. 2018; Cho and Engel 2017). Substantial differences occur between simulations based on grid-distributed versus spatially averaged rainfall if a storm has marked spatial variability, as is the case for a localized convective storm (Cho 2020; Zhang et al. 2004). Therefore, a hydrologic model that enables the use of radar-based high spatiotemporal resolution precipitation and the implementation of spatially distributed rainfall–runoff simulations needs to be developed in order to gain the advantage of flow computations with adequate temporal and fine spatial resolution data (Cho 2020).

HEC-HMS has been successfully applied widely for the analysis of flash floods in mountainous regions around the world (Xin et al. 2019; Yuan et al. 2019). Several authors have tried to implement a hydrological model for the forecast of runoff in the reservoirs basins, to be used as the first module for a future decision support system aimed at reducing the flooding risk downstream of dams (Srinivas et al. 2018; Yavuz et al. 2012; Haberlandt 2010). Among many hydrological models, HEC-HMS has evolved to address radar-based precipitation data for modeling a watershed on a grid level using the associated data processing software including HEC-GeoHMS, HEC-DSSVue, and HEC-GridUtil with advanced techniques (Bartles et al. 2022; Cho 2020; Fleming and Doan 2013; Steissberg and McPherson 2011; CEIWR-HEC 2009). Albeit limited, several pilot applications using NEXRAD QPEs were made for the Salt River, the Illinois River, and the Muskingum River in the USA (Cho 2020; Kull and Feldman 1998; Peters and Easton 1996; Kull et al. 1996; CEIWR-HEC 1996). In all of the above-mentioned cases, the ModClark algorithm, a modified version of the Clark unit hydrograph transformation (Cho 2020; Clark 1945; Sabol 1988) developed by HEC (Bartles et al. 2022), was adopted to accommodate for spatially distributed precipitation. This semi-distributed Clark model has also been adopted in many other studies with HEC-HMS (Cho 2020; Shakti et al. 2019; Yoo et al. 2016; Saleh et al. 2016; Anderson et al. 2002). For gridded precipitation data applications, Cho (2020) and Shakti et al. (2019) utilized the regional radar QPEs, whereas Pappenberger and Buizza (2009), Ye et al. (2014), Saleh et al. (2018) and Haiden et al. (2019), respectively, coupled the atmospheric model of the European Centre for Medium-Range Weather Forecasts (ECMWF). In Romania, mainly due to the described constraints, only limited efforts have been made for the evaluation of the influence of precipitation on the surface runoff and these include the simple simulation with the HEC-HMS lumped model of past singular extreme events (Strapazan and Petrut 2017; Gyori et al. 2013) and the adoption of the semi-distributed Clark model a simplified HEC-HMS-based study (Chitu et al. 2017). The direct use of these spatially distributed data sets (i.e., radar-based QPEs, ECMWF grid products) in hydrologic applications such as HEC-HMS is not without challenges, due to the requirements for a thorough understanding of the radar precipitation map system and georeferencing systems (e.g., coordinate transformations) as well as due to the complex procedures for obtaining the HEC-DSS file (Cho 2020; CEIWR-HEC 2009). In the USA, since the NEXRAD QPEs data set based on the Weather Surveillance Doppler Radar (WSR-88D) network adopts the Hydrologic Rainfall Analysis Project (HRAP) coordinate system to define the location of each estimated rainfall value, Cho 2020; Reed and Maidment 1999 developed a specified method for transforming HRAP grid cells into a coordinate system commonly used for mapping geographic information system (GIS) data to conduct HEC-HMS hydrologic modeling with gridded precipitation and other geospatial products. A standard hydrologic grid (SHG) whose map system is the Albers equal-area projection was proposed. Similarly, Xie et al. (2005) also introduced automated NEXRAD Stage III precipitation data processing approaches for GIS-based data integration and visualization using the standard coordinate system (Cho 2020). Nonetheless, the data processing for obtaining gridded rainfall inputs for the HEC-HMS applications is still challenging, as it can involve development of user-based computer script programs. This may cause the HEC-HMS model to be of limited use for some users, even before they reach the main hydrologic modeling process (Cho 2020). In some cases, the averaged data from point rainfall measurements employed for hydrologic simulation were used only with the ModClark algorithm (Cho 2020; Paudel et al. 2011; Ghavidelfar et al. 2011; Alexakis et al. 2014).

3. FIRIZA BASIN

3.1. Study area and context

The Firiza basin has a high level of urbanization along the last 14 km of the main water course, and this is expressed via the high density of houses, factories, and other infrastruc- ture, which were developed predominantly in the last century. The area has been exposed to floods, either as extended or flash flood events and these resulted in significant material damages. In particular, along the last 8 km, the river flows through Baia Mare, the county capital, which is a heavily urbanized area (pop. 140,000, Figure 2).

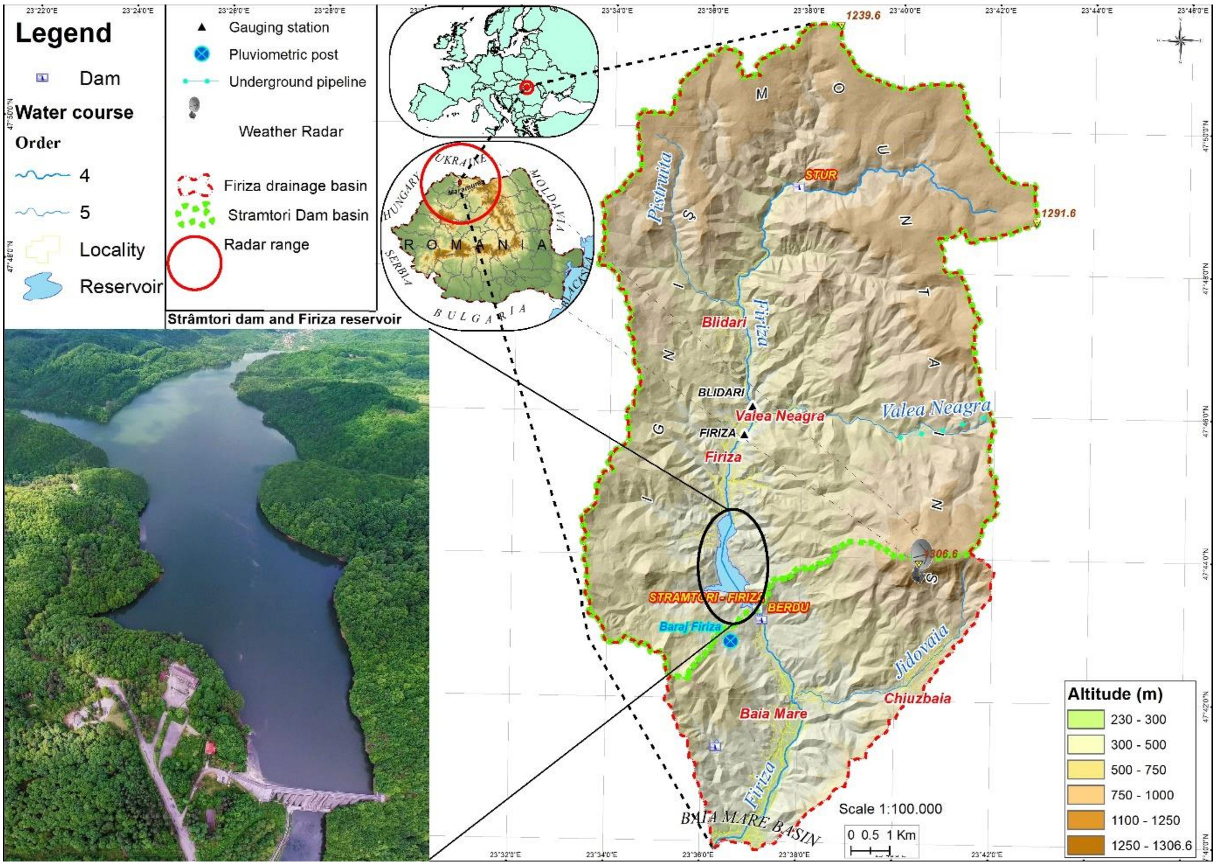

Figure 2. Geographical location of the studied basin (adapted from Sabău et al., 2022b)

The Strâmtori Dam was designed and built between 1960 and 1964, to allow for supplying of water for the Baia Mare city and the neighboring mining area, as well as for hydro-power production (Sabău et al. 2020). Strâmtori-Firiza reservoir has no dedicated volume for flood attenuation. The protection against flooding in the downstream area of Baia-Mare is assured only by the coordinated exploitation of the reservoir. Currently, the spillways (270 m^3/s flow installed) are the only solution available for flood protection. However, this flow limit is much higher than the 110 m^3/s limit, which is the threshold limit above which damage to the properties along the riparian areas will occur as indicated by the dam manager (pers.comm.).

