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Verification of the automated flood forecasting system on the Stryi River

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The physical and geographical location of the Stryi River Basin causes the formation of catastrophic floods, which are regularly forming in this region and cause significant material damage and, sometimes, the death of people. The last catastrophic flood took place on the Stryi River in June 2020. Thus, the creation of a modern system for forecasting the streamflow of the Stryi River is a very important task. This paper describes such an automated flood forecasting system (FFS Stryi) that is developed at the Ukrainian Hydrometeorological Institute of the State Emergency Service of Ukraine and the National Academy of Sciences of Ukraine. The basis of the system is the hydrological module NAM of the Rainfall-Runoff software complex MIKE 11 (Denmark), which uses the forecasted weather parameters from the numerical mesoscale atmospheric model WRF ARW v. 3.6.1 (USA). The objective of this study is to verify this system and identify the factors that affect the accuracy of flood forecasting of the Stryi River. The system of streamflow forecasting of the Stryi River uses the continuous series of calculated (historical) levels and discharges, air temperature, precipitation, evaporation, as well as the forecast of meteorological indicators for 5 days. The system is set to work with a three-hour time step in the automatic regime. Verification of FFS Stryi according to the historical meteorological data showed that the system reproduces the streamflow of the Stryi River with satisfactory quality. The accuracy of discharge forecasting depends on the accuracy of weather parameters forecasting and, above all, the quantity of precipitation and the time of their falling out. Errors of hydrological forecasting are caused by an imperfect hydrometeorological network of observations (number of points and frequency of measurement), a digital model of the relief of the Stryi River basin and errors of weather parameters forecasts.

KEY WORDS: short-term forecasting, weather forecast, NAM RR MIKE 11, WRF ARW v. 3.6.1, Stryi River

Introduction

The formation of extreme floods is a common problem around the world, and in particular in Ukraine (Susidko and Luk'yanets, 2004; Sofia and Nikolopoulos, 2020; Khrystiuk et al., 2020; Merz et al., 2021; Yang et al., 2021). The most flood-prone region of Ukraine is the Carpathians, where frequent rain floods, sometimes catastrophic, cause significant material damage associated with the destruction of settlements, agricultural lands, communications, etc. (Susidko et al., 2011). Of course, early warning about future floods is the paramount importance for this area, both in view of the timely implementation of flood control measures, and to improve the efficiency of the operation of hydropower and other water facilities (Romashchenko and Savchuk, 2002; Gorbachova, 2012).

In the world, modern hydrological services are using computer simulation systems for river runoff forecasting, which are based on a hydrological model that works automatically using weather forecast (WMO, 2009; Roelevink et al., 2010; Gorbachova, 2012; Shakirzanova et al., 2019). Today in Ukraine such a modern direction is insufficiently developed. In Ukraine, a lot of scientific developments in hydrological forecasting use methodological achievements that were formed in the 60-70s of the twentieth century (Susidko, 2000; Luk'yanets, 2004; Priymachenko, 2010; Susidko et al., 2011; Dutko and Sosedko, 2011; Moskalenko, 2012; Khrystyuk, 2014; Shakirzanova et al., 2019). This applies to the development of methods for short-term forecasting of floods in the Dniester River Basin, which were started at the Ukrainian Hydrometeorological Institute of the State Emergency Service of Ukraine and the National Academy of Sciences of Ukraine (UHMI) in the 70s of last century. The methods were based on the regression dependences or on the mathematical models of rain and snow-rain runoff formation that were proposed by the specialists of the Hydrometeorological Center of the former USSR (GHF, 1989; Priymachenko, 2010).

