Communication

Pre-Operational Application of a WRF-Hydro-Based Fluvial Flood Forecasting System in the Southeast Mediterranean

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Abstract: The Southeast Mediterranean (SEM) is characterized by increased vulnerability to river/stream flooding. However, impact-oriented, operational fluvial flood forecasting is far away from maturity in the region. The current paper presents the first attempt at introducing an operational impact-based warning system in the area, which is founded on the coupling of a state-of-the-art numerical weather prediction model with an advanced spatially-explicit hydrological model. The system's modeling methodology and forecasting scheme are presented, as well as prototype results, which were derived under a pre-operational mode. Future developments and challenges needed to be addressed in terms of validating the system and increasing its efficiency are also discussed. This communication highlights that standard approaches used in operational weather forecasting in the SEM for providing flood-related information and alerts can, and should, be replaced by advanced coupled hydrometeorological systems, which can be implemented without a significant cost on the operational character of the provided services. This is of great importance in establishing effective early warning services for fluvial flooding in the region.

1. Introduction

The geomorphological complexity of the Southeast Mediterranean (SEM) has a significant influence on the atmospheric processes in the area, especially on those related to rainfall [1]. The combined effects of large-scale atmospheric circulation, land-sea temperature contrast and orographic forcing produce frequently huge amounts of rainfall, exceeding 100–150 mm even within a few hours and/or with hourly intensities higher than 50 mm [2–6]. Such heavy rainfall episodes favor saturation and/or infiltration excess, and subsequently the occurrence of floods, which can be devastating in terms of damages and human losses, in the numerous small- and medium-sized catchments present in the SEM. Indeed, Vinet et al. [7] found an increasing flood mortality trend in the SEM. This fact highlights the urgent need to provide timely and accurate flood-related information, including warnings and recommendations.

Considering the above, rainfall is traditionally used as an indicator in operational weather forecasting activities in the SEM, for assessing the potential of water-associated disasters' occurrence. However, the onset of a flood incident depends on the hydrological features and processes in the catchment where rain occurs. Thus, combining numerical

weather prediction (NWP) and hydrological modeling is required in order to provide a comprehensive assessment of forthcoming atmospheric phenomena and their projected impact on the hydrological response at watershed level. In this direction, significant progress has been made in past decades concerning the development of physically-based and spatially-explicit hydrological models, and their coupling to advanced NWP systems [8,9]. Although the coupling hydrometeorological framework has been adopted in several retrospective forecasting experiments in the SEM [10–15], little documentation exists with respect to operational forecasting practices and concerns (e.g., Israeli Hydrological Service [16]).

The present paper discusses the pre-operational experience in a flood forecasting system targeted over three watersheds in Cyprus (Larnaca region) and Greece (Attica region) in the framework of the first attempt at introducing impact-based flood warnings in the SEM. This experience includes prototype results derived during the tentative application of the system, which started in September 2020. The system is based on the coupling between the Weather Research and Forecasting (WRF) NWP model and its hydrological extension package (WRF-Hydro). The modeling architecture of the system is presented in detail, as well as future advancements with respect to evaluating thoroughly the system's performance and enhancing its efficiency. The key aim of the system is to estimate the potential impact of fluvial flooding in the catchments of interest, and provide relevant information and advice. The presented work is the first of its kind in both Cyprus and Greece. It is also the first step towards establishing an advanced early warning service, capable of interpreting and evaluating hydrometeorological information in terms of flood risk levels and possible effects under an operational context in both countries.