Although there have been significant floods in the last decades (1970, 1995, 2001, 2005), resulting in significant damage, reaching ~ 6 million euros (Mustăţea 2005), the dam still lacks a forecast-based flood warning system (Sabău et al. 2020) for reducing the damage in the study case urban area (Table 1).

Table 1. Maximum flows with probabilities of exceeding for the most significant floods recorded in the Firiza basin (after the Someș-Tisa" Water Basin Administration, Cluj)

Gauging station	Q_0	1970			1993			1995			2001			2005		
	(m^3/s)	Q max (m^3/s)	Date	P (%)	Q max (m^3/s)	Date	P (%)	Q max (m^3/s)	Date	P (%)	Q max (m^3/s)	Date	P (%)	Q max (m^3/s)	Date	P (%)
Blidari	2.3	148	5/13/1970	2	79.3	12/21/1993	10	66.5	4/28/1995	12	106	3/5/2001	5	69.7	5/24/2005	11
Firiza	3.19	168	5/13/1970	3	100	12/21/1993	8	111	4/28/1995	7	150	3/5/2001	4	105	5/24/2005	8
Strâmtori Dam	4	199.9	5/13/1970	3	119	12/21/1993	8	132	4/28/1995	7	179	3/5/2001	4	124.9	5/24/2005	8

Baia Mare is located in a temperate continental climate, with the average annual values of precipitation in the Baia-Mare Depression of 892 mm; however, the annual precipitation amount can reach 1400 mm year−1 in the high mountain areas, where the slopes are exposed to the oceanic air masses (Sabău et al. 2022).

The mountainous landforms in the area are the main factor influencing the distribution of climatic parameters in the studied area. The elements that favor the occurrence of floods, especially the fast ones, are related to the physical-geographical and anthropogenic characteristics of the basin and the hydrographic network. The watercourses in the Firiza basin have specific features, such as very high average slopes, of torrential organisms. The spatial distribution of land use within the basin is shown in Figure 3, with the land cover being dominated by forests (~ 85% of the basin area), with the forests also playing a major role in regulating runoff in the basin. The artificial areas (urban, industrial, rural, etc.) represent ~ 3.38% of the basin area. The presence of Andisols reveals that the region belongs to volcanic mountains (Rusu et al. 2006).

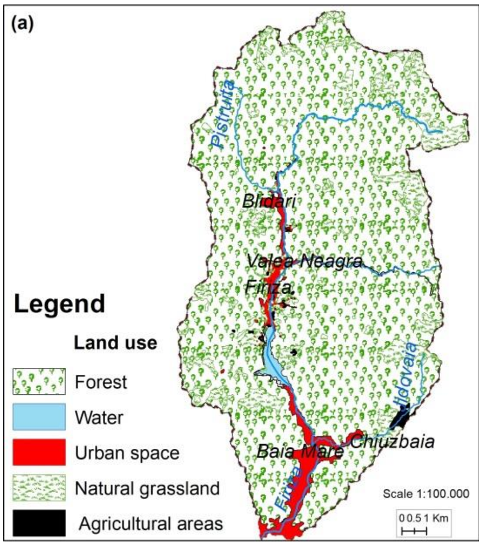

Figure 3. Land use in the study area (data source: Corine Land Cover, 2018; Soil Map of Romania, 1964-1998). (adapted from Sabău et al., 2022b)

4. CREATING THE DATABASE

In Romania, the availability of data regarding the characteristics of the basins is limited, with the bulk of the data being in non-digital format, not publicly available and in many cases outdated as most of the data has been produced between 1950 and 1980. In 2000, the Romanian National Institute of Meteorology and Hydrology (NIMH) started developing the first stage of the National Integrated Meteorological System (NIMS)—SIMIN project (Ioana et al. 2020) plan to modernize Romania's capabilities for detecting, monitoring and predicting meteorological and hydrological phenomena affecting Romania. SIMIN has concluded the transition of the Romanian weather radar network from exclusively manually operated and obsolete systems, to one of the most modern and unique radar networks in the world. SIMIN has installed modern WSR-98D S-band Doppler radar systems, to replace the obsolete 1960s era weather radars previously used and to complete the national network

(Ioana et al. 2020). The WSR-98D system manufactured by the Beijing Metstar Radar Co. Romania is based on the technology and meteorological algorithms developed over more than 30 years in the US NEXRAD network (Ioana et al. 2020).

After the historic floods registered in March of 2001 in Maramureş county, it was seen how vulnerable the county is in the activity of preventing and combating the effects of flash floods. In 2004, at 1307 m above sea level, on the peak of Ignis, a high-performance C-band radar from Gematronik (METEOR 500C type) was installed. The C-band METEOR 500C radar has been integrated into the SIMIN national radar network. Data from the C-band radar are converted to 88D/98D formats, to facilitate integration with all applications in the system. In recent years, the radar on the Igniş peak has gone through a system modernization process, with the transition to the dual polarization system.

A major update and renewal of the stream monitoring network within the basins open the way for a warning system based on the hydrological forecast (Table 2). Datasets on river flow and precipitation were obtained from the "Somes-Tisa" Water Basin Administration, Cluj (STWBA), and National Meteorological Administration (NMA) for the period 2012–2020.

Observed and statistical data on precipitation, temperature, evaporation, evapotranspiration (ET), snow layer, SWE, and runoff were processed for a series of calibration events. Data required for the flood forecast included the future meteorological conditions, precipitation (QPF), and temperature as shown in Table 2, 3. A reasonable range of model parameters was obtained through model calibration.

Table 2. Details regarding the hydrometeorological and hydrometric stations (after the"Someș-Tisa" Water Basin Administration, Cluj)

Station name	Administrator	Altitude (m)	Data frequency	Years of operation
Hydrometric stations				
Blidari	A.B.A.S.T	419.7	10 minute	1965-2023
Firiza	A.B.A.S.T	403.8	10 minute	1962-2023
Pluviometric and nivometric posts				
Baraj Firiza	A.B.A.S.T	435	12 ore	1964-2023
Vârful Igniș	A.B.A.S.T	1307	10 minute	2015-2023
Weather stations				
Baia-Mare	A.N.M	186	1 ora	1871-2023
Meteorological radars				
Igniș	A.B.A.S.T	1306.6	10 minute	2004-2023

Table 3. Information on datasets (adapted from Sabău et al., 2022b)

Dataset	**Source**	**Year**	**Resolution**	**Data type**
Land Cover	Copernicus Land Monitoring Service	2020	100 m	Satellite
Digital terrain model (DTM)	PPPDI project	2016	3 m	Raster LiDAR Data
Orthophotoplans	ANCPI	2019	1:2000	Raster
River flow and precipitation	”Somes-Tisa” Water Basin Administration and National Meteorological Administration	2012-2020	10 min	Time series
Soil	National Institute for Pedology, Agrochemisty and Environmental Protection	1964 - 1998	100 m	Raster
Soil depth	World Soil Information Service (WoSIS)	2020	100 m	Raster
Transversal profiles and surveys of bridges and dams	PPPDI project	2012		Topographic data
Radar images	SIMIN system	2017-2020	1 km	Raster
Weather forcast grid	ECMWF IFS HRES	2020	9 km	Raster

5. RESEARCH METHODOLOGY

The control specifications for this study were defined based on available data on precipitation and flow rates recorded at the automatic stations between 2012 and 2020. The temporal resolution of the model set as 10 min for rain events and 1 h for snow events.

A schematic diagram of the runoff processes at basin scale, consistent with the scale used in HEC-HMS model, is shown in Figure 4. The ECMWF Integrated Forecast System (IFS) HRES model products are first downloaded from the ECMWF website. Together with the Igniș radar products, this information provides the input and boundary conditions for the HEC-HMS hydrological model. These boundary conditions are subsequently used for producing 2–240 h’ time difference forecasts of precipitation depth on a grid covering the Firiza basin, which will also be used in the HEC-HMS model.

The GageInterp program (CEIWR-HEC 2016) was used for developing the gridded precipitation records required by HEC-HMS, by interpolating point rainfall from time series recorded at the pluviometric stations. The output from GageInterp program was a dss file including the precipitation grid in UTM coordinates. Estimates of precipitation are generated by GageInterp at regular intervals (i.e., 10 min or 1 h depending on the even) for each grid cell by reading the values in the time series stored in the HEC-DSS database files.