It should be noted that the former models of rain and snow-rain runoff formation on the Carpathian rivers have not lost their physical nature so far, but their practical use is limited by the lack of observation points for hydrometeorological indicators in the areas of the intensive runoff formation and the low observation frequency of these indicators, as well as the imperfect technology of observation, transmission and processing of hydrometeorological data. In addition, the forecasts of river runoff according to these models offer slight lead time, as they do not fully take into account the forecasts of weather parameters. Another disadvantage is that different models are used to forecast floods of different genesis. It is clear that modern hydrological forecasts should be based on a detailed (in space and time) forecast of weather parameters that can be obtained by the numerical meteorological models (WMO, 2009; Roelevink et al., 2010). For the above reasons, in the UHMI there has been created, as an alternative to the existing models of short-term forecasting of rivers runoff on the Dniester Mountain tributaries, an automated short-term flood forecasting system on the example of the Stryi River Basin (FFS Stryi), which uses the MIKE module 11 (Denmark) and the numerical mesoscale atmospheric model WRF ARW v. 3.6.1 (USA). Thus, the objective of this paper is to verify this system and identify factors that affect the accuracy of streamflow forecasting of the Stryi River.

Materials and methods

The Stryi River Basin is located on the eastern slopes of the Carpathian Mountains (Fig. 1). The Stryi River belongs to the right-bank tributaries of the Dniester River, which are mountain rivers with significant slopes of channels and terrain and with little permeable soil cover (Kaganer, 1969). In their basins, the mean annual rainfall is 750–1000 mm and they are the main area of formation of the Dniester River (Priymachenko, 2010; Khrystiuk, 2017).

Melting snow in the mountains in spring and winter, during thaws, as well as prolonged rains and rain showers by summer and autumn, combined with a well-developed hydrographic network, cause the floods of varying duration and discharges on the Stryi River. Particularly dangerous are the floods of the warm season, which are formed after heavy rains in the mountains (Priymachenko, 2010).

During the whole period of observations on the Stryi River at Verkhne Synovydne village, the largest catastrophic flood was the flood in June 1969. The maximum discharge consisted of 2610 $m^3 s^{-1}$ and was observed on June 9. This flood was the most dangerous not only in the Stryi River Basin, but also in the entire Carpathian region. Its frequency is estimated as once in 100 years. In the recent past, high rain floods were observed in 2008, 2010 and 2020. The floods of 2008 were caused by heavy rains with thunderstorms that covered the basins of the Tysa, Dniester and Prut rivers. The consequence of this catastrophic flood was not only the destruction of the region infrastructure, but also, unfortunately, the death of people. At the hydrological gauge of the Stryi River - Verkhne Synovydne village the maximum discharge consisted of 1720 $m^3 s^{-1}$ and was observed on July 25. In 2010, a catastrophic flood occurred in June and the first half of July in the basins of the Dniester and Eastern Carpathian Mountain. At the hydrological gauge of the Stryi River – Verkhne Synovydne village the maximum discharge consisted of 932 $m^3 s^{-1}$ and was recorded on July 8. (Adamenko, 2014; Lyalko et al., 2017). So, the rain flood of 2010 was chosen to verify the automated system of short-term flood forecasting on the Stryi River (FFS Stryi). This is due to the fact that the flood of 2010 was quite high, but not catastrophic, as the flood of 2020, during which there was a significant destruction of the regional infrastructure. Usually, after such catastrophic events, the maximum discharge in rivers is determined by an approximate method, namely by high water marks. Thus, the historical observation materials for the 2010

Fig. 1. Location of the Stryi River and the meteorological stations in its basin.