2. Methodology

The flood forecasting system is built upon the state-of-the-art WRF and WRF-Hydro models [17,18]. As illustrated in Figure 1, a special procedure is applied on a daily basis for assessing the necessity of initiating the hydrometeorological forecasting over the targeted catchments. At a first stage, WRF operates once daily (1200 UTC forecasting cycle) to simulate the meteorological conditions for the next 3 days (72 h) over Cyprus and Greece. The second step in the flood forecasting modeling chain involves the examination of the precipitation forecasts, provided over Cyprus and Greece, in the targeted watersheds. In case of high-impact rainfall thresholds exceedance, the WRF-Hydro model is activated under its fully coupled mode (i.e., two-way interaction between the atmospheric and hydrological processes) to provide 36 h streamflow forecasts over the catchments of interest. The last step in the forecasting process involves the post-processing and visualization of the WRF-Hydro output, including flood warnings in case of exceedance of flood-associated streamflow thresholds (Figure 1). It is important to note that the operational modeling methodology demonstrated above allows for scalability (e.g., expansion of the hydrometeorological forecasting over more catchments in Cyprus and Greece). Additionally, it is flexible with respect to computational demands and timeliness of the forecasts' delivery. Concerning the latter, the flood forecasting system is initialized once per day in the late afternoon (1930 UTC) and, in case of its full implementation (i.e., hydrometeorological prediction activation over all three targeted watersheds), the forecasting products are available early in the morning of the next day (~0600 UTC). In particular, the WRF meteorological forecast implementation requires 1.5 h and 3 h over Cyprus and Greece, respectively. The WRF-Hydro simulation for each catchment of interest is executed in 45 min, while post-processing the outcomes of each WRF-Hydro run takes 15 min (Figure 1). Considering that the WRF-Hydro forecasts are extended to a horizon of 36 h, the nighttime period of the model's implementation is overlapped by the previous forecast.

The WRF model configuration is based on the integrated HERMES weather forecasting system developed at the National Observatory of Athens (NOA; [5]). It consists primarily of two two-way nested modeling domains (Figure 2a): (a) d01 covering most of Europe and North Africa to capture synoptic-scale atmospheric conditions (10 km horizontal grid increment), and (b) d02_GR focusing over Greece and neighboring countries (2 km

horizontal grid increment). The model uses initial and boundary conditions based on the $0.25° \times 0.25°$ spatial resolution and 6-h temporal resolution Global Forecast System (GFS) operational data. After the weather forecast implementation over Greece, a one-way nesting approach is applied for the 3-day weather forecast over the domain d02_CY that focuses on the greater area of Cyprus (2 km horizontal grid increment; Figure 2a), using the "ndown" WRF capability [17]. The initial and boundary conditions for this finer-grid run are obtained from the coarse domain (d01), while high-resolution terrestrial data are used for initializing the run, as in the case of Greece (d02_GR).
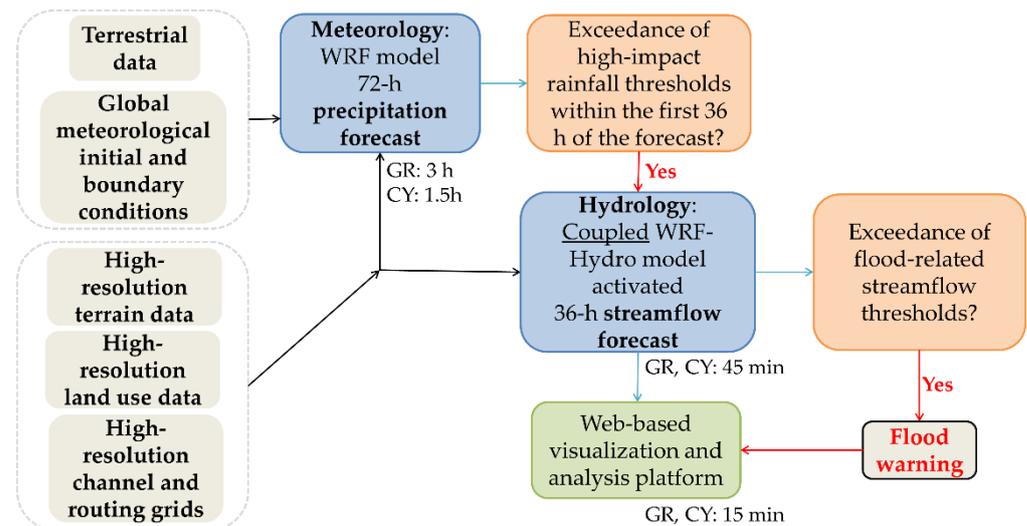

Figure 1. Flowchart of the flood forecasting service. Timings correspond to the implementation of the WRF meteorological and WRF-Hydro hydrological forecasts, and to the post-processing of the forecasts over Cyprus (CY) and Greece (GR).