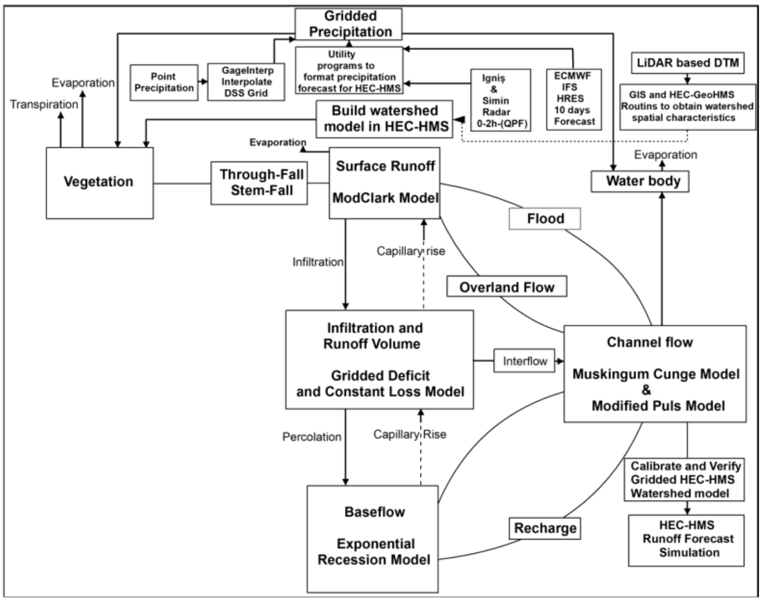

Figure. 4 Dual schematic diagram of the runoff process from the basin in flow symmetry between modules at a scale that is consistent with the scale modelled in HEC-HMS (adapted from Sabău et al., 2022b)

Adapting radar precipitation to grids for HEC-HMS requires collecting radar-based precipitation data, reformatting the data, and then converting the data to a DSS file that HEC-HMS can use. Radar data from the SIMIN system (Ioana et al. 2020) and from the Igniș radar use the 1970 Romanian stereographic projection or do not include geographical references. The data downloaded from the radar software are in a grid format with a spatial cell resolution of 1000 m. Before the radar precipitation data could be used in HEC-HMS, the following five steps were followed (Figure 5): (1) conversion from ASCII file format to ESRI raster; (2) georeferencing when needed; (3) conversion of the georeferenced raster files to UTM 34N and resampling of the grid to a cell size of 2000 m; (4) re-convert raster files back to ASCII file format; and (5) conversion of ASCII files to grid records (i.e., DSS files as required by HEC-HMS) using the ASC2DSSGrid. ArcMap's ModelBuilder tool was used for automatically processing of multiple files. The final step for processing ASCII files from step 4 to grid records in DSS is based on using ASC2DSSGrid utility. These five steps for processing radar data are shown schematically in Figure 5.

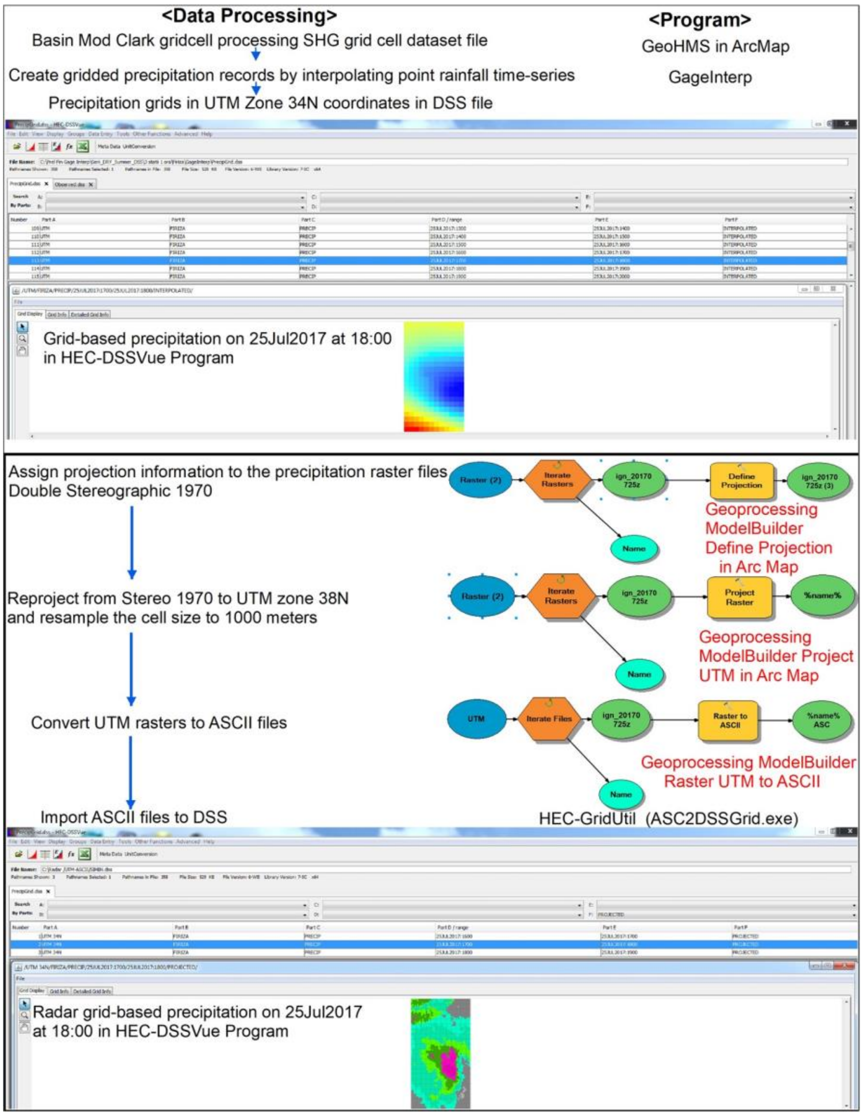

Figure 5. Flowchart of processing point rainfall data from pluviometric and radar stations (adapted from Sabău et al., 2022b)

More than 50% of precipitation returns to the atmosphere through evapotranspiration in many areas of Romania (Neculau and Stan 2016). The monthly average method was used to represent ET rates in the river basin. The average monthly ET (i.e., actual evapotranspiration) rates were determined by processing the data from the CARPATCLIM project (Antolovic et al. 2013) (Table 4). Once determined, ET values were incorporated into the HEC-HMS model.

Table 4. Average monthly potential evapotranspiration at the level of the Firiza hydrographic basin 1961-2010 (adapted from Sabău et al., 2022b)

Month	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Rate (mm/mth)	0.75	2.94	18.69	53.95	77.43	121.5	131.1	117.03	78.06	47.77	14.17	1.24

The temperature index method uses a wide range of parameters to define the snowfall, rain on snow, and snowmelt components within the hydrological process. The representative parameters are summarized in Table 5. Moreover, the final snowmelt parameters were established for each sub-basin after evaluating the existing parameters and consulting the HEC technical guidelines (HEC 1956, 1998). The initial values of the grid with the snow layer water equivalent (SWE) were developed using GIS processing. Elevation classes were introduced in the meteorological model to take into account the differences between snowfall and snow layer over the entire range of elevations in each sub-basin. Surface elevation relations were determined from the DTM using GIS tools to extract zone sectors from each elevation range for each sub-basin. These surface elevation relations were segmented at the natural break points in the topography to define the elevation classes for each sub-basin. For each defined class, the initial snow layer parameters were computed to evaluate any snow layer that may be present for the duration of the hydrological model simulation.

Table 5. General snowmelt parameters for the entire model (adapted from Sabău et al., 2022b)

Parameter	Value
PX Temp (C°)	-1
Base Temp (C°)	0
Wet Meltrate (MM/C°-day)	7.2
Rain Rate Limit (MM/day)	1
ATI Meltrate Coef	0.98
ATI Meltrate Fxn	Function
Cold Limit (MM/Day)	15
ATI Coldrate Coef	0.4
Water Capacity (%)	3
Groundmelt (MM/Day)	0.05

Any initial water storage in the river basin was accounted for by using the initial water deficit parameter in the soil loss method. The rate at which vegetation retention capacity recharges depends on the rate of ET. The estimated initial values of the maximum retention capacity at the canopy and superficial depression levels are shown in Figure 6a and 6b, respectively. Estimates vary greatly depending on slope, soil texture, land use, vegetation, and other factors (RSSC 1980).