flood are of higher quality, which will improve the verification of the hydrological model.
The MIKE 11 software complex (developed by the Danish Hydraulic Institute) is widely recognized worldwide and is used for research and operational forecasting (Gorbachova, 2012; WMO, 2009; Roelevink et al., 2010; MIKE11, 2012; Shamsudin and Hashim, 2002). The MIKE 11 has a modular structure, which consists of the following basic modules: hydrological, hydrodynamic, advection-dispersion and bound sediments transport, water quality, transport of unbound sediments. Each of these modules has additional more detailed modules. The Rainfall-Runoff (RR) hydrological module contains additional modules, among which are the hydrological module (NAM), the unit hydrograph module (UHM), and the soil moisture accumulation model (SMAP). The NAM module is the most widely used, as it allows the best simulation of the streamflow from the catchment area, which is formed by melting snow and rainfall (Kumar et al., 2022; Bahremand and De Smedt, 2008; Shamsudin and Hashim, 2002). Therefore, the NAM module is suitable for simulating streamflow in the Stryi River Basin, which is characterized by snow-rain and rain floods. The Rainfall-Runoff NAM module is the balance model with lumped parameters. It takes into account the inflow of water to the catchment surface after rains and snowmelt, evaporation from the catchment surface and the formation of surface, subsurface and groundwater flow.
The input data of the Rainfall-Runoff NAM module are the continuous series of air temperature, rainfall and evaporation and discharge with a certain step in time and for a long period (up to 3 years). All these data can be obtained from the archives of the Central Geophysical observatory named after Boris Sreznevsky (CGO), except for evaporation from the catchment surface, as direct measurements of this characteristic are not carried out. Usually, the evaporation values from the Ukrainian catchment are calculated according to methodological approaches by Konstantinov, Polyakov, Buduko et al. (Iofin, 2016). Such calculations require the information on the radiation balance, air and soil humidity, etc. Observations of these indicators are not carried out in all river basins, which significantly complicates, and sometimes makes it impossible to calculate the evaporation from the surface of some watersheds. The paper of Iofin (2016) notes that the factors that affect the evaporation from the soil have much in common with the factors that determine the evaporation from the water surface. Thus, the evaporation depth (*E, mm*) from the catchment of the Stryi River was determined by an empirical formula, the structure of which has the form:

$$E=0,21*(0,255+0,1*V)*d^{0,78} \qquad (1)$$

where:
d – is the air moisture deficit [hPa];
V – is the wind speed [$m\ s^{-1}$].

After automatic calibration of the parameters of the NAM module of the Rainfall-Runoff model for a specific catchment, the streamflow forecast was carried out with use of the forecasted weather parameters, which are calculated by the numerical mesoscale atmospheric model WRF ARW 3.6.1 (Wang et al., 2015). The WRF ARW 3.6.1 model is intended for both research of atmospheric processes and for operational forecasting. In the UHMI, calculations according to different versions of the WRF model have been carried out regularly since 2008 of 4 times a day (Doroshenko et al., 2020; Gorbachova et al., 2021).
The quality of streamflow modeling according to the NAM module of the Rainfall-Runoff model was evaluated by the ratio of the standard deviation of the actual discharges from the mean value $(\overline{\sigma})$ to the mean square error of the simulated discharges ($\overline{S}$), i.e. $\overline{S}/\overline{\sigma}$. Such values are determined by formulas (GOH, 2012):

$$\overline{\sigma} = \sqrt{\textstyle\sum_1^n (y_i - \overline{y})^2 /(n-1)} \qquad (2)$$

$$\overline{S} = \sqrt{\textstyle\sum_1^n (y_i - y_i')^2 /n} \qquad (3)$$

where:
y_i – is the actual discharge;
$\overline{y}$ – is the mean discharge;
y_i' – is the simulated discharge;
n – is the members number of the series.

The calibration quality determines by indicators according to Table 1.
Periodicity of operational information receipt from the observation network of the Department of Hydrometeorology of the State Emergency Service of Ukraine and weather forecasts according to the model WRF ARW 3.6.1 is 3 hours. Thus, the NAM module of the Rainfall-Runoff model was set to work with a three-hour step in time.

Results and discussion

The Stryi River Basin is characterized by the formation of dangerous floods of different genesis. Thus, the priority aim is the simulation namely maximum discharges. So, the calibration of the NAM module was carried out with the definition of parameters set that well provide exactly this type of simulation.
Parameters calibration of the NAM module of the Rainfall-Runoff model of the MIKE 11 software complex for the catchment of the Stryi River – Verkhne Synovydne village was carried out according to the hydrometeorological data for the period 01.07.2007–30.06.2010. The historical discharges of the Stryi River at the Verkhne Synovydne village water gauge were used for modeling, as well as data on air temperature, precipitation, air humidity deficit and wind speed at Turka, Slavske and Stryi meteorological stations. The mean values of meteorological indicators for the catchment of the Stryi River at the Verkhne Sinyovydne village water gauge were calculated taking

into account the weight coefficients of each meteorological station. These coefficients were determined by the combined approach based on the Thiessen polygons taking into account the topography of the catchment area, as well as partial optimal selection in the calculations (Befani and Kalinin, 1983; WMO, 2009) (Table 2). To calibrate the NAM module of the Rainfall-Runoff model by interpolation a historical continuous series of observations of the discharges and precipitation with a step in time of 3 hours for the period 01.07.2007–30.06.2010 were created. Continuous series of evaporation depth (*E, mm*) for three-hour time intervals are determined by formula 1.