For examining the precipitation forecasts, provided by the 2 km resolution domains over Cyprus and Greece, in the targeted watersheds, an automated algorithm is applied. The algorithm investigates if any 1 h rainfall or 6 h moving sum of rainfall exceeds 10 mm or 18 mm, respectively, within the first 1.5 days (36 h) of forecast over the Archangelos/Kamitsis river basin in Cyprus (red outline in Figure 2b). For the same forecasting period over Greece, the algorithm examines if any 1 h rainfall or 6 h moving sum of rainfall surpasses 15 mm or 30 mm, respectively, over the Rafina and Sarantapotamos stream basins (red outlines in Figure 2c). The rainfall thresholds for identifying a potential high-impact event were defined based on previous hydrometeorological and impact analysis studies, and experience in forecasting and monitoring weather and natural disasters in the areas [5,19–22].

For the hydrometeorological forecasting, the WRF-Hydro setup includes high-resolution (~667 m horizontal grid increment) domains over Cyprus (d03_CY; Figure 2b) and Attica, Greece (d03_GR; Figure 2c), where the meteorological conditions are simulated. Over these domains, ultra-high-resolution (~95 m horizontal grid increment) domains are configured for simulating the hydrological procedures over the Archangelos/Kamitsis (Figure 2b), Rafina and Sarantapotamos (Figure 2c) watersheds. Under the fully coupled mode, the meteorological forcing to WRF-Hydro is provided by the WRF model. Additionally, specific hydrological-related land surface state variables modeled by WRF-hydro in the ultra-high-resolution domains, including soil moisture, feed back to the WRF-simulated atmospheric processes. This feedback has the potential to enhance the model's rainfall forecast skill, as two recent research works conducted in the SEM have shown [23,24]. The highly-resolved modeling of surface and saturated subsurface water, and the exchange of information between the meteorological and hydrological component of the model, are taking place through a sub-grid aggregation/disaggregation process [18], using ultra-high-resolution terrain, land

use and channel/routing grid data. Prior to its pre-operational setup, the WRF-Hydro model was calibrated and validated over the configured domains following a manual stepwise approach based on the comparison of the modeled output with observations [23].
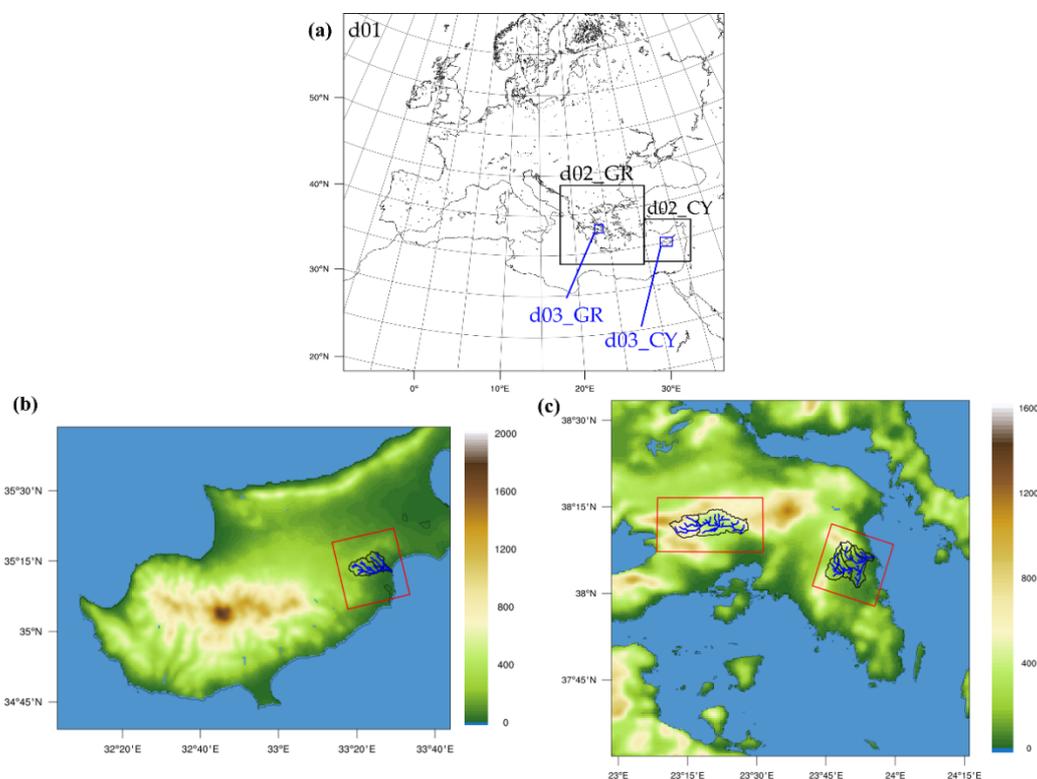

