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Application of a GIS based distributed model for rainfall runoff simulations

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Abstract: In this research work, the development and application of a distributed rainfall – runoff model, to be used in flood related simulations was performed. The model utilizes the time–area diagram theory in order to calculate and route the runoff of each grid to the basin's outlet. The selected study area is the upper part of the Alfeios river basin, the Karitaina basin, located in southern Greece, while historic rainfall data from regional rain gauges were used, which were interpolated through GIS tools into spatially gridded rainfall fields, with a one-hour temporal scale. The performance of the distributed model was evaluated through its comparison with two lumped models, one based on GIS techniques and the other one based on the unit hydrograph derived from historical rainfall-runoff events. Finally, the abovementioned models were also compared and evaluated with the observed hydrograph of the studied event. The results showed that the distributed model performed well considering that no calibration has been carried out regarding the hydrological losses.

Keywords: Hydrological modelling, rainfall-runoff, GIS, Alfeios, distributed model

1. Introduction

Hydrological models are nowadays considered as an important and necessary tool for water and environment resource management. According to Sorooshian et al. (2008), a model is a simplified representation of real-world system. Rainfall-runoff models are classified based on model input and parameters as well as the extent of physical principles applied in the model. It can be classified as lumped and distributed model based on the model parameters as a function of space and time and deterministic and stochastic models based on the other criteria. The two fundamental inputs required for all models are rainfall data and drainage area. Along with these, water basin characteristics like soil properties, vegetation cover, watershed topography, soil moisture content, characteristics of ground water aquifer are also considered (Devi et al., 2015). Especially, the development of distributed hydrological models with varying degrees of complexity to address a wide range of scientific questions has become widespread in recent years (Kampf and Burges, 2007; Smith and Gupta, 2012; Bournas and Baltas, 2021).

In this research work, the development and application of a distributed rainfall – runoff model, to be used in flood related simulations was performed. The model utilizes the time – area diagram theory in order to calculate and route the runoff of each grid to the basin's outlet, while historic rainfall data from regional rain gauges were used, which were interpolated through GIS tools into spatially gridded rainfall fields, with a one-hour temporal scale. The performance of the distributed model was evaluated through its comparison with two lumped models based on the unit hydrograph (UH) theory, one derived using GIS techniques and the second one derived from historical rainfall – runoff events. Finally, the abovementioned models were also compared and evaluated with the observed hydrograph of the studied events.

2. Study Area and Data Used

The selected study area is the upper part of the Alfeios river catchment, the Karitaina basin, located in southern Greece (Figure 1). The basin is surrounded by Mount Taygetus in the south, Mount Lykaion on the west and Mount Mainalo on the northeast, while its outlet is located in the northwest of the basin, near the Karitaina settlement. The basin total area is 871 km^2 with a mean, elevation height of 762 m. The most significant stream is the Alfeios river, whose source lie in the Mount Taygetus, while the smaller Elissonas stream springs from Mount Mainalo and joins Alfeios near the Megalopoli settlement (Figure 1). The basin has a nearly symmetric shape, close to an oval shape rather than an elongated shape, which has the effect of generating hydrographs with steep rising limb; as a result, high peak discharges are often observed.