Calibration results of the NAM module of the Rainfall-Runoff model for the catchment area of the Stryi River - Verkhne Synovydne village for the period 01.07.2007-30.06.2010 are quite satisfactory because the coefficient of determination is 0.84 according to Table 1. The highest historical and simulated discharges are generally well coordinated (Fig. 2). The difference between the mean year historical and mean year simulated discharges range from -10.5 % (01.07.2009–30.06.2010) to +2.3 % (01.07.2008–01.07.2009) and in mean consist -3.5 % for the period calibration. The calibration quality by ratio $\overline{S}/\overline{\sigma}$ was 0.40, which corresponds to the "good" category according to Table 1. This calibration quality indicator allows full use of the NAM module of the Rainfall-Runoff model for historical and forecasting modeling for the catchment area of the Stryi River – Verkhne Synovydne village.

The flood, which was observed on July 7–10, 2010 on the Stryi River near the village of Verkhne Synovydne, was caused by heavy rainfall that fell in its catchment area during July 6–8, 2010. During this period the precipitation depth at meteorological stations in the Stryi River Basin reached: Turka – 51.6 mm, Slavske – 94.0 mm and Stryi – 70.5 mm. The flood started at 2 pm on July 7, 2010 and reached its peak at 8 am on July 8, 2010. The peak discharge of this flood was 932 $m^3\ s^{-1}$.

Table 1. Indicators quality of the calibration at the members number of the series $n \geq 25$ (GOH, 2012)

Category	Indicators quality	
	$\overline{S}/\overline{\sigma}$	coefficient of determination *(R)*
good	≤ 0.50	≥ 0.87
satisfactory	0.51 – 0.80	0.86 – 0.60

Table 2. List of meteorological stations, the data of which were used for the catchment of the Stryi River to the Verkhne Synovydne village

№	Meteorological station name	Height above sea level [m]	Weight coefficient	Meteorological station code
1	Turka	594	0.33	33511
2	Slavske	592	0.33	33516
3	Stryi	294	0.33	33513

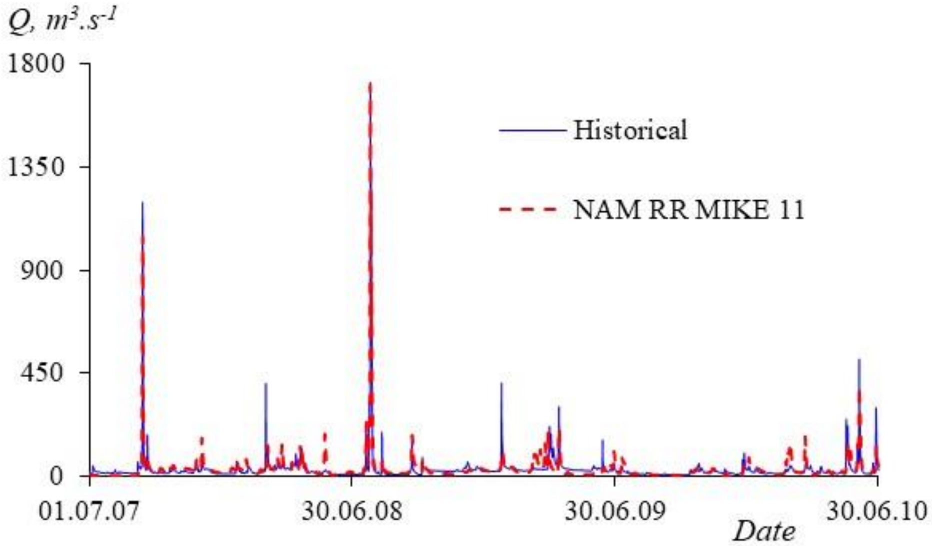


Fig. 2. Calibration results of NAM module of the Rainfall-Runoff model for the Stryi River at the Verkhne Synovydne village water gauge, 01.07.2007–30.06.2010.