Figure 2. (**a**) WRF modeling domains; (**b**) topography of Cyprus in the d03_CY modeling domain with identification of Archangelos/Kamitsis catchment; (**c**) topography of Attica, Greece in the d03_GR modeling domain with identification of the Rafina (East) and Sarantapotamos (West) stream basins.

During the WRF-Hydro output post-processing, automated computing scripts produce maps that demonstrate the spatial distribution of streamflow in the targeted catchments. Hydrographs illustrating the temporal evolution of river/stream discharge and basin-averaged rainfall are also being created for specific locations at risk. Further, the exceedance of flood-associated streamflow thresholds is being examined at the high-risk locations. Currently, the latter procedure is applied only for the Rafina stream basin, where preliminary impact-based thresholds have been defined according to the outcomes of a recent study on the hydrometeorological and socioeconomic impact assessment in the area [22]. In case the discharge thresholds are exceeded, an alert message is created providing information on the potential impacts in the watershed and on the preparedness level. At present, the products described above are being automatically published in a dedicated web portal (https://w1.meteo.gr/cypjp/index.cfm, accessed on 9 June 2021), which is publicly accessible under a pilot demonstration mode, constructed in the frames of the CyFFORS project (Cyprus Flood Forecasting System, http://cyirg.frederick.ac.cy//cyprus-flood-forecasting-system/, accessed on 9 June 2021).

3. Prototype Results

Figure 2 presents two examples of the gridded streamflow maps that are produced with a temporal resolution of 1 h, when the WRF-Hydro-based hydrometeorological forecasting is activated.

The first map (Figure 3a) was issued for Rafina stream basin (Greece; Figure 2c) on 13 December 2020 and it is valid for 0600 UTC of the next day. The presented case is related to a 3-day period (12–14 December 2020) of heavy rainfall over Attica, Greece, due to the

