A HYDROMETEORLOGICAL ANALYSIS OF AN EXTREME FLASH FLOOD EVENT IN THE URBAN AREA OF WEST ATTICA, GREECE

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1 Introduction

Floods are considered the most frequent natural disaster and in 2011 six out of ten biggest natural disasters were flash floods. According to The Centre for Research on the Epidemiology of Disasters (CRED), “flash flood” is usually defined as a rapid inland flood due to intense rainfall with short duration (Guha-Sapir et al., 2012). In this type of phenomena, in highly sloped terrain, the water flows rapidly with high destruction potential while in flat areas it cannot infiltrate into the ground or run off fast enough. Flash floods can be a source of significant damage and serious loss to infrastructures and human lives and are typically associated with thunderstorms which can occur at any place (Karymbalis et al., 2012). Globally the frequency of flooding events has increased and a warmer climate is expected to aggravate the effects on human life (Hirabayashi et al., 2013). All climate model projections show that higher precipitation extremes are expected in warmer climates (Kundzewicz et al., 2007), particularly at mid and high latitudes (Meehl et al., 2005). This directly affects the risk of flash and urban flooding.

Flash floods are a frequent occurrence in several parts of the Mediterranean region due to the local climate, which is prone to short and very intense rainfalls (Gaume et al., 2016). The Mediterranean Basin is a transitional zone between the cold and wet climates of Northern Europe and the hot and dry climates of low latitudes (North Africa) and is characterized by highly diverse climatic conditions (Camarasa Belmonte and Segura Beltran, 2001). Therefore. the types of rainfall that can generate flooding events vary along its coasts (Gaume et al., 2016). In general, convective thunderstorms and showers, which are usually produced in summer and early autumn, due to low level instability and high temperatures, are the dominant cause of flooding episodes (Llasat, et al., 2016). In addition, the form and geometry of the local drainage networks, the morphology of the basin and various anthropogenic interventions modify the catchment response of a basin and its physical properties (Runge and Nguimalet, 2005), potentially exacerbating the phenomenon and its negative effects.

Early warning systems are essential elements in the development of disaster preparedness and response strategies [UNISDR, 2009, Directive 2007/60/EC]. Effectiveness of early warning procedures depends highly on the accuracies of the precipitation monitoring systems involved (Westra et al. 2014). The impact of accurate representation of rainfall spatial variability on simulating the flash flood response has been demonstrated by several studies (Zoccatelli et al. 2010). Moreover, recent studies (Marra et al. 2014) have shown the importance of accurate rainfall estimates at small spatial scales for the prediction of debris flow/landslide initiation. Therefore, to improve the accuracy of flood hazard warning systems, it is critical to acquire accurate estimates of precipitation rates at high resolution. The quantification of precipitation over complex terrains, where these phenomena typically occur, is rather complex, and topography plays a dominant role in shaping precipitation variability (Barros et al. 2000). Current operational rainfall monitoring systems from national weather radar networks do not provide sufficiently accurate measurements of precipitation variability over mountainous areas (Maddox et al. 2002).

Numerical models are employed to predict these adverse phenomena. Nevertheless, flood prediction in urban areas is still an open scientific issue and remains a challenge. A sophisticated approach is the combination of atmospheric-hydrological modeling methods assimilated with high-resolution surface precipitation observations. This approach is becoming more attractive to the scientific community since they are fully coupled in a single advanced observation-modelling system. Many studies performed on flash flooding events focus on numerical modelling, applying a multitude of systems like DRiFt (Discharge River Forecast, Giannoni et al., 2000) and CREST (Coupled Routing and Excess Storage, Shen et al., 2014) for the hydrological part and AROME (Applications of Research to Operations at Mesoscale model, Seity et al., 2011), WRF (Weather Research and Forecasting model, Skamarock et al., 2007) and others for the atmospheric component, with the main issue being the successful prediction of high-intensity rainfall associated with convection (Llasat et al., 2016). Other studies rely on the combination of rain gauges and meteorological radar data (Llasat et al., 2016). In general, a successful numerical simulation of a flash flood event requires the combination of an accurate atmospheric model, a suitable hydrological model and rainfall data of adequate spatial and temporal resolution (Atencia et al., 2011).