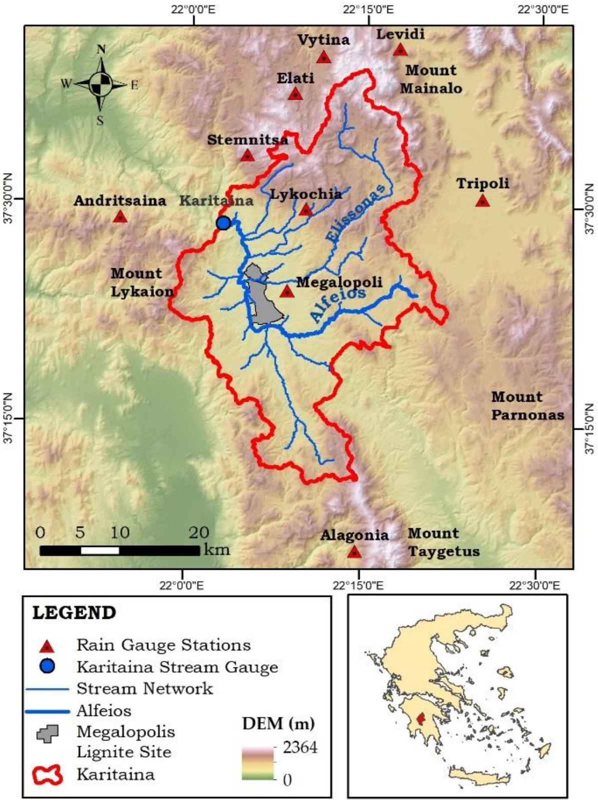

Figure 1. Study area, Karitaina subbasin

The datasets used in the analysis were mainly the Digital Elevation Model (DEM), the Corine Land Cover (2012), and the hydrological soil type, according to SCS (1972) and the work of Bournas and Baltas (2021) were taken into consideration. Other DEM-derived geomorphological and hydrological attributes, such as the slope and streams definition. The DEM (Figure 1) was provided by the National Cadastre and Mapping Agency S.A., and features a cell size of 5 m x 5 m. The flood events studied, were based on available precipitation datasets of the most recent and severe historic flood events occurred within the study area. More specifically, the rainfall – runoff events studied occurred on 01/03/2013, on 01/03/2014, on 23/01/2015, on 26/02/2015 and on 05/03/2015, code named in this studied as Event 1, 2, 3, 4 and 5 respectively. The precipitation datasets of the adjacent to the catchment area rain gauges, depicted in Figure 1, were provided by the National Observatory of Athens network (NOANN) (Lagouvardos et al., 2017), which feature 10-minute precipitation recordings. Finally, the streamflow data were derived from water level measurements by applying a derived rating curve as shown in the work of Bournas and Baltas (2021).

3. Methods

The distributed model used was developed in a GIS environment, using python (ArcPy) and GIS tools in order to perform a series of processes between raster datasets. A brief flow chart is presented in Figure 2. The raster datasets spatial resolution was of a 500 m x 500 m grid size, and a 1-hour temporal scale although any grid size and temporal scale is applicable, although the computational demands and simulation times increases substantially. The output of the model is the flow hydrograph on the basin outlet. The main processes of the model are as follows:

Since the input of the model are the rain gauge raw precipitation datasets, the first component of the model is to aggregate these datasets into 1-hour time step and then apply Inverse Distance Weighting (IDW) to interpolate and create rainfall gridded dataset. The next step deals with the precipitation losses, where the SCS – Curve Number (CN) method is incorporated, considering the input of the gridded CN dataset of values throughout the watershed area. The CN is an empirical parameter used in hydrology for predicting direct runoff or infiltration from rainfall excess based on the area's hydrologic soil group, land use and soil moisture conditions. Kadam et al. (2012), Saravanan and Manjula (2015), Vinithra and Yeshodha (2016) have used this method to estimate the net rainfall in their studies. The raster dataset is calculated only once, based on the hydrological type of soils and the current land use. The product of this process, is the generation of the effective rainfall raster dataset, available for each time step.

The second component of the distributed model concerns with the estimation of the cells travel time to the basin outlet based on the time – area diagram method. The time - area methods was developed in recognition of the importance of the time distribution of rainfall on runoff. The basic idea of this method is the time – area histogram, which indicates the distribution of partial watershed areas contributing to runoff at the watershed outlet as function of travel time. These areas are bounded by isochrones curves. An 'isochrone' is a contour joining those point in the watershed that are separated from the outlet be the same travel time (Singh, 1992). Derivation of the time - area diagram requires knowledge of the soil roughness, the terrain slope, as well as the distribution of flow directions and velocities over the watershed (Muzik, 1996). This process is run once, in order to produce the time-area raster dataset, which is then used to produce the flood hydrograph.

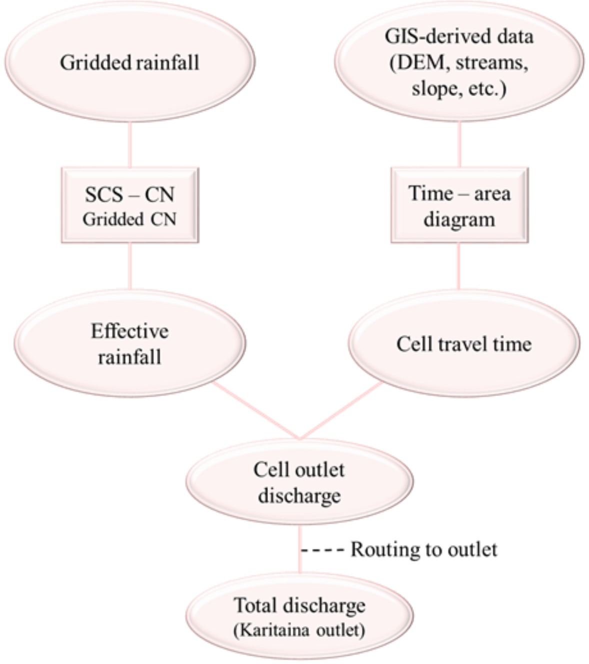

Figure 2. Distributed model structure

Finally, given the net rainfall time series occurred over each cell of DEM and the grid dimensions, the runoff hydrograph corresponding to the outlet of the cell is calculated and routed downstream depending on the cell travel time which was specified with the time-area dataset, as described above. The appropriate superposition of the individual hydrographs, sum up for each time interval to create the total flood hydrograph.