occurrence of two consecutive low-pressure systems that affected the area in that period. On 15 December 2020, the second surface low affected Cyprus, and particularly the Larnaca region, while moving from the west towards the east. Thus, the second map (Figure 3b) refers to the Archangelos/Kamitsis river basin (Cyprus; Figure 2b). The map was issued on 15 December 2020 and it is valid for 1900 UTC of the same day. The interpretation of the results and information shown in the maps is facilitated by (a) the light blue (low streamflow) to red (high streamflow) color map, (b) the identification of regions (written on map) and (c) the background map that highlights the road network. For instance, in Figure 3b, a user can quickly identify the highest values of discharge exceeding 4 m^3/s in the Archangelos/Kamitsis section that passes through the Livadia residential area, close to the river's outlet. Interactive points of interest (i.e., locations at risk) are also provided in the maps (illustrated as yellow circles), so a user can view and even download the 36-h time series of streamflow and basin-averaged rainfall at these points.
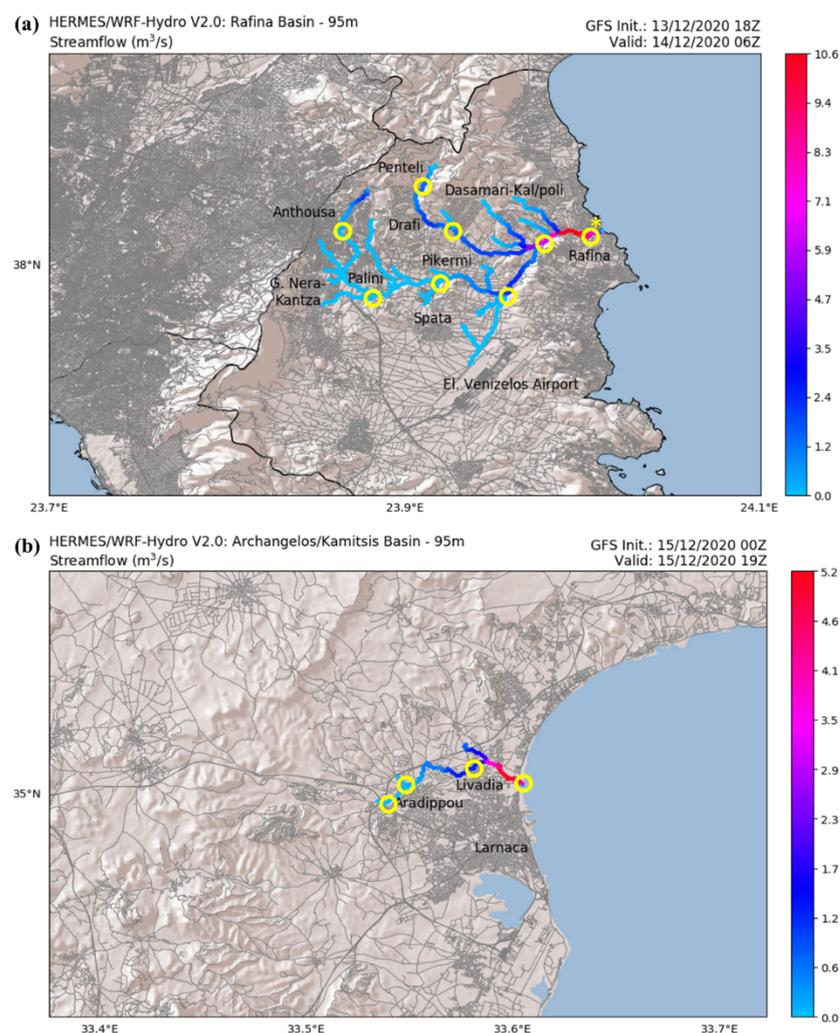

Figure 3. Example of streamflow forecasting map for (**a**) Rafina stream basin (Greece), valid for 14 December 2020 at 0600 UTC, and (**b**) Archangelos/Kamitsis river basin (Cyprus), valid for 15 December 2020 at 1900 UTC. The yellow circles denote specific points of interest.

Figure 4 shows the 36-h time series of streamflow and basin-averaged rainfall at a point of interest targeted over the outlet of the Rafina stream basin (denoted by an asterisk in Figure 3a), as an example of the hydrographs provided in the framework of the hydrometeorological forecasting. In order to communicate flood-related information, which is of great usefulness for both stakeholders and the general public, the hydrographs

include the maximum streamflow forecasted within the 1.5-day prediction range at the specific location at risk (Dmax; Figure 4). This information is elaborated in an explanatory description, which is available in the section "HYDRO" of the web portal, where the hydrographs are presented. Further, for the purpose of the impact-based warnings for the Rafina catchment, a table describing the alert level and its corresponding potential impacts is provided (Table 1), following Giannaros et al. [22].
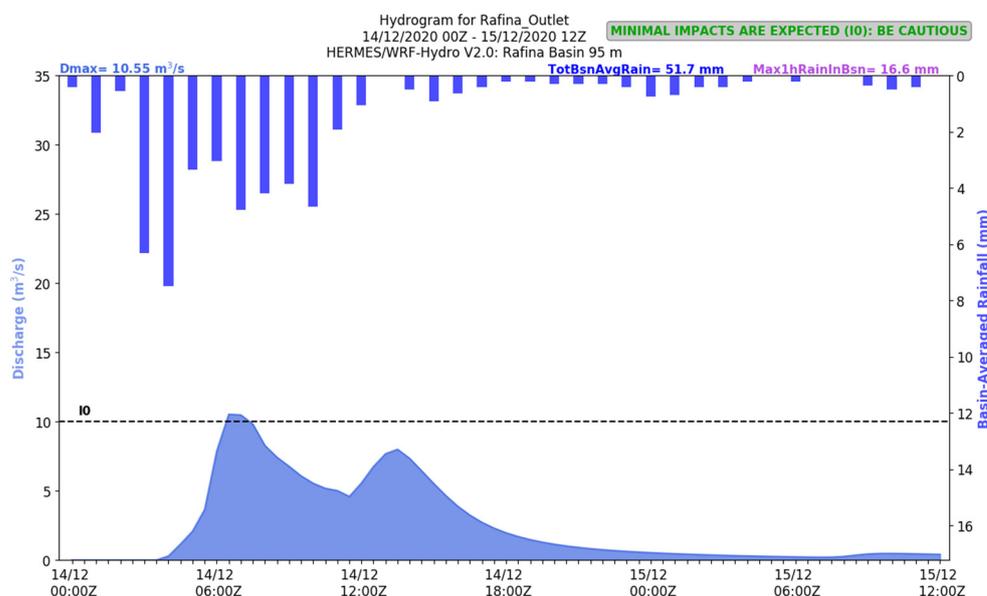