Greece experiences a variety of catastrophic weather events, namely floods and flash floods that are frequently followed by severe consequences on the social and economic activity (Papagiannaki et al., 2013) and are primarily connected with strong convective storms developed during the warm season, especially over continental areas. These are mesoscale events with small spatial coverage (5-10 Km) and small-time scales, usually 1-2 hours (Wallace and Hobbs, 2006). The potential of these storms to become hazardous for human life and infrastructure depends on whether the convection organizes into mesoscale convective systems, or into the long-lived convective cells (supercells). In any case they distribute large amounts of water in a limited area very fast. In some cases, the response of watersheds to this type of rainfall events and their runoff rates, are not fast enough, leading to flooding events (Gaume et al., 2016). The negative effects of these phenomena are aggravated in built riverside areas as prevention is a parameter usually ignored during urban planning (Despiniadou and Athanasopoulou, 2006).

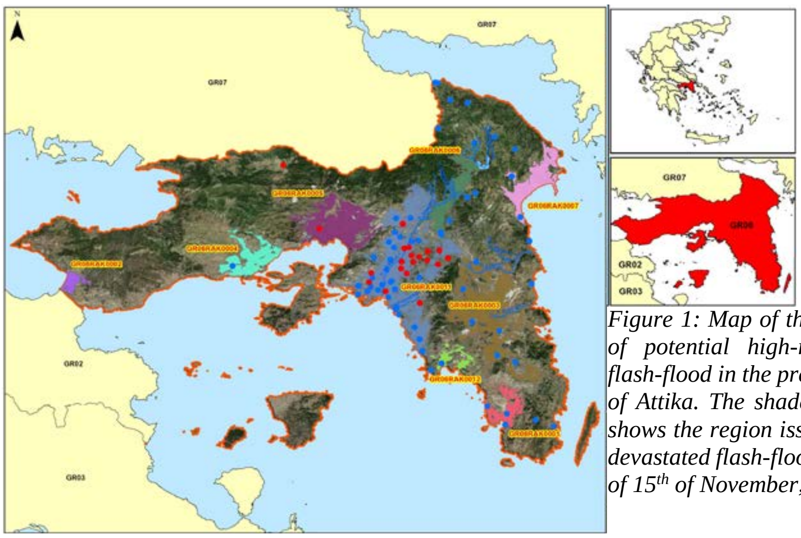


Figure 1: Map of the zones of potential high-risk on flash-flood in the prefecture of Attika. The shaded area shows the region issued the devastated flash-flood event of 15th of November, 2017.

A significant part of the drainage network of Greece consists of mountain torrents and small to medium size drainage basins with limited amount of discharge capabilities for most of the year (Diakakis et al., 2012). Even worse, several parts of the network were diminished, turned into streets or built upon, thus cutting off critical river cross sections (Baltas and Mimikou, 2002). The combination of highly intense convective storms and bad urban planning has led to a series of severe flash flood occurrences in Greece over the past years. A notable event, leading to one of the most devastating flash floods in Attika (suburban city of Mandra), occurred on the 15th of November 2017. Attica prefecture contains the capital, Athens, and it is currently the most populated region in Greece. According to the technical study “FLOOD RISK MANAGEMENT PLAN AND PRIORITIES: for the river basins of Attica prefecture” issued from the Ministry of Environment and Energy, specific secretary of inland waters for the effective elaboration of high risk flood hazard maps and management plans, issued the specific region (GR06RAK0005) of high risk danger and susceptible to flash-flood (see map in Figure 1) This study aims to provide a hydrometeorological analysis to an extreme flash flood event took place in the sub-urban area of Mandra, Attica, Greece.

2 Description of the synoptic and atmospheric instabilities

During the last month of fall 2017 and particularly the last two weeks of November the wider Mediterranean region including the eastern Mediterranean and the Aegean Sea was affected by successively organized barometric lows accompanied by corresponding frontal activities, causing locally strong phenomena. One such rare organized Mediterranean cyclone (named Medican Numa/Zenon), formed on the 11th of November between Tunisia and Libya (Figure 2), which accompanied an organized surface low with its center at the Gulf of Syrtis and a hot front along Sicily - South Italy and the North Ionian Sea. It's the type of storm we're accustomed to seeing in the tropical waters of the Atlantic and Pacific Oceans, perhaps leaving a trail of destruction through the Caribbean and Gulf of Mexico.