The performance of the model was evaluated through intercomparing with the observed runoff, as well as, the runoff simulated by two lumped based models, based on the UH theory. The first model was a UH derived from rainfall – runoff observations analysis by HPPC for the Karitaina station, and should match the studied events with high accuracy, while the second model was based on the time – area diagram method as in the case of the distributed model, although a UH approach is used against the distributed nature of the rainfall and cell routing methods used earlier.

In all cases where the time-area diagram was used, i.e. the distributed and the second lumped model, the time area gridded dataset was calibrated by changing the over channel velocities for each segment of the stream network according to Strahler's stream ordering method. The Nash – Sutcliffe efficiency coefficient was then calculated for the lumped UH derived from the time-area diagram, and the given UH values based on the historical events. The selected velocities resulted in a Nash – Sutcliffe efficiency coefficient equal to 0.93, which showed high correlation

4. Results

The results derived from the simulation of the examined rainfall events by applying the three models described in methodology section, are presented in Figure 3 - 7, where the "Q Model", the "Q UH" and the "Q Isochrone" represent the distributed model, the lumped model using the given UH and the lumped model UH developed with the time – area diagram method, respectively.

In all of the rainfall events analyzed, the lumped models resulted in higher peak and flood volume values compared to the distributed model, which is mainly the result of adapting a lower loss rate overall by using a single CN across the catchment area, equal to the average value of the spatially distributed CN. In events where the highest rainfall was recorded in the central and southern parts of the hydrological basin, e.g. in events 1, 2, 3 and 4, the peak appeared earlier than the observed for all models applied. This systematic underestimation of the time to peak is the result of the small time required for the volume of water received in these areas, to actually flow out of the catchment outlet. In three of the events examined, the distributed model approached the observed peak flow with a 90% or greater accuracy, while the corresponding rate applying the isochrones model or the model of UH derived from rainfall – runoff measurements was achieved in two and one of the events only, respectively. In regards with the performance of the models in the time to peak value, the distributed model led to an underestimation of 15% on average in four out of five episodes and an overestimation of 27% in the fifth event, which all models did not perform well.