Figure 4. Example of hydrograph forecast for the Rafina stream basin outlet (Attica, Greece), issued on 13 December 2020.

Table 1. Socioeconomic impact intensity classification.

	I0: Minimal	**I1: Minor**	**I2: Significant**	**I3: Severe**
Human life	Not expected	Risk for vulnerable groups of people and/or involved in endangered situations	Danger to life due to physical hazards associated with flooding water	Danger to life due to physical, chemical and utility hazards associated with flooding water
Damage to properties and public structures	Not expected	Light damage to individual properties	Important damage to many properties and/or public structures	Extensive damage to multiple properties and/or public structures
Transportation	Little or no disruption to river crossings and/or roads close to the river/stream	Small-scale disruption (local and short term)	Large-scale disruption (broad and long term) and/or important damage to the transport network	Extensive disruption (broad and long term) and/or extensive damage to the transport network
Utilities	Not expected	Small-scale disruption (local and short term)	Large-scale disruption (broad and long term)	Extensive disruption (broad and long term) and/or loss of utilities

For the provided example over the Rafina stream basin, an alert associated with potential minimal impacts (I0 class; Table 1) was issued, as the maximum streamflow, which was found in the watershed's outlet, exceeded 10 m^3/s (Figure 4). This warning corresponds well to the localized flooding reported in the area by the local media (https://www.irafina.gr/rafina-afti-ine-i-katastasi-stis-gefires-tis-arionos-ke-tou-varda-pou-plimmirisan-apo-tin-kakokeria-foto/, accessed on 9 June 2021). On the event day (14 December), 60.2 mm of rain was recorded in the Rafina meteorological station

(close to the point of interest denoted by the asterisk in Figure 3a), which is part of the NOA's dense network of automated weather stations [21]. The 24 h rainfall simulated by the WRF-Hydro model at the nearest to the location of the station grid point during the episode was equal to 45.1 mm, indicating an adequate model performance in capturing the observed rainfall's intensity. The encouraging performance of the model is also supported by the observed and modeled rainfall time series (Figure 5). As can be seen in Figure 5, the WRF-Hydro-simulated rainfall was close to the observed one in terms of both timing and intensity.
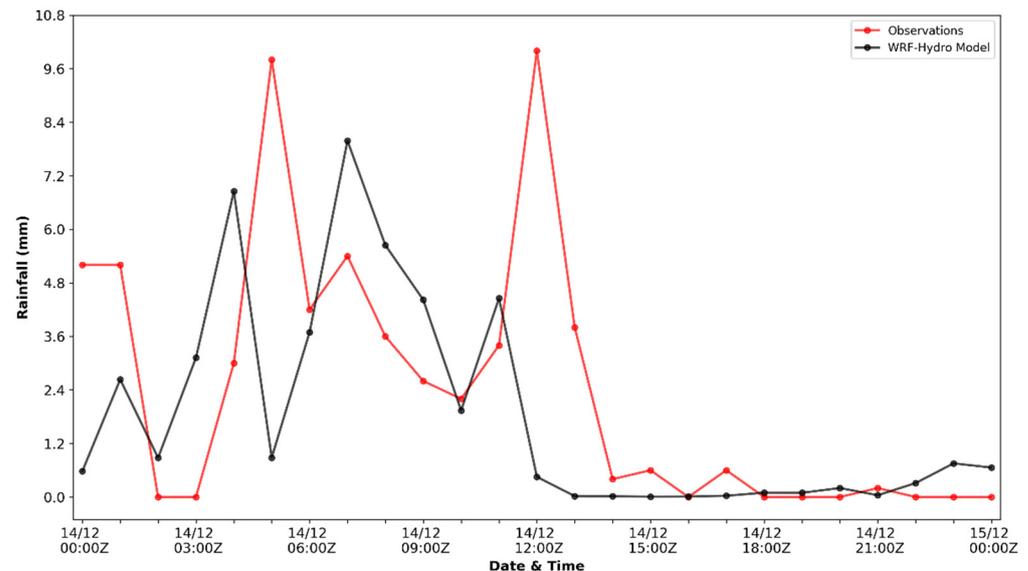