This situation affected the western, central and northern parts of Greece with showers and storms, with local adverse phenomena affect the North Ionian - Epirus and particularly the Corfu island. Subsequently, during the 12th of November the above closed low in the upper troposphere moved N-NE during the early hours of 13th November it gradually began to influence from the west - southwest the rest of the country. In the early morning of the 13th of November, a secondly organized instability in the upper tropospheric with cold air masses affect the whole country. In particular, the synoptical behavior of this particular low was the main factor for the shape and evolution of the adverse phenomena in Greece from 14-11-2017 until 19-11-2017. One of the main features of this extended upper low was the fact that it remained almost stationary in the region between Southern Italy - Sicily and the Tyrrhenian Sea.

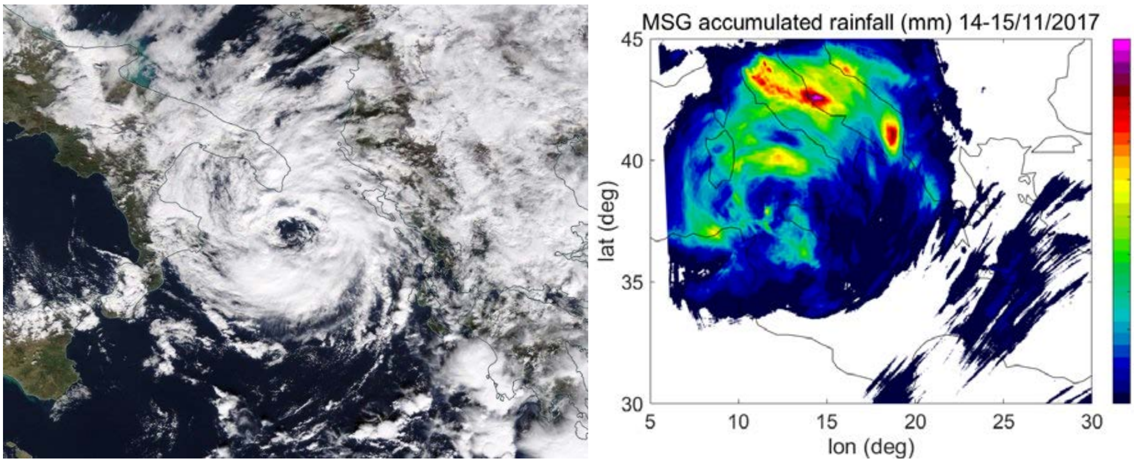


Figure 2: A Mediterranean "hurricane" named Numa struck Greece during 11-19 November 2017. Credit: NASA

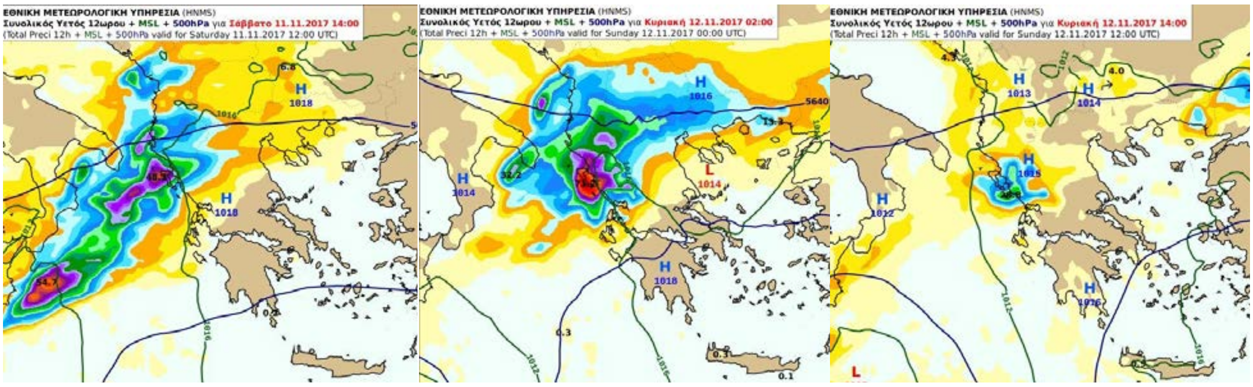


Figure 3: Official prognostic maps (rain accumulation and 500/surface HPa) issued from National Hellenic Meteorological Service (HNMS) associated with the flash flood events during the 11-12 November 2017 in Corfu island. Credit: HNMS

