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Simulation of an urban flash flood: the 2017 flood event in Mandra, Attica

HANDRINOS S.[1], BELLOS V.[1,2]* and SIBETHEROS I.A.[1]

[1]University of West Attica, 250 Thivon & P.Ralli Str, 12241 Egaleo

[2]National Technical University of Athens, 9 Iron Polytechniou str., 15780, Zografou

*corresponding author:
e-mail: vmpellos@mail.ntua.gr

Abstract

This study deals with the 2D flood simulation of an urban flash flood event that took place on November 15, 2017 in Mandra, Attica. The well-known hydrodynamic software HEC-RAS was used for the flood simulation. The model input was an ensemble of 100 hydrographs, derived from the simulation of the rainfall-runoff process of the Agia Aikaterini catchment, which flows into Mandra. The study focuses on a grid search-based calibration of the model parameters, by comparing simulation results to post-flood field data. A Morris-based sensitivity analysis was used in order to reduce the number of parameters to be calibrated and therefore reduce the dimensions of the problem and the computational cost. Five parameters were selected for the sensitivity analysis: a) the Manning coefficient of the city roads; b) the Manning coefficient of urban blocks characterized by low roughness; c) the Manning coefficient of urban blocks characterized by high roughness; d) the confidence interval of the empirical distribution of the 100 hydrographs ensemble; e) the energy slope used for the downstream boundaries. It was found that the parameters with the most significant impact were the input hygrograph's confidence interval (first) and the Manning coefficient of the city roads (second).

Keywords: urban flood, flash flood, 2D hydrodynamic model, HEC-RAS.

1. Introduction

Floods are the most common natural hazard in the world in the last 50 years (Ritchie and Roser, 2019), and second only to forest fires in Greece during the same period. In most cases they have negative impacts on people and property in the affected areas, or even cause major disasters. In the region of Attica, Greece in particular, over 100 urban flash flood events of various levels of severity have the occurred during the 2001-2017 period, causing damages buildings, infrastructure and vehicle; transport disruption; flooded roads; and in some cases, human fatalities. A flash flood (FF) is defined as a flood that follows within a few hours after a heavy or excessive rainfall event (Georgakakos, 1986). In the 1950-2006 period, 40% of the flood-related casualties in Europe were due to FF events that took place in different geographical regions (Gaume et al., 2009). In the Mediterranean region, FFs usually occur in spring and autumn, after intense, heavy and irregularly distributed rains (Diakakis et al., 2012).

In this study, we focused on the flood simulation of the 2017 Mandra FF, which had a death toll of 26 and caused significant property damage. Comparison of simulation results to post-flood field data, allowed the calibration of the simulation model parameters and the identification, via a sensitivity analysis, of the most important parameters.

2. Materials and Methods

2.1. Case Study

The study area is situated in the west part of the region of Attica in Central Greece along the eastern-southeastern foothills of Mt Pateras (1132m). The town of Mandra is situated on the western margin of the Thriassion plain which borders with Mt. Pateras, within the catchment of the Soures torrent and its main tributary Agia Aikaterini. (Figure 1)

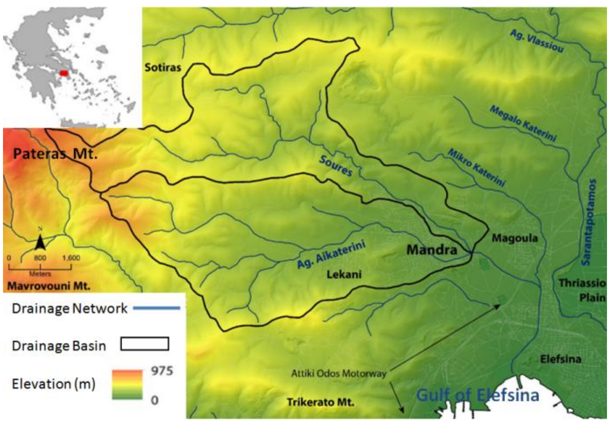

Figure 1: Location map of the study area.