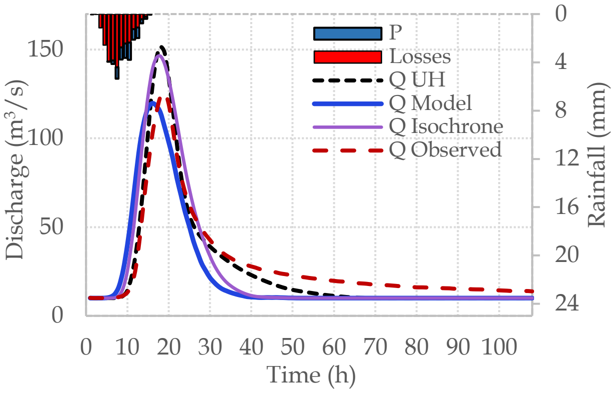

Figure 3. Flow hydrograph, event 1

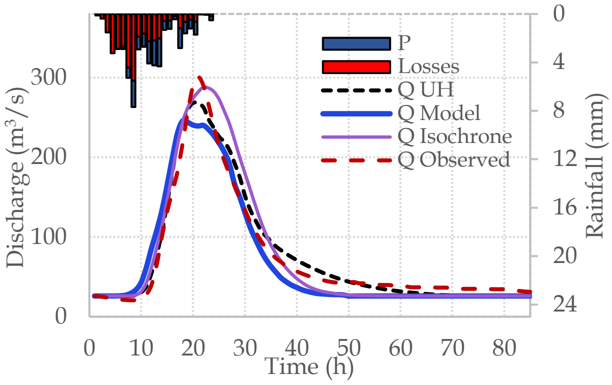

Figure 4. Flow hydrograph, event 2

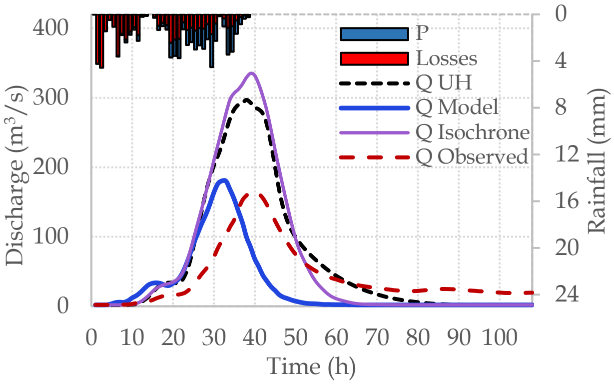

Figure 5. Flow hydrograph, event 3

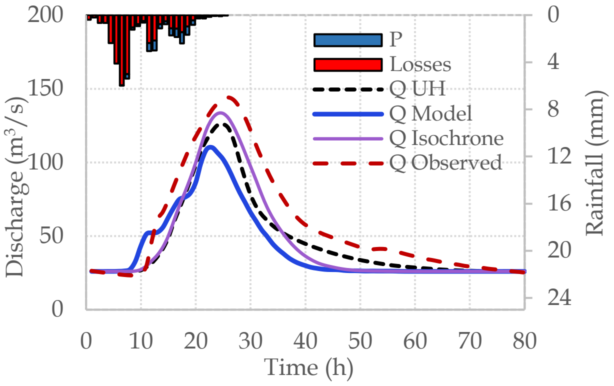

Figure 6. Flow hydrograph, event 4

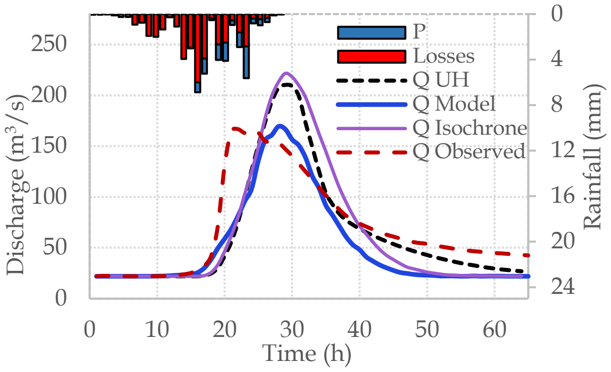

Figure 7. Flow hydrograph, event 5

The isochrone curve model in four of the episodes approached the observed peak time by more than 92%, while the given UH model by more than 95%. The great adaptation of the given UH model to the observed values is probably justified by the fact that the given UH must have been calibrated based on the observed data used, and thus it is logical to perform. The behavior of the two lumped models showed significant similarities, as seen in the results, which was to be expected, as the UH produced using the time – area diagram method was calibrated in order to approach the given UH derived from field observations. However, the performance of both models was arguably bad in event 3 where a huge overestimation of the peak flow was performed, while the distributed model performed much better.

5. Conclusions

The objective of this research work was to develop and implement a distributed hydrological model for the simulation of historic rainfall – runoff events that occurred in the Karitaina basin. Alongside, two lumped models were used for the simulation of the same events and a comparison between simulated and observed flow hydrographs was performed.

Results indicated that the spatial discretization of rainfall significantly affects the response of the hydrological model used to simulate the rainfall-runoff process. Furthermore, hydrological losses are still considered the most crucial parameter for any rainfall – runoff model since they influence the response of the entire catchment. The correct allocation of the spatially distributed CN coefficient within the catchment is thus significant. Regarding the peak discharge, there is a discrepancy between simulated and observed value at a rate of 11.6%, 33% and 30% on average, applying the distributed model, the isochrone model and the UH model, respectively. The peak time of the observed flood hydrograph is approached more correctly by a lumped model. The deviation rate for the three models averages 17.4%, 9.9% and 9.7% for the distributed, the isochrone and the UH model, respectively. In the majority of simulations, the model deviation led to an underestimation of the peak runoff time.

Overall, it can be said that the effect of the spatial discretization of the rainfall on the form of the runoff hydrograph resulting at the outlet of the hydrological basin should be addressed as it leads to more robust solutions. In addition, the use of accurate data related to geomorphology and soil moisture conditions, as well as the availability of high-precision rainfall and runoff datasets are also key factors regarding the final performance of the hydrological model in terms of representing the natural system. Hence, further investigation should be conducted concerning the appliance of GIS – based distributed models for forecasting and water resource management purposes.

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