3 The flash flood case study of Mandra, Attika

In the early morning on the 15 of November an intense persistence precipitation event was observed at the mountain of Patera, 10 km north-west of the sub-urban city of Mandra, west of prefecture of Attika, in the preferences of urban capital city of Greece, Athens (see map in Figure 5). The region hosts the largest industrial units in Attica such as refineries, metallurgical industries, factories, shipyards as well as the waste landfill of all Attica prefecture. The intense presence of heavy industrial use, urbanization and other land changes have deteriorated to the worse the environmental pressures while have significantly increasing flood the risk. The anarchy residential and industrial development and activity did not follow any appropriate infrastructure network for flood protection and drainage rainwater collection (Mavrakis et al. 2004).

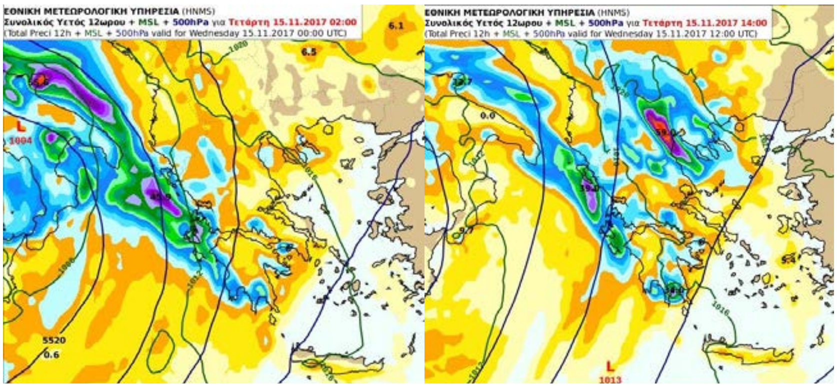


Figure 4: Similar to Figure 3 but for the case of Mandra flash flood in Attica region, during the 15th of November 2017. Credit: HNMS

The hydrographic network (see map in Figure 6) of the water basin that drain the large volumes of surface runoff from the steep gradients of surrounding mountainous end up in the Thriasio plateau (in the city of Elefsina) are extremely rich. The main streams apart this large water basin are the Sarantapotamos and St. Vlasiou (Fig 6b). During this event, rainfall data were collected from the XPOL radar of the National Observatory of Athens located on the Penteli mountain (about 30 km NE of Mandra). The XPOL radar was operated during rain events in plan position indicator (PPI) mode taking measurements in a sector scan of 180°, at 0.5°, 1.5° and 2.5°elevation sweeps with a range resolution of 120 m for the total range of 65 km. Antenna rotation rate was 6 deg s^{-1} and he time period for a full volume scan was less than 3 minutes.

Figure 5: map of the west of Attika indicating within the shading area (Thriasio) the main drainage network (with blue lines) and the region affected from the flash flood event of 15th of November 2017

The study domain is also covered by an operational C-band radar of HNMS at the mountain of Hymettus, about 10 km south of XPOL radar. Based on the HNMS official report, the total estimated rainfall accumulation recorded on 15 of November from 00:00 UTC until 12:00 UTC was 80 mm with the highest recorded rainfall rates (at the mountain of Patera) was above the 300 mm/hr.