Figure 5. Time series of the observed and WRF-Hydro-modeled rainfall over the Rafina meteorological station from 14 December 2020, 0000 UTC, to 15 December 2020, 0000 UTC.

4. Discussion

Decision-making on the assessment of flood risk and on the issuing of river- and stream-scale alerts is a significant challenge in the context of operational weather forecasting. Combining NWP and hydrological models has been proven to be valuable in addressing this difficult task [25–28]. However, the production and dissemination of flood-related information using advanced hydrometeorological models and convenient communication methods on an operational basis have received little attention in the Southeast Mediterranean.

The current paper presents the modeling framework and pre-operational use of a river/stream flood forecasting system in the SEM region. The system is targeted over three catchments in two highly flood-prone regions (Larnaca in Cyprus and Attica in Greece; Figure 2b,c). It is based on the advanced coupling between the WRF NWP model and the WRF-Hydro hydrological model, exploiting a flexible forecasting scheme in order to provide streamflow predictions when a heavy rainfall event is expected. The river/stream discharge forecasts are compared to specific thresholds in one of the watersheds of interest, namely in the Rafina stream basin, and a warning can be issued depending on the impact that is associated with the potentially reached threshold [22]. Although a comprehensive evaluation of the system's performance has not yet been carried out, the preliminary results indicate that the system has the capability to adequately forecast flood-associated levels of river/stream discharge, as in the case related to localized flooding in the Rafina catchment (Figure 4).

A thorough evaluation of the system in terms of rainfall and streamflow forecasting accuracy is expected to take place after the end of its pre-operational application. Further, potential developments of the system will be examined in the future in order to increase its effectiveness in providing impact-based fluvial flood warnings. These developments

include the continuous assessment and improvement of the rainfall forecasts provided by the WRF-based HERMES weather forecasting system (e.g., [5]). Additionally, they could include the introduction of more frequent daily operational runs, instead of the current once-a-day implementation of the system. This approach provides the potential of using the most up-to-date and accurate initialization data. The latter may include real-time rainfall data, exploiting the dense network of automated weather stations operated by NOA [21], as forcing the WRF-Hydro model with observations can enhance the streamflow predictions [24]. In this case, the one-way coupling mode of WRF-Hydro can be utilized.

Concerning the initialization data that are associated with the initial and boundary conditions (IBCs), they are critical to the WRF model's performance, as even a 6-h difference in the IBCs' lead time can result in significant differences in the simulated meteorological fields, including those of rainfall [29]. In the direction of considering the uncertainties in atmospheric IBCs, ensemble forecasting approaches can be beneficial [30], leading to probabilistic streamflow forecasts that can assist in quantifying the likelihood of impact-based thresholds' exceedance [31]. However, it should be noted that IBCs' ensemble forecasting introduces increased demands for computing resources and thus, it may not be feasible under an operational context. An alternative approach could be a multi-model ensemble using meteorological forcing data derived from different NWP models, for the one-way coupled WRF-Hydro model. Beyond the WRF model, these could include the BOLAM [32], MOLOCH, ICON and APREGE models, which are currently used by NOA for its operational weather forecasting activities. Finally, future work should focus on defining impact-based discharge thresholds in the Archangelos/Kamitsis river basin and Sarantapotamos catchment, as soon as data from flood events are available, as well as on the expansion of the forecasting system over more watersheds in Cyprus and Greece.

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