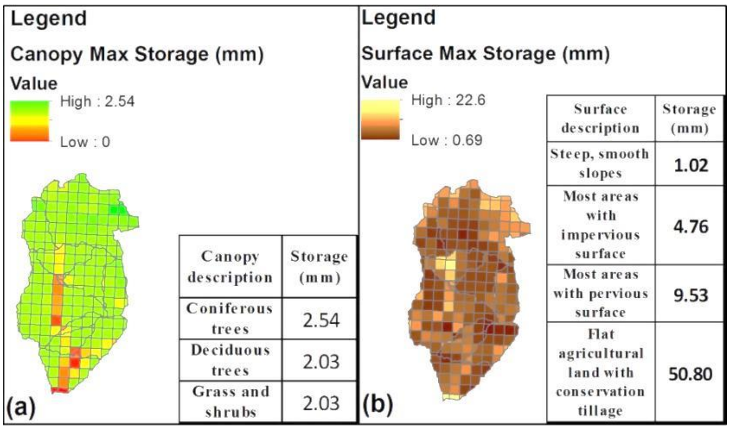

Figure 6. Maximum retention capacity at the canopy level (a), maximum retention capacity. at superficial depressions level (b). (adapted from Sabău et al., 2022b)

A GIS zonal statistics tool has been used to estimate the infiltration parameters using GIS data. The parameters necessary for the deficit and constant loss method were esti- mated based on soil texture and values in the literature, especially the tables. Estimated values of water characteristics for texture classes, texture class estimates, soil hydro- logical properties by soil texture were retrieved from literature (HEC 1994; Saxton and Rawls 2006; Skaggs and Khaleel 1982). Maximum deficit, constant loss rate, and per- cent impervious surface) have been estimated using GIS (Figure 7).

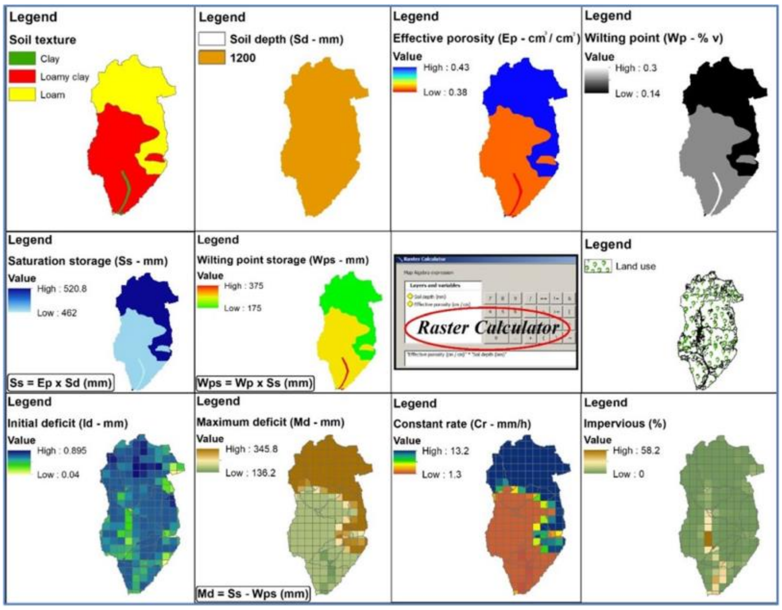

Figure 7. Process diagram of estimating the input parameters in the gridded deficit and constant loss model (source for all equations: HEC 1994; Saxton and Rawls 2006; Skaggs and Khaleel 1982) (adapted from Sabău et al., 2022b)

ModClark is a distributed parameter model in which the spatial variability of fea- tures and processes is explicitly accounted for (Kull and Feldman 1998; Peters and Eas- ton 1996; Feldman 2000). The flexibility of the ModClark methodology allows it to be adapted to new technologies, such as geographic information systems (Usul and Yilmaz 2002; Bhattacharya 2012). Figure 8 shows the flow chart of the methodology used to estimate the parameters required for the ModClark model.

To accurately represent the characteristics of the river sectors found throughout the basin (e.g., shapes, slopes, and transport capacity), two propagation methods were used. Muskingum–Cunge propagation method uses physical parameters such as length, slope, Manning coefficient, and geometry in cross-section to estimate the translation and attenuation of flood hydrographs across each riverbed. Length and roughness were estimated from maps, aerial photographs, and field studies, and the slope was taken from the HEC-RAS hydraulic model.

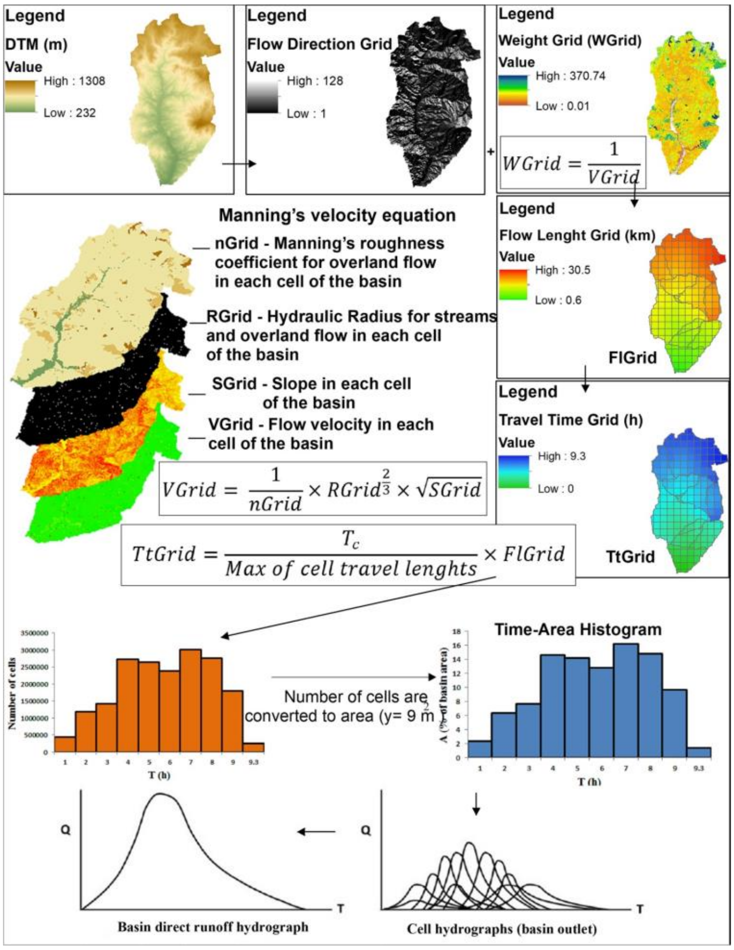

Figure 8. ModClark methodology flowchart (adapted from Sabău et al., 2022b)

The method has been shown to compare well for full unsteady flow conditions over a wide range of flow regimes (Ponce 1983; Brunner 1989; HEC 1994). The ModCLark model is based on the combination of the continuity equation and the diffusion form of the momentum equation and linearizing proposed by Miller and Cunge (1975), as described, with the following convective diffusion equation:

$$\frac{\partial Q}{\partial t} + c\frac{\partial Q}{\partial x} = \mu\frac{\partial^2 Q}{\partial x^2} + cq_L \qquad (1)$$

where Q = discharge (m^3/s^{-1}), A = flow area (m^2), x = distance along the channel (m), Y = depth of flow (m), q_L = lateral inflow per unit of channel length, S_f = friction slope, S_0 = bed slope, c = the wave celerity in the x direction as defined below.

For riverbed sectors, where the backwater effect has a significant influence on the flood wave hydrograph, the modified Puls propagation method was chosen, which is based on an approximation of the finite difference of the continuity equation coupled with an empirical representation of the impulse equation. The modified Puls routing method, also known as storage routing or level-pool routing, is based upon a finite difference approximation of the continuity equation, coupled with an empirical representation of the momentum equation (Chow 1964; Henderson 1966). For the modified Puls model, the continuity equation is written as (Feldman 2000):

$$\underline{I_t} - \underline{O_t} = \frac{\Delta S_t}{\Delta t} \qquad (2)$$

where ($\underline{I_t}$) = average upstream flow (inflow per sector) during a period Δt, ($\underline{O_t}$) = average downstream flow (outflow downstream of the sector) in the same period, and ΔS_t = change of storage in the sector during the period.