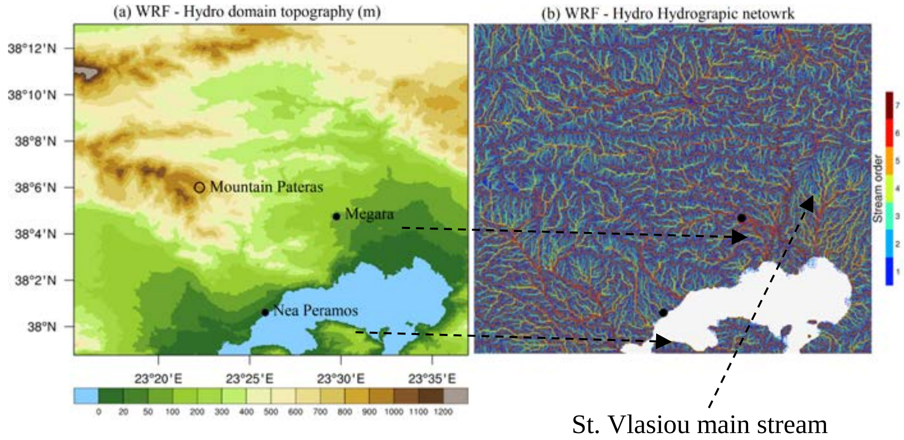


Figure 6: (a) topography and (b) hydrographic map of the water basin used for the hydrological runs

On the other hand, the XPOL recorded total accumulated precipitation (in the core of the storm at the mountain of Patera) of more than 200 mm (Figure 7b). More impressive was the fact that the highest precipitation rates of the core of the storm recorded during the time 03:00 to 06:00 UTC was more than 120 mm/hr (Figure 7a). This caused the sub-basin of St. Aikaterini to overflow and flood the area of Mandra, located in west Attica (see map in Figure 5), causing extensive damages on property and infrastructure, and the death of 23 people.

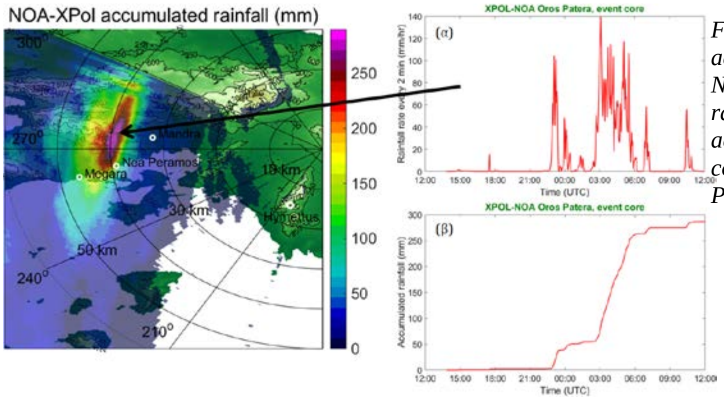


Figure 7: XPOL PPI rain accumulation during the 15th of November flood event with (a) rainfall rate and (b) accumulation rainfall, over the core of the storm in the mountain Patera

Comparisons of the total accumulation rainfall estimations recorded from the IMERG (Integrated Multi-satellitE Retrievals for GPM) satellite precipitation product (Figure 8a) with the aggregated 10x10 km XPOL rainfall product (Figure 8b) agrees very well, indicating of more than 200 mm rainfall (from 00:30 UTC until 07:30 UTC of 15 of November) over the city of Mandra (Figure 8c).

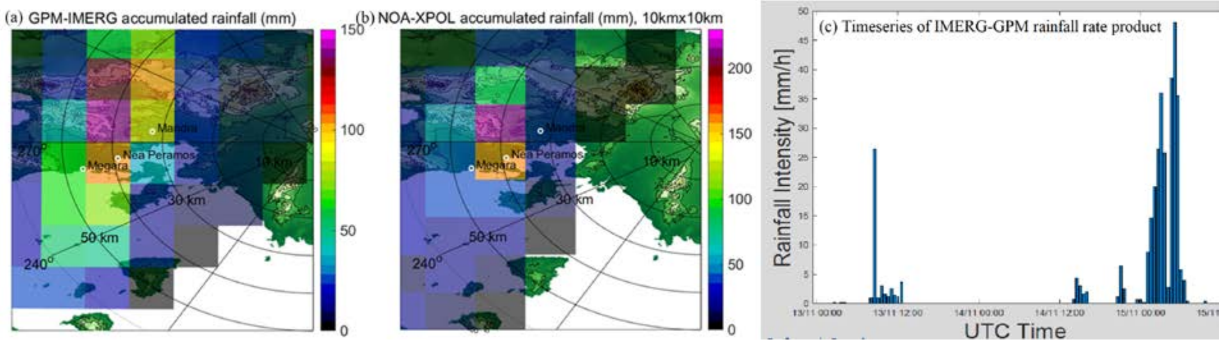


Figure 8: rain accumulation estimates during the 15th of November flood event from (a) GPM-IMERG product, (b) XPOL 10x10 km aggregated product and (c), timeseries rainfall rate from the IMERG-GPM over the city of Mandra.