The storm event that occurred between 14th November 2017 at 23:00 UTC and 15th November 2017 at 12:00 UTC, was captured by the NOA (National Observatory of Athens) X-band polarimetric radar (XPOL). According to the XPOL Doppler, the total rainfall on Mt. Pateras, above Nea Peramos and Mandra, exceeded the 200 mm height during the 6 hour main storm event, with instant rainfall intensities reaching peak values of up to 120 – 140 mm/hr (NOA, 2017). This rainfall amounts to 3.5 times the average rainfall of the whole month of November in this area.

2.2. HEC-RAS

The well know hydrodynamic software HEC-RAS, designed by the U.S. Army Corps of Engineers, was used for the flash flood simulation. It is capable of performing 1D steady flow, 1D and 2D unsteady flow calculations, sediment transport/mobile bed computations, and water temperature/water quality modeling. For this study we performed 2D unsteady flow modeling of the Mandra FF event, applying the Diffusion Wave equations, which are a simpler form of the Shallow Water equations. A spatial resolution of 5m was used, matching the resolution of the available digital elevation model. First, we determined the mesh boundaries of the model's 2D area (1.6 km^2), inserted manually (233) flow breaklines around urban blocks and then modified the 2D mesh by generating orthogonal cells around the breaklines, thus improving computational speed and accuracy of the model. For the whole 2D mesh 121.583 cells were generated with the average cell area being about 13 m^2. Assigned boundary conditions (BC) at the upstream and downstream ends of the 2D mesh. For the upstream BC, input data from a Confidence Interval (CI) analysis (at various confidence levels) of 100 hydrographs were used, based on the uncertainty analysis of the flood event, performed by Bellos et al., 2020. For the downstream BC the single parameter option for the Manning equation was chosen, namely the energy slope (S_f). Three different Manning roughness coefficients were considered: a high (n_H), and a low (n_L) Manning coefficient for urban blocks, and a Manning coefficient for the city roads (n_r). Finally, we adjusted all input and output data for the unsteady flow simulation.

2.3. Sensitivity Analysis

The next step was to perform a sensitivity analysis, based on the method proposed by Morris (1991), in order to identify the model parameters exerting the most influence on the model results. This method has been widely used for model parameter sensitivity analysis in various scientific fields (Christelis et al., 2018). It is based on the calculation of the Elementary Effect (EE), for each input parameter, which is the ratio between the change of the model output value (due solely to a change of the specific input parameter value) and the parameter value change. For each input parameter, the absolute mean $\mu_j^* = \frac{1}{n}\sum_{i=1}^{n}\left|EE_{i,j}\right|$, and the standard deviation of the EEs, $\sigma_j = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left[EE_{i,j} - \frac{1}{n}\sum_{i=1}^{n}(EE_{i,j})\right]^2}$ are computed. In both equations, j denotes the jth input parameter, and i the ith sample. It should be mentioned that the sampling process is described in Morris (1991) and implemented via the SAFE toolbox (Pianosi et at., 2015)

Simply stated, the higher the value of the μ_j^* the greater the effect of the input parameter (j) on the model results. σ_j is a metric of the nonlinearity and/or interaction effects of the parameter in question (j) with other input parameters. High values of σ_j denote nonlinear effects or interactions with at least one other parameter.

3. Results

3.1. Sensitivity Analysis Results and Model Calibration

The global sensitivity analysis (GSA) involved 5 model parameters, that is: (1) the Manning's coefficient for the roads, n_r, (2) the Manning's coefficient for the urban blocks (high value), n_H, (3) the Manning's coefficient for the urban blocks (low value) n_L, (4) the coefficient interval, CI, for the upstream hydrograph, (5) the downstream energy slope, S_f.

The range of the values which were assigned to each of the five parameters are presented in Table 1.

Table 1. Parameter limits for the sensitivity analysis.

Parameter	**Lower Limit**	**Upper Limit**
n_r [s/m$^{1/3}$]	0.03	0.06
n_H [s/m$^{1/3}$]	40	60
n_L [s/m$^{1/3}$]	15	25
CI [%]	10	90
S_f [-]	0.01	0.03

The robust and well-documented SAFE Toolbox (Pianosi et al., 2015), was used for the GSA task. First, 90 scenarios were produced with different parameter combinations. Then, the HEC-RAS based hydrodynamic analysis for these scenarios was performed, and the root mean square error (RMSE) of the differences (errors) between the post-flood data (Raptaki, 2019) and simulated maximum flood depths at several locations was calculated. Finally, with the given input of 90 RMSEs, SAFE Toolbox calculated the mean and standard deviation of the EEs, for each of the selected five parameters (Figure 2). It can be observed that the CI of the 100 hydrographs has had by far the most impact on the final results, followed by the Manning's coefficients of the city roads n_r.