The storage–outflow ratio required for the modified Puls propagation model was determined by calculating profiles with the free surface of water for each riverbed sector under the influence of the backwater effect. The profiles of water surfaces with steady flow were determined using the HEC-RAS program (HEC 1982).

The water volume stored for each riverbed sector is the storage from the downstream end of the riverbed to a specific upstream cross-section. The storage on the riverbed area of concern was computed as the difference between the accumulated storage from the upstream cross-section and accumulated storage at the downstream cross-section for each profile.

Statistical methods are used to quantify how simulated values compare to the observed values. Four different efficiency criteria were used to quantitatively assess the performance of the model: coefficient of determination (R2) (Eq. 3) (Willmott 1981), Nash–Sutcliffe efficiency (NSE) (Eq. 4) (Nash and Sutcliffe 1970; O'Connell et al. 1970), root-mean-square error (RSR) (Eq. 5) (Legates and McCabe 1999) and percent bias (PBIAS) (Eq. 6) (Gupta et al. 1999).

$$R^2 = \left[\frac{\sum_{i=1}^{n}\left(Y_i^{obs} - \underline{Y}^{obs}\right)\left(Y_i^{sim} - \underline{Y}^{sim}\right)}{\sqrt{\sum_{i=1}^{n}\left(Y_i^{obs} - \underline{Y}^{obs}\right)^2}\sqrt{\sum_{i=1}^{n}\left(Y_i^{sim} - \overline{Y}^{sim}\right)^2}}\right]^2 \quad (3)$$

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right)^2}{\sum_{i=1}^{n}\left(Y_i^{obs} - \mathrm{y}^{medie}\right)^2}\right] \quad (4)$$

$$RSR = \frac{RMSE}{STDEV_{obs}} = \frac{\left[\sqrt{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right)^2}\right]}{\left[\sqrt{\sum_{i=1}^{n}\left(Y_i^{obs} - \overline{Y}_i^{sim}\right)^2}\right]} \quad (5)$$

$$PBIAS = \left[\frac{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right)\times 100}{\sum_{i=1}^{n}\left(Y_i^{obs}\right)}\right] \quad (6)$$

Unde:

Y_i^{obs} - is the ith observation for the evaluated constituent;

Y_i^{sim} - is the ith simulated value for the evaluated constituent;

$\overline{Y}^{obs}$ - is the average of the observed data for the assessed constituent;

$\overline{Y}^{sim}$ - is the average of the simulated data for the evaluated constituent;

n - is the total number of observations.

Model performance evaluation includes sensitivity analysis, calibration, and validation (Fanta and Feyissa 2021). The sensitivity analysis was conducted to determine the most sensitive parameters for runoff generation (Table 6).

Table 6. Performance ratings of the model (adapted after Moriasi et al. 2007)

Performance Rating	**R^2**	**NSE**	**RSR**	**PBIAS**
Performance Ratings for Evaluation Metrics for a daily and weekly time step				
Very Good	$0.65<R^2 \le 1.00$	$0.65<NSE\le 1.00$	$0.00<RSR\le 0.60$	PBIAS< ±15
Performance Ratings for Evaluation Metrics for a monthly time step				
Good	$0.65<R^2\le 0.75$	$0.65<NSE\le 0.75$	$0.50<RSR\le 0.60$	+10≤PBIAS< ±15

The exploitation of reservoirs according to the forecast of the developed model is conditioned by the transport capacity of the riverbed downstream of the dam, and this was determined with HEC-RAS hydraulic model following the methodology presented in Sabău and Șerban (2018a, b) and Sabău et al. (2020).

The actual run-time for a ModClark model is relatively small, depending on basin size, length of simulation, and traffic on the server (Cho 2020; Kull et al. 1996). A major drive behind the implementation of ModClark is the improved representation of the spatial and temporal rainfall distributions by NEXRAD. Precipitation input from NEXRAD radar should be more closely aligned with the reality of basin-averaged gauged data. The ModClark method has significant potential for improving forecasting capability when the accurate radar rainfall is used adequately (Cho 2020; CEIWR-HEC 1996).

6. RESEARCH RESULTS AND DISCUSSION

6.1. Model calibration and verification by modeling historical floods

Calibration is necessary to generate a useful model and is often an iterative process (Yavuz et al. 2012; Uysal 2012; Uysal et al. 2014, 2016, 2018; Che and Mays 2015; Sensoy et al. 2018; Braud et al. 2018; Srinivas et al. 2018). The selection of appropriate modelling methods for the study during the initial model setup was based on the following criteria: suitability of methods for the study area type of terrain and suitability of physically based methods for areas with limited measured data; the selected time step (i.e., hourly) should capture the level of detail of the observed data. Several methods that have been adjusted during calibration are initial and maximum deficit, constant rate, etc. The calibration showed that the selected modelling methods performed well.

To develop the parameter sets for the wet/typical and dry basin conditions, the model was calibrated to events representing each of the conditions. The wet/typical condition was assumed to represent average basin conditions, while the dry condition was considered to represent the basin with little or no precipitation for an extended amount of time. One wet/typical event, one wet/snowmelt event, and one dry event were used to calibrate the model. Details of each calibration event are shown in Table 7.

Table 7. Calibration events for different conditions in the river basin (adapted from Sabău et al., 2022b)

Basin conditions	Start date	End date	Description
wet/typical	07-Mar-18	21-Mar-18	March 2018 average rainfall at basin level with persistent rains, precipitation continuing until April
wet/snow melt	07-Dec-17	31-Dec-17	Snow (final of December) with ice rain (start of January), combined with higher than normal temperatures
dry	21-Jul-17	04-Aug-17	Significant drought in the summer of 2017, heavy rains brought by the cyclone totalled 81 mm in 24 hours

The Firiza model was calibrated to match peak flows, hydrograph shape, and hydrograph volume (HEC 1994). For the Firiza, peak flow and hydrograph shape were given priority over total runoff volume. Figures 9, 10, 11 show the computed versus observed hydrographs from one of the gauged locations in the middle portion of the Firiza basin for each of the calibration events.

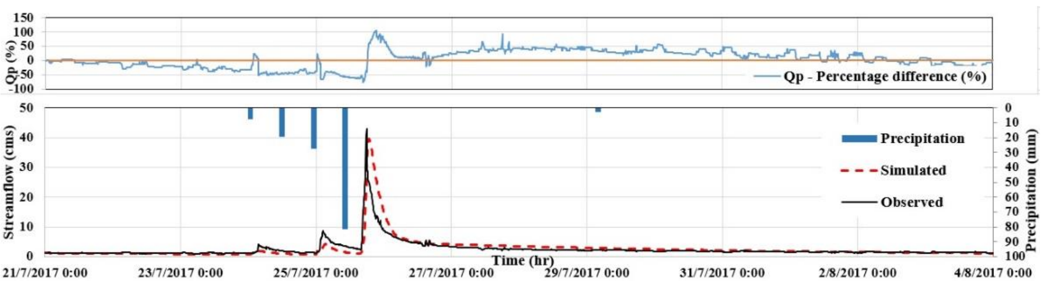

Figure 9. 2017 Calibrated hydrograph at Firiza gauging station, for dry basin conditions (adapted from Sabău et al., 2022b)

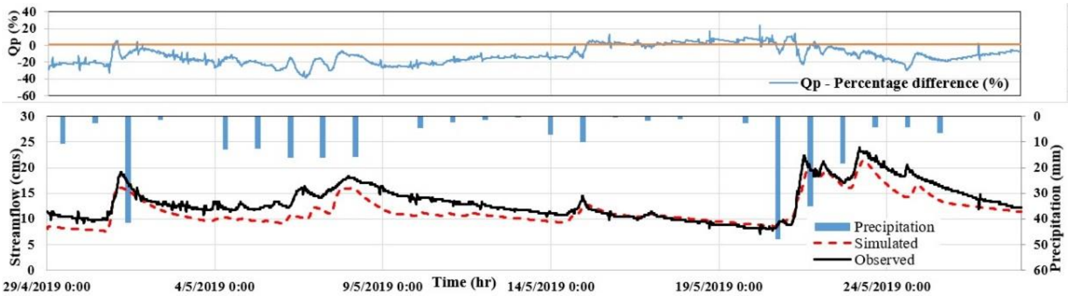

Figure 10. 2019 Calibrated hydrograph at Firiza gauging station, for typical wet basin conditions (adapted from Sabău et al., 2022b)