Both the increase and decrease of levels and discharges during the flood were quite quick (Fig. 3). Analysis of simulation results, which are shown in Fig. 3 shows that the NAM module of the Rainfall-Runoff model quite satisfactorily reproduced discharges according to historical data of weather parameters. The simulated flood peak time differs from the historical (actual) time by 3 hours, and the simulated maximum discharge (724 m^3 s^{-1}) differs from the historical discharge by 22%. The discrepancy between the simulated time of the flood peak and the historical is explained by the fact that the amount of precipitation at meteorological stations in the Stryi River Basin is measured twice a day, while the NAM module of the Rainfall-Runoff model requires the meteorological data every three hours. The values of the precipitation amount that fell on the surface of the river catchment with a frequency of three hours were determined by linear interpolation, which introduced errors in the simulated values of discharges and the time of their occurrence, and in the model parameters during their calibration. The quality of streamflow modeling and calibration of the NAM module of the Rainfall-Runoff model parameters is also affected by the insufficient number of meteorological stations in the Stryi River Basin. So, only three meteorological stations are characterizing the river basin with the difficult mountainous terrain and catchment area is 2400 km^2.

Discharges that are modeled using the forecasted indicators of weather parameters according to the model WRF ARW 3.6.1 from July 6, 2010, were significantly lower than the historical discharges (Fig. 3). This result is due to a significant underestimation of the forecasted amount of precipitation that formed the rain flood. In addition, the WRF ARW 3.6.1 model is inflating the forecasted values of air temperature, humidity deficit and wind speed compared to historical values (Fig. 4). This contributes to the fact that when modeling in the NAM module of the Rainfall-Runoff model, the evaporation depth from the catchment surface is increasing and, consequently, the forecasted discharges are decreasing (Fig. 3). Also, one of the reasons for the forecast errors of numerical atmospheric models for specific meteorological stations, is the imperfection of the digital terrain model.

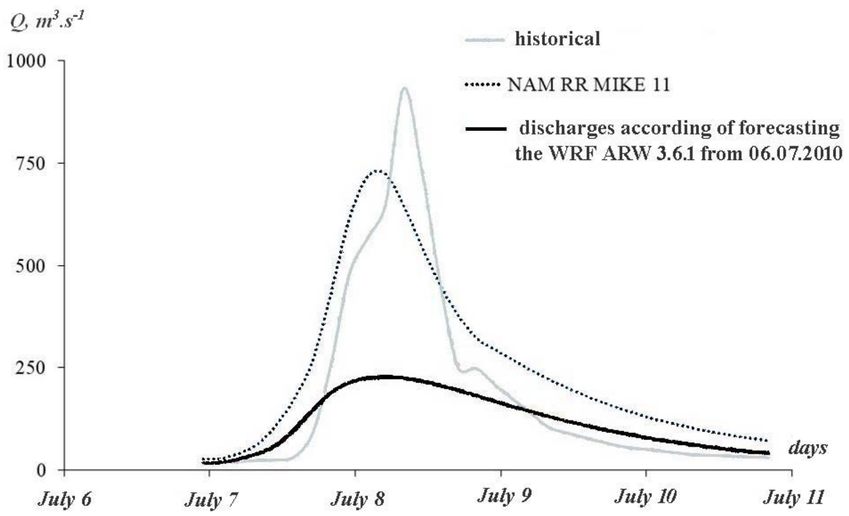
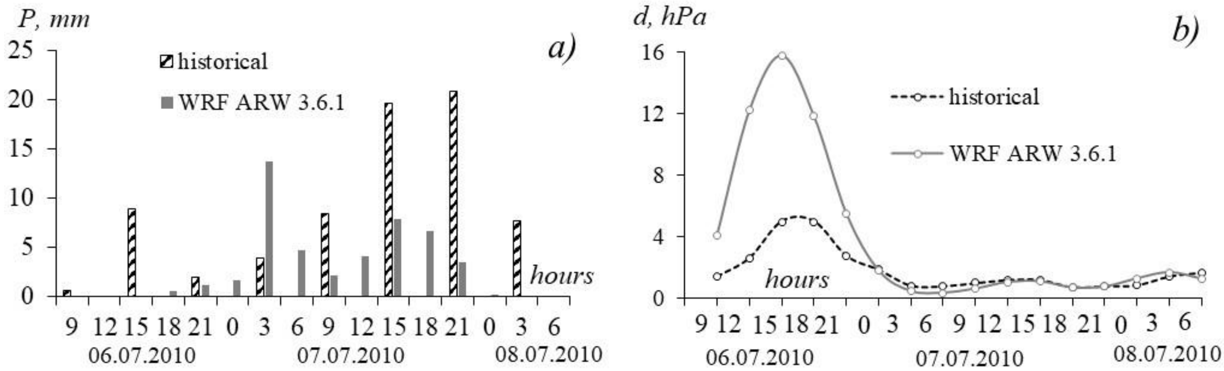