3.1 Configuration of the Hydrological model based on the CHAOS (WRF-Hydro)

The potential benefit in using short-range X-band dual-polarization high-resolution observations for flood modeling applications is examined by comparing the different radar, satellite and prognostic simulations, with the later used as reference throughout the hydrologic analysis. Dynamic downscaling of the GFS (0.25°×0.25°) setting up the forecasting model of CHAOS (WRF-ARW) in the study domain with horizontal resolution of 9 km × 9 km, 3 km × 3 km, 1 km x 1 km and 0.25 km × 0.25 km covering the Europe, Greece and region of Attica, respectively. Coupling the CHAOS (WRF-Hydro model 50 m × 50 m) with the atmospheric forecasting model precipitation (Varlas et al. 2017), satellite and radar precipitation estimates in the city of Mandra every hour in the 0.25 km x 0.25 km grid. The hydrological configuration of the network is based on a 90 meters digital elevation map and the methodology followed for the stream ordering is on Strahler.

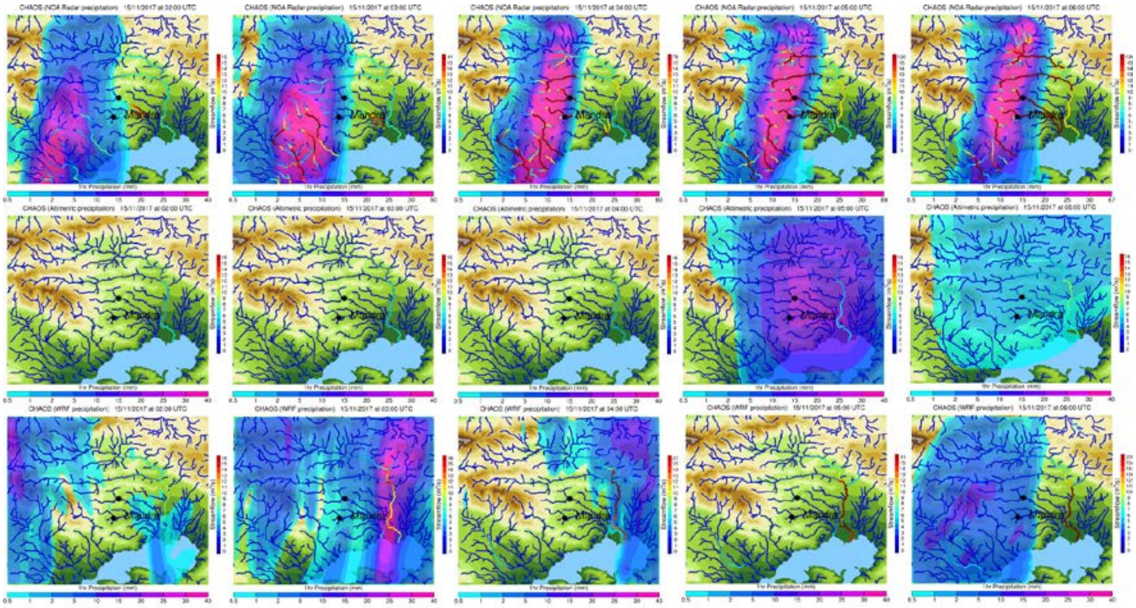


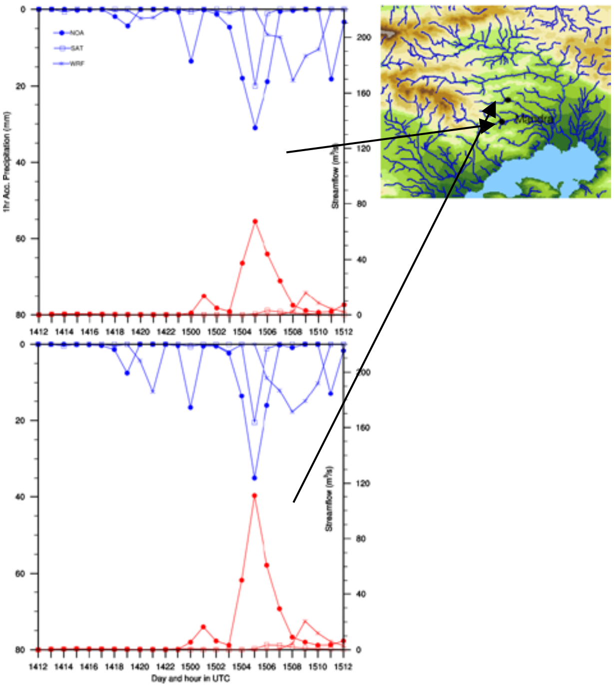
Figure 9: surface hourly rain accumulation estimates from the NOA's XPOL radar (upper five subplots), the IMERG-GPM (middle subplots) and the WRF-ARW (lower subplots). On the same plots are superimposed the simulated streamflows forced from each of the three rainfall estimates.

Simulated streamflow of the 02:00 until 06:00 UTC of 15th of November is shown in Figure 9 superimposed the surface hourly rainfall accumulation (mm) of NOA's XPOL in the upper five subplots, the IMERG-GPM in the middle ones and the WRF-ARW in the lower, ones. Due to the absence of any ground validation stations, a more qualitative approach will be followed. It is obvious that there are different characteristics in the spatial pattern and intensities of all three different the surface precipitation estimates. However, the satellite is missed the majority of the peak of the storm. It only indicates precipitation during the last two hours (i.e. 05 and 06 UTC). On the other hand, the WRF-ARW forecasting model is closer to the radar rainfall estimates, however, not that much in the pattern of the storm but in the total duration and in some cases in the intensity. Similarly, the streamflow simulations assimilated from the three estimates is clearly indicates that the simulation coupled from the radar precipitation estimates is the one that gives the higher streamflows, where in turn this can be assumed as flooding.