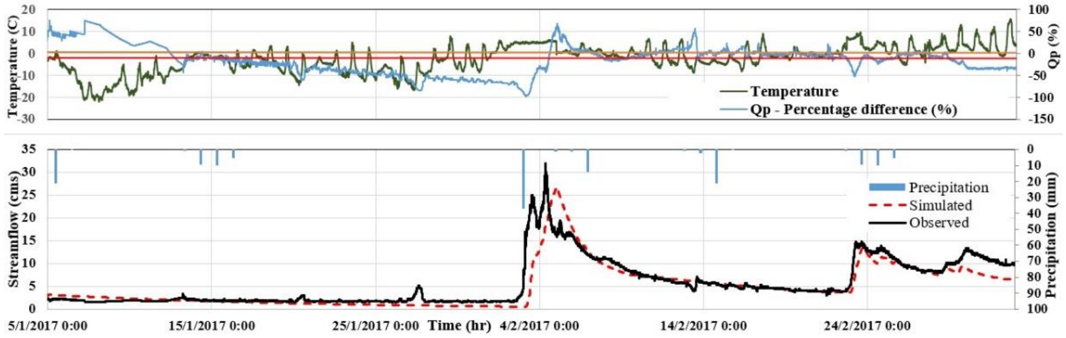

Figure 11. 2017 Calibrated hydrograph at Firiza gauging station, for wet/snowmelt basin conditions (adapted from Sabău et al., 2022b)

Figures 9, 10, 11 and Table 8 illustrate the quality of the calibration but also show that model fitness was not constant over the simulated period, as it varied depending on the flow regime (e.g., high and low flow periods) and the location in the basin of the stream gauge. In most cases, model calibration quality was dependent on the accuracy and availability of precipitation data. For some of the events (e.g., May 2019), the event calibration was not as accurate for the upper portion of the basin; however, the Firiza gauge, located in the central part of the basin, shows a good fit. In general, the calibration quality was high for all events evaluated for the Firiza basin, which implies that the precipitation from radar and ECMWF was not only more accurate for Firiza basin but also that the location of the available Igniș Radar and pluviometric stations better captured the spatial and temporal distribution of the storm event.

Table 8. Performance statistics of the HEC-HMS model (adapted from Sabău et al., 2022b)

Gauging station	Event	R^2	NSE	RSR	PBIAS
Firiza	Mar-18	0.71	0.73	0.56	12
	Dec-17	0.65	0.67	0.53	14
	Jul-17	0.78	0.86	0.37	7
	Jun-20	0.67	0.82	0.45	13.5

6.2. Flood forecasting application

Streamflow forecasting typically includes simulation of past and future conditions. The process begins with the selection of the time of forecast. The time of forecast represents the last available time for meteorological observations of precipitation, temperature, and other variables. The simulation is started hours or days before the time of forecast. Results computed between the start time and the forecast time are called the "look back period." Observations of current watershed conditions were compared with computed results from the look back period to make calibration adjustments that improve model performance. After the time of forecast and meteorological predictions of future values were used. Therefore, the quantitative precipitation forecast (QPF) from Igniș radar provides a meteorological prediction of future precipitation depths. Similar predictions were used for other meteorological variables such as temperature. The future streamflow response is simulated based on the predicted meteorological conditions. This period of time in the future may be called the "forecast" (HEC—HEC-HMS Applications Guide 2021).

Forecast alternatives are one of the components that can compute results. Each alternative is composed of a basin model, meteorological model, and time control information. The alternative also includes zone configurations for loss rate, transform, base flow, and reach routing parameters. The alternative may optionally include blending elements with observed flow. Results are available at each element after the simulation is complete (HEC—HEC-HMS Applications Guide 2021).

After creating the alternative forecast simulation, the model was configured to use editors specific to the alternative forecast. Necessary adjustments were made for the basic model, due to the conditions existing in the period before the forecast interval in the river basin and possible errors in the observed data.

Time is essential when performing streamflow forecasting and modeling techniques must consider this fact. The first step for configuring the forecast alternative was to configure the zones and elements in each zone for parameter adjustments. The sub-basin areas of the Firiza basin were divided into two configuration areas: areas by gauging station locations, called the “gauge” configuration, and areas by soil types, called the “soil” configuration. The first makes possible the grouping of sub-basins according to the position; this facilitates a quick comparison of the parameter adjustments with the monitored flows (HEC—HEC-HMS

Applications Guide 2021). The soil configuration is composed of two areas representing areas with different soil types.

A riverbed configuration has not been developed for Firiza, as it has been established that the riverbed propagation elements will not be modified during the on-line forecast simulations.

The wet/typical basin condition was selected for the Firiza forecast model, because the natural conditions in this watershed were more similar to parameters in the same type of watershed model.

The meteorological model represents the observed and future precipitations forecasted for the alternative. Based on the existing data and to identify the maximum flow from the hydrograph, a time step of one hour was chosen (HEC—HEC-HMS Applications Guide 2021).

The hour was selected along with the forecast date to be close to the date of the last observed data available. The start time of the simulation was nine days before the start time of the forecast, and the end time was selected as nine days after the start time of the forecast, for a total simulation of the eighteen (HEC—HEC-HMS Applications Guide 2021).

The retrospective period was used to compare the observed and calculated results to support the calibration (Figure 12).

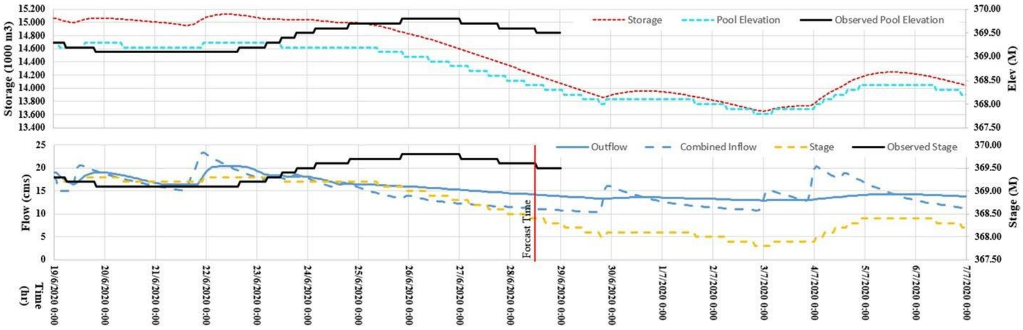

Figure 12. Initialization of Firiza reservoir for the forecast (adapted from Sabău et al., 2022b)

The threshold conditions in the Firiza basin are represented by precipitation and evapotranspiration, both highlighted in the meteorological model. The observed flow is also a threshold condition.

Base flow initialization sets the flow status for sub-basins at the beginning of a forecast simulation. Based on the observed flow, the initial state of the base flow was calculated. Ratios have been adjusted until the observed and computed initial base flow values were similar. Developing appropriate ratios or ratio ranges can be completed when calibrating the model or before running the model in a true flood forecast mode. The ratio should be somewhat consistent; only minor adjustments might be needed from one simulation to the next (HEC—HEC-HMS Applications Guide 2021).

Reservoir initialization sets the initial pool storage based on elevation from observed stage gauges and the input storage-elevation tables in the HEC-HMS model. In the Forecast Reservoirs editor, the forecaster selected the applicable stage gauge for each of the reservoirs at the start time and the forecast time (HEC—HEC-HMS Applications Guide 2021).

Reservoir initialization sets the initial pool storage based on elevation from observed stage gauges and the input storage-elevation tables in the HEC-HMS model. In the forecast editor for reservoirs, the level station was selected for each of the reservoirs at start time and forecast time. Figure 12 shows the initialization of the Firiza reservoir at the beginning of the simulation.

Figure 13 shows the results of the forecast alternative. These results were then used in reservoir flood operations or imported into additional model software like HEC-ResSim.