Fig. 3. Historical and modeled by the NAM module of the Rainfall-Runoff model according to the historical data and weather parameters forecast (WRF ARW 3.6.1) discharges on the Stryi River – Verkhne Synovydne village for July 7–10, 2010.



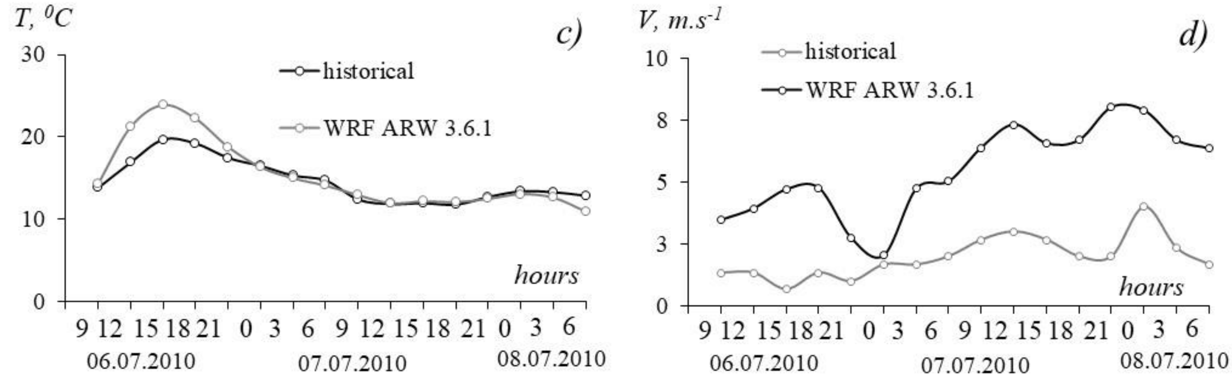


Fig. 4. Historical and forecasting values according to the WRF ARW 3.6.1 model of precipitation (a), air moisture deficit (b), air temperature (c) and wind speed (d) that are averaged over the basin of the Stryi River – Verkhne Synovydne village

Conclusions

The results of the verification of the automated system (FFS Stryi) show a satisfactory reproduction of the discharges of the Stryi River according to historical meteorological data. At the same time, on the Stryi River the accuracy of forecasting discharges of rain floods depends on the accuracy of forecasted weather parameters and, above all, the amount of precipitation and the time of their falling. Also, significant errors in hydrological forecasting are due to insufficient frequency of precipitation measurements (twice a day) at meteorological stations and too few of these stations in the river basin, which does not allow to accurately determine the average meteorological indicators for catchment, which are used to forecast discharges and to calibrate the parameters of the NAM module of the Rainfall-Runoff model. Thus, on the Stryi River the results improving of forecasting the discharges of rain floods is possible by increasing the observation points for meteorological indicators in its basin and the frequency of precipitation measurements and, of course, improving weather forecasts according to WRF ARW 3.6.1. However, it should be noted that the obtained results of verification FFS Stryi show that even with the above problems, this system makes it possible to forecast dangerous floods which will no doubt improve the operative and timely informing of relevant management bodies to prevent their consequences.

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