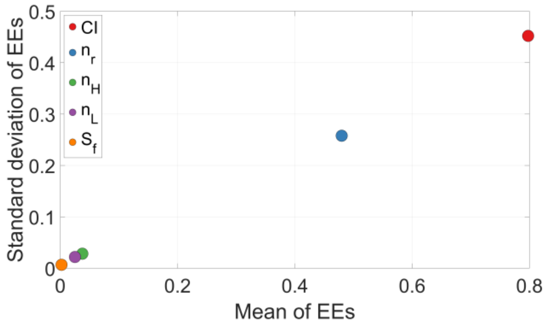

Figure 2: Schematic representation of the sensitivity analysis based on the RMSE of the points.

Based on the previous analysis, and focusing on the pair of the most influential parameters (CI, n_r), a grid-search calibration was held, in order to find the optimal combination of the pair values. Assuming a step of 10% for the CI and 0.01 s/m$^{1/3}$ for the n_r, we produced 9x4=36 scenarios. Then, we performed again the hydrodynamic analysis for these scenarios and we derived the RMSEs of the max depths against the observed data (Figure 3).

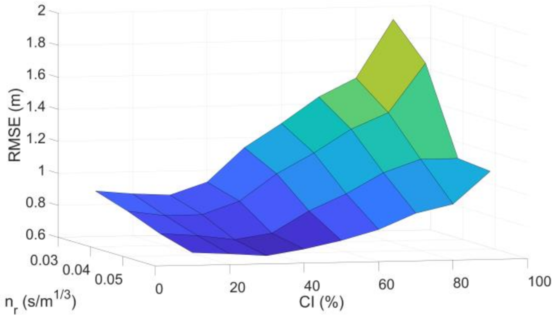

Figure 3: 3D representation of the calibration based on the RMSE of the points.

Since the target is the combination of the CI and n_r values for which the RMSE is minimized, it can be deduced from Figure 3 that these values are 30% and 0.06 s/m$^{1/3}$ respectively.

3.2. Flood Mapping

The results of the reconstructed flood event were visualized via the RAS-Mapper, an extensive data integration and mapping system within HEC-RAS. Maximum flood water levels were reconstructed over the flooded area of the town of Mandra (Figure 4). The flood water enters from the north-west side of Mandra (green area), then follows a south – east path (light green - orange - light orange area), dictated obviously by the topographic shape of the area, and exits through the north – east side of the town (yellow area).

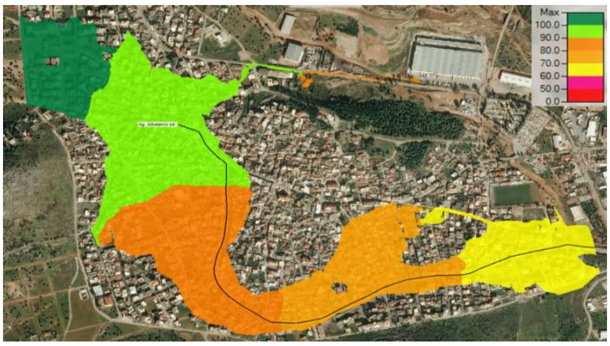

Figure 4: Simulated water surface elevation of the town Mandra. (1:5000)

The largest flood water volume is concentrated along Agia Aikaterini str., which was one of the main streets inundated during the flood event (Figure 4, black line). The 44 surveyed points within the city and the map of the simulated maximum flow depths are presented in Figure 5. It should be noted that, the simulated flow depths didn't exceed 3 m in the entire computational domain, and only 35 of the 44 surveyed points came in contact with the simulated flood.