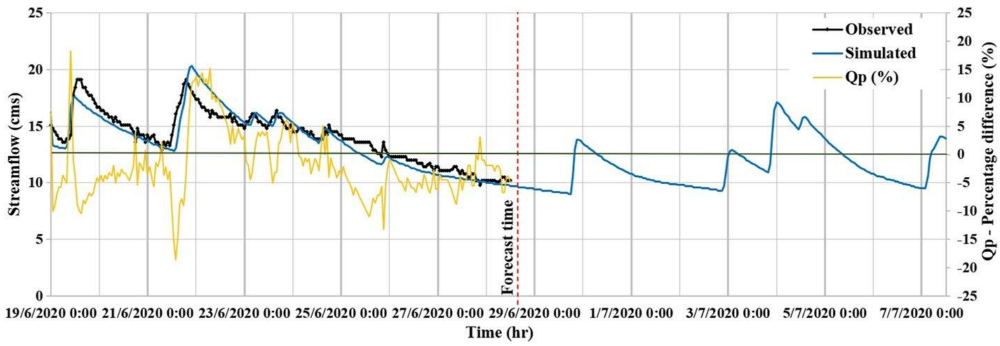

Figure 13. Forecasted hydrograph at the Firiza gauging station (adapted from Sabău et al., 2022b)

6.3. Discussion

An important factor in considering the magnitude of the potential damages of floods is the insufficient capacity of the bridges. According to the hydraulic model, the transport capacity of the minor riverbed is 60 m^3/s, and the bridge with the lowest transport capacity is limited to 50 m^3/s (Figure 14). Of the total of 10 bridges situated downstream of Strâmtori Dam and analyzed in the hydraulic calculations, at flows exceeding 1% and 10% probabilities, it was found that two bridges do not have transport capacity even at flows Q 10%. Furthermore, at flows with probabilities lower than 1% the number of bridges without transport capacity increases to 6.

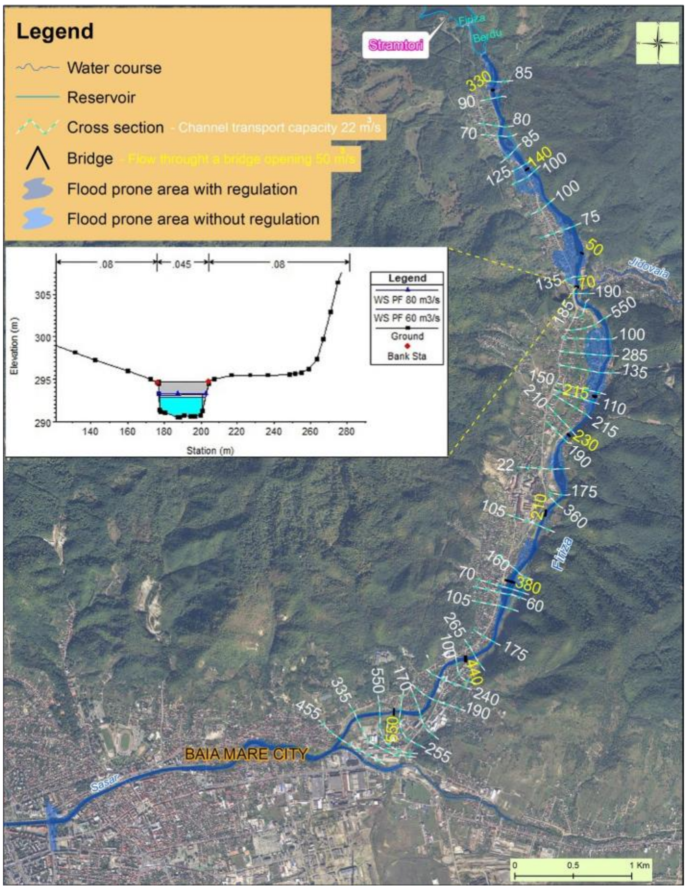

Figure 14. Flooding area extent map according to scenario event simulation without regulation and with regulation together with transport capacity of the minor riverbed and of the bridge sections downstream of the Strâmtori Dam (adapted from Sabău et al., 2022b)

In the first part of the analysis, the flood wave formed at the last significant historical flood event recorded in March 2001 was transited through the Firiza reservoir. In the second part, the synthetic hydrograph was transited for a 24-h precipitation event, with a return period of 100 years (Figure 15).

Thus, for a significant spring flood, which has a prolonged rise time, with pluvio-nival feeding, the hydrological forecast model must produce the most accurate simulations of the imminent hydrograph with a warning time of at least 30 h, to be able to carry out an optimal preventive discharge with a maximum allowable flow (flow that can be transported through the minor riverbed without damage) of 50 m^3/s (Table 9).

Table 9. Determination of preventive discharge time of Firiza reservoir at NNR at the upper edge of the spillway (adapted from Sabău et al., 2022b)

Elevation (m)	Volume (mil.m^3)	Discharged volume (mil.m^3)	Discharge through spillway and HPS I	
			Q (m^3/s)	T
370	17			
369.5	16	0.52	160	56’
369	16	0.51	115	77’
368.5	15	0.5	86	139’
368	15	0.49	40	3h 40’
367.5	14	0.48	20	8h
Total discharge time				15h 5’

In the case of rapid floods with a short rise time (Figure 14), the hydrological forecast model must produce the most accurate simulations of the imminent hydrograph with a warning time of at least 48 h.

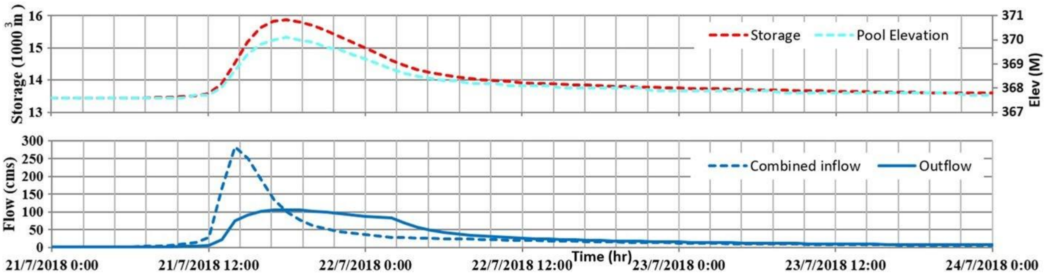

Figure 15. Flooding area extent map according to scenario event simulation without regulation and with regulation together with transport capacity of the minor riverbed and of the bridge sections downstream of the Strâmtori Dam (adapted from Sabău et al., 2022b)

To better monitor the evolution of a major floods and their impact on people and infrastructure, Romanian Water Basin Administrations are required to develop a decision support systems (DSS) for flood emergency management. Although more than 10 years have passed since National Administration ‘‘Romanian Waters’’ (ANAR) started the pilot project to develop a DSS for flood management in the Argeş basin, it has not yet been completed (Adler et al. 2006; Popescu et al. 2012; Rata et al. 2016). One of the main issues identified in the previous attempts for development of a DSS for Romanian basins was the limited expertise and access to complex commercial software packages and databases within the National Administration "Romanian Waters" (ANAR) agency (Adler et al. 2006; Popescu et al. 2012; Rata et al. 2016).

During the winter period, when events that include sudden warming and liquid precipitation occur, the limits reach critical values in terms of percentage volume errors. For seasons without frost and snow, the modelling process is simpler and the automated sensors at the meteorological and stream gauging stations work more accurately, thus reducing errors (Sensoy et al. 2018).

The reason for having relatively larger volume percentage errors is that the simulated recession parts are slightly different from the observed flows during the falling limb. The hydrological model shows sharp recessions, while the observations show a more moderate trend. For the fall period, the events are of short duration; the soil is unsaturated and hydrographs have sharp recessions. However, in winter and spring, the events are long-lasting; the soil is saturated and exhaustion is extensive. Thus, the percentage differences in volume in winter and spring are greater than those during the fall periods, which is in agreement with the results of other studies (Sensoy et al. 2018).

Optimizing exploitation is a short-term reservoir management measure that aims at in advance evacuation of an amount of water sufficient to compensate the volume of water conveyed by an upcoming flood. The lead time for the forecast cannot be more than 12 h, given the rapid nature of floods in the upstream basin. At the Firiza reservoir, there is a single bottom outlet with a diameter of 1 m and a discharge capacity at normal retention level (NRL) of 12 m^3/s (Figure 16).

In the HEC ResSim model, the following pre-storm releases scenarios were considered: If the level in the lake at the time of issuing the forecast is at the NRL and taking into account a 12-h lead time, approx. 500,000 cubic meters can be released. If the volume between NRL and extraordinary maximum level (EML) of 1.75 million m^3 is added, the total capacity available for mitigation increases to about 2.25 million m^3. It was expected that a flash flood with a 1% exceedance probability would result in a rapid increase of the water level in the lake, due to the limited capacity of the bottom outlet (Figure 16).

Evacuation could also occur through the spillway, provided the water levels reach the spillway crest. For medium flood events, the total outflow should be maintained within the discharge capacity of the downstream reservoir (Berdu), estimated at 17 m^3/s and the transport capacity of the minor riverbed, currently determined at 60 m^3/s. In case of an extraordinary flood event, the total outflow should be within threshold up to which no damage occurs to the riparian owners, currently determined at 110 m^3/s. Maintaining the outflow within these limits can be achieved by the proper operation of the dam's tainter gates, which would result in a slowing the rise of the water level in the lake above the spillway crest. When reaching an elevation close to the EML, the tainter gates will have to be fully open to prevent the level from rising above the EML.