Figure 10, on the other hand, is a more quantitative comparison approach, showing the hourly streamflow simulations from 12 UTC of 14 of November up to 12 UTC of 15 of November forced from radar, satellite and forecasting rainfall estimations. Both plots are extract from the two black dotes shown in the upper right map of the figure. We notice that the peak rainfall intensities of radar match with the satellite but underestimate the total rainfall accumulation, while the model estimates, even though are shifted in time, they are better comparable to the total rainfall accumulation to the radar estimates. Similarly, the streamflow simulations are match better in time between the forcings from radar and satellites, but, in total quantity of streamflow, the forcing of WRF-ARW matches better with the radar estimates.

4 Conclusion

This study presented the hydrometeorological analysis of an extreme flash-flood event in the sub-urban area of west Attika in Greece. A three-day (14–16 November 2017) wave of hazardous weather with intense precipitation rates persisted around the mountain Pateras in the sub-urban town of Mandra, resulting to tremendous flooding with landslides, extensive damages and a total of 23 fatalities. The area is highly urbanized with complex terrain effect. This case study has been simulated by the non-hydrostatic WRF-ARW atmospheric model coupled with an advanced hydrological module CHAOS (WRF-Hydro) able to offer improved simulation of land surface hydrology and energy states and fluxes at a fairly high spatial resolution using a variety of physics-based and conceptual approaches. The CHAOS (WRF-Hydro) simulated this case study under three different precipitation forcings. The first was based on WRF-ARW hindcasts (WRF-Hydro), the second one was based on XPOL and C-Band radar estimates (XPOL-Hydro) and the third on core GMP/IMERG estimated precipitation rates (GMP/IMERG-Hydro). The initial precipitation forcings are evaluated against surface raingauge and disdrometer observations close to the area of interest. Preliminary results indicate that XPOL-Hydro outperforms the WRF-Hydro and the GMP/IMERG-Hydro in terms of water level and surface runoff estimations.



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