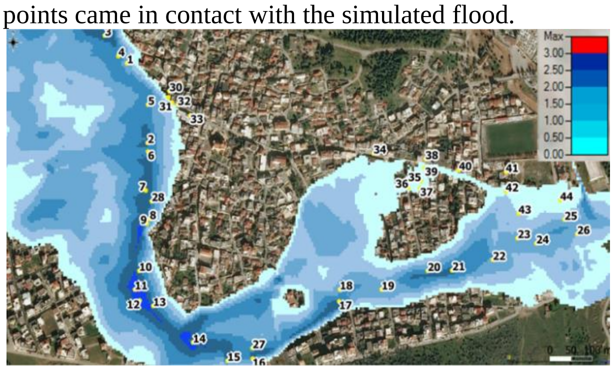

Figure 5: Simulated flood map and the location of the 44 surveyed points.

A comparison of the results derived by HEC-RAS and the observed flood depths each one of the 35 surveyed points that came in contact with the simulated flood are depicted in Figure 6 in the form of a bar chart. The difference between simulated results and post flood depth measurements in these 35 points range from -1.88 m (underestimation) to + 0.68 m (overestimation). Specifically, 60% (21 points) of the simulated flow depths were lower than the measured ones by 0.63 m on average, whereas the remaining 40% (14 points) of the simulated flow depths were higher than the measured by 0.39 m on average. The RMSE of the simulated vs observed flow depths at the 35 points was calculated during the model calibration process and is equal to 0.651 m.

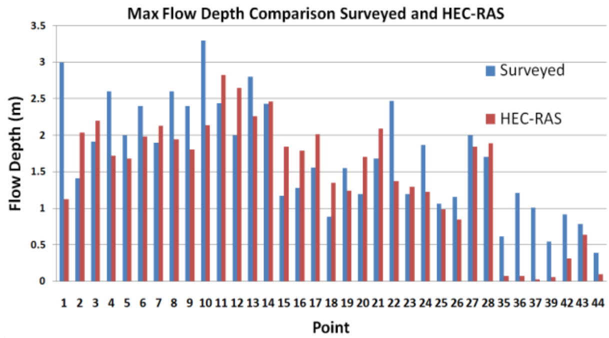

Figure 6: Simulated and surveyed flood depths.

In Figure 7, a longitudinal section of the Ag. Aikaterini str. is presented, depicting terrain and simulated flood water surface profiles, as well as observed flood water elevations at 19 points adjacent to this street section. The average simulated flow depth along the 1865 m stretch of the Ag. Aikaterini str. was 1.9 m with an average flow velocity of 3.6 m/s. The RMSE between the simulated and observed flow depths at the 19 points was 0.686 m.

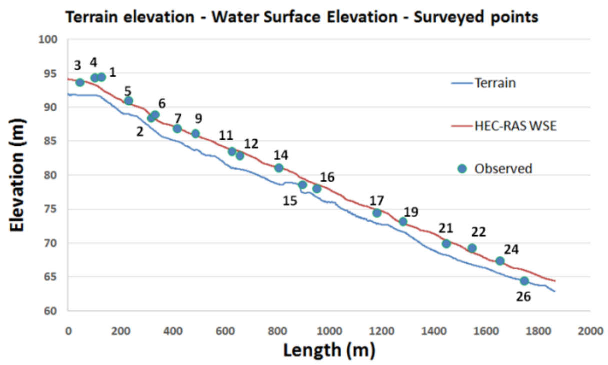

Figure 7: Simulated and surveyed water profile for Ag. Aikaterini str.

4. Conclusions

In this work, a simulation of the flood event that hit the town of Mandra was attempted, based on the hydrodynamic software HEC-RAS 5.0.7.

A global sensitivity analysis was performed, in order to identify the most important input parameters, followed by a model calibration based on surveyed-post flood data of the actual flood event. The comparison of simulation vs. surveyed data shows that an accurate flood simulation is quite difficult, even with a powerful simulation software such as HEC-RAS, and the availability of a relatively large number of reliable post-flood flow depth measurements for model calibration. In addition, it is also hard to determine and rank the different input parameters of the model, and assign proper values to them.

In conclusion, we recommend following these instructions, when attempting a flood simulation.

1. Search for flood field data.
2. Select the model's parameters and assign value ranges to them very carefully.
3. Perform a global sensitivity analysis on the model's parameters.
4. Rank the most essential parameters, based on the findings of the global sensitivity analysis.
5. Calibrate the most essential parameters, with a proper calibration method.

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