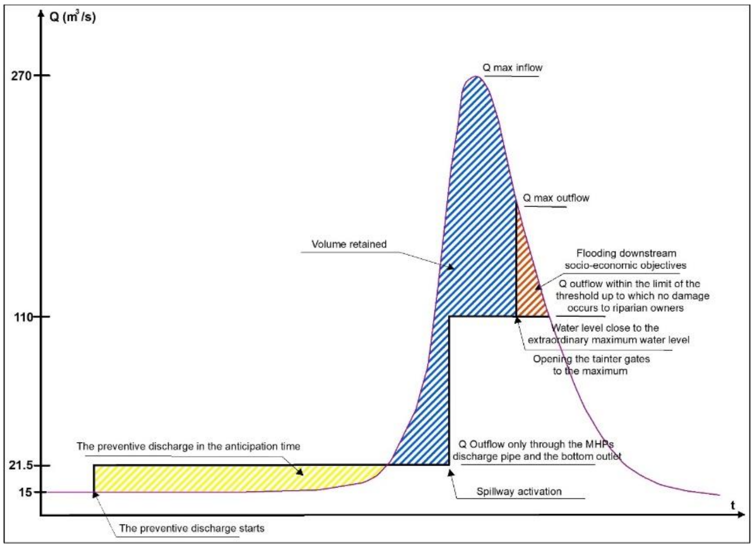

Figure 16. Inflow hydrograph with 1% exceedance probability vs Outflow (adapted from Sabău et al., 2022b)

The operation of the tainter gates was studied using HEC ResSim 3.3 (Klipsch and Hurst 2021), both from the point of view of operational safety and for an optimal distribution of downstream outflow. A portion of the flow is diverted into Strâmtori-Firiza reservoir by operating the Runcu reservoir, while the evacuation of the water from the Strâmtori-Firiza can be managed such as the NRL level will be decreased, and thus, the volume available for mitigation will grow. The purpose of the Hec-ResSim simulations was to optimize the exploitation of the Firiza-Strâmtori accumulation so that the EML is never reached or is reached as late as possible during the flood. If the EML is reached, the outflow increases above the current transport limit of the riverbed, and the nonstructural flood defense measure must be supplemented with other measures (Figure 17).

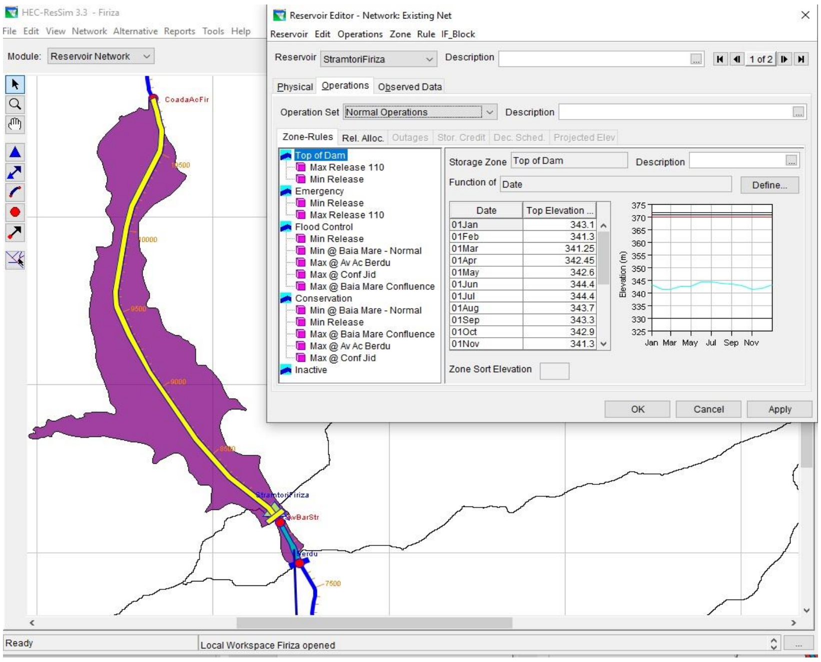

Figure 17. HEC-ResSim model of the Firiza and Berdu reservoirs (adapted from Sabău et al., 2022b)

The strategy of the previous regulation of the exploitation of the Firiza reservoir and the planned monthly curves were replaced by the new exploitation methodology, which operates with forecasts of the tributary flow and meteorological conditions in real time, and these were incorporated into the newly developed DSS. The performance indicators consisting of downstream flood risk, flood storage Index, end storage water level share, combined with the tainter gates maneuvers show that the proposed methodology provides higher performance compared to the previous FBC strategy.

The use of the new decision support system led to the avoidance of frequent conflicts of interest of the various uses, by ensuring a precise forecast of the tributary flow. In addition, the level in the accumulation was kept at a satisfactory rate for providing sufficient water supply for other uses. The hydrologic model is capable of producing estimates and forecasts of tributary discharge, particularly for snowmelt. The difference between observed and simulated total volume values was 17.5%, and the efficiency of the Nash–Sutcliffe model is about 0.67.

The majority of the Water Basins Administration from Romania flood forecasting offices use hydrological models calibrated and validated using gauge data (Mătreață et al. 2013). However, due to lack of long-term radar data archives, and the high cost and the time required to recalibrate existing models, updating the existing hydrological models using bias-corrected radar QPEs is recommended to simulate streamflow input to hydraulic models to produce flood inundation maps. Furthermore, in the future, the HEC-RTS framework can be used to produce flood extent maps using bias-corrected radar QPEs for future storm events (Wijayarathne et al. 2021). These maps could be used to make appropriate decisions and take immediate actions to reduce human and economic losses. In the future, the HEC-RTS framework could be upgraded to an automated Flood Early Warning Systems (FEWS) using methods available in HEC-RTS to retrieve, compute, view, and manage real-time Romanian and NEXRAD radar precipitation data to issue real- time flood forecasts for operational use (Wijayarathne et al. 2021).

CONCLUSIONS

For the development of the research paper, the general objective was taken into account: the development of a complex hydrological model, essential in the definition of a S.S.D.S that integrates G.I.S. with hydrological and hydraulic applications.

Given the controversy and the existing urban context in the Firiza basin, the correlation of the time needed to preventively discharge the Firiza in safe conditions for the downstream objectives with the warning time provided by the hydrological forecast model, in order to ensure a volumetric attenuation tranche was one of the major objectives of this study.

In the activity of exploitation of Firiza reservoir there is often a conflict of interests between the different uses. The most important conflict, that can be generally resolved based on the hydrological forecast, is found between the requirement to keep the reservoir at low levels, for protection against floods, and the need to exploit it intensively to ensure a high degree of security for the water supply and to produce as much energy as possible. Additional investments in reservoirs are far less economical than the realization of an operational forecasting system (even if such a system requires real-time observations, rainfall–runoff mathematical models and dedicated computers, for immediate data processing to enable the development of forecasts and decisions for the operation of reservoirs). These circumstances require the implementation of advanced operating frameworks.

Advanced hydrological modeling confirms the fact that with uniformly distributed rain on the Săsar river basin, the accumulation time from the confluence with the Firiza river is shorter for Săsar than for Firiza, given the shape and size of the basins upstream of the confluence and the presence of Strâmtori-Firiza reservoir. Thus, the developed model can provide real-time decision support for the decoupling of flood waves at the confluence of the two watercourses.

Also, the regularization projects could be easily adapted on the Firiza to include some areas of ineffective flow/retention, which would further delay the propagation of the flood wave on this watercourse, hence a lower probability of compounding at the confluence. The one-by-one transit of the floods from the two river sources through Baia Mare could solve the problem of flooding in the municipality.

Through this paper, we propose the development of a spatial decision support system for integrated flood risk management in the Firiza basin (SSDSBF). SSDSBF is a real time decision support system that expands and improves the data and information available to ABAST staff members who must make decisions regarding the operation of hydraulic structures. Data and information made available through the SSDSBF include precipitation data and forecasts, as well as data and information on the current state of watersheds, the likely future state of watersheds, and the consequences of management actions. Data and information help water managers and others make informed operational decisions.

In conclusion, an integrated DSS is established and tested for a critical dam reservoir that promotes operators' decisions in addition to being used as an early flood warning tool by the local authorities.

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