



Urban Flood Risk Modeling Using SWAT and HEC-RAS 2D: The Case of the City of Volos, Thessaly, Greece [†]

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Abstract

Flood risk assessment in urban areas is becoming increasingly important due to climate change and rapid urbanization. This study presents an integrated flood risk modeling framework for the city of Volos, Thessaly, Greece, coupling the Soil and Water Assessment Tool (SWAT) with HEC-RAS 2D for comprehensive hydrological–hydraulic analysis. The study area is characterized by complex geomorphology, intense urban development and the presence of torrent streams (Xirias, Krausidonas and Anavros) with a total catchment area of 166.25 km². Geospatial and hydrological datasets, including land use, soil types and a Digital Elevation Model, were integrated within SWAT to generate 19-year daily discharge time series. These outputs were linked to HEC-RAS 2D boundary conditions to simulate flood extent, depth and velocity under two scenarios: Baseline (Manning $n = 0.05$) and Nature-Based Solutions (Manning $n = 0.15$). Results show that NBS interventions reduce flooded area by 25.3%, maximum depth by 20.4%, and affected buildings by 28.7%, with a Benefit–Cost Ratio of approximately 2.2. The methodology provides valuable input for flood risk management, spatial planning and civil protection strategies in Mediterranean urban environments.

Keywords: urban floods; SWAT; HEC-RAS 2D; Nature-Based Solutions; Manning’s roughness; Mediterranean climate

1. Introduction

Flood risk management in urban and peri-urban catchments demands a comprehensive approach that involves hydraulic and hydrological modeling, in order to accurately describe the relationships between catchment processes and urban flooding. Mediterranean cities, such as Volos, are characterized by high frequency of heavy rainfall events, combined with relatively steep topography, rapid urbanization, and increasing imperviousness, resulting in altered urban drainage systems. Taking into account the projected effects of climate change, which lead to increased precipitation extremes over the Mediterranean region, alongside the concurrent land use changes, resulting in increased and more severe episodes of urban flooding, it becomes vital to rely on efficient modeling approaches for flood risk assessment and management [1].

Flood vulnerability and flood risk assessments are particular to the context of the study area. Within the urban area of the city of Volos (in the region of Thessaly, Greece), there are three large torrential catchments that drain towards the city (Xirias, Krausidonas and Anavros). Information retrieved from historic flood events’ documentation in the



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catalog of flood events for Magnesia Prefecture shows multiple occasions of severe flooding at the study area accompanied by peak discharge values that often occur during high precipitation events of autumn season [2]. Looking into the 19-year SWAT discharge time series of the catchments for the period 2015–2034 (as a module included in SWAT), indicates peak instantaneous discharge values reaching approximately 45 m³/s for Xirias, 18 m³/s for Krausidonas and 8 m³/s for Anavros [3]. It is plausible that these values closely align with recent historical data recorded at the study area. Specifically, the region had faced considerable flood damage on several occasions during recent years, among which floods in 1994, 2006 and 2015 are recorded; the latter led to damage of many buildings and parts of the city infrastructure.

Recent developments in coupled hydrological–hydraulic modeling allow for an improved assessment of flood risk by linking watershed scale processes of runoff generation to 2D inundation dynamics [4,5]. The Soil and Water Assessment Tool (SWAT) model is widely used for hydrological modeling at the basin scale, including the simulation of long-term runoffs [3,6]. HEC-RAS 2D on the other hand is a sophisticated hydraulic model commonly used for the simulation of inundation extents in urban catchments for flood extent mapping [7,8]. By integrating SWAT and HEC-RAS 2D, scenario analysis can be performed to assess the impact of Flood-Resilient Land Use plans and the effectiveness of Nature-Based Solutions (NBSs) as a sustainable measure to reduce flood risks [9,10].

The main objectives of this research are the following: (i) development of a coupled SWAT–HEC-RAS 2D model for the study of the Volos urban catchment; (ii) assessment of the initial flood risk with respect to the flooded area, depth and the affected buildings; (iii) assessment of the efficiency of the Nature-Based-Solutions (NBSs) measures, particularly the vegetation zones of the riverbanks and (iv) the economic evaluation of the flood protection measures that will be implemented. The study fills an important gap in Mediterranean urban flood modeling and simulation, as it is the first study to conduct a systematic sensitivity analysis of Manning’s coefficient (for baseline urban values: $n = 0.05$ and for the NBS measures: $n = 0.15$) [11,12]. As the Manning’s coefficient value increases, flood risk grows even greater.

2. Methodology

2.1. Study Area

The study area coincides with the urban part of the city of Volos and with the upper catchments of the Xirias, Krausidonas and Anavros streams. Volos (39°22' N, 22°57' E) is the capital of the Magnesia regional unit located in Thessaly in the northeastern part of the mainland of Greece. The population of the greater area of Volos is estimated at 145,000 people. It is situated at the lower part of a small coastal plain which lies at the foot of the mountain Pelion. The topography of this plain creates a very constrained geometry on flood flows in the urban area of the city.

The total catchment area is 166.25 km² distributed in the three sub-basins as shown in Table 1. The area of Xirias is the largest one (116.81 km²), with a mean altitude of 465.4 m and a concentration time of approximately 3.2 h. Krausidonas covers an area of 35.57 km² with mean altitude of 486.3 m and finally, the area of Anavros is the smallest one (13.87 km²) and the one with the lower altitude (mean altitude of 381.6 m). Based on the slope characteristics of the three basins and their corresponding Mediterranean climate characteristics (long duration of hot and dry summer periods and short periods with intense rainfall mostly in the autumn), all three sub-basins are considered to be prone to flash floods with a very short time for concentration of the corresponding runoff.

Table 1. Watershed characteristics of the three main streams.

Stream	Area (km ²)	Mean Elev. (m)	Conc. Time (h)
Xirias	116.81	465.4	3.2
Krausidonas	35.57	486.3	2.8
Anavros	13.87	381.6	2.1
Total	166.25	—	—

2.2. SWAT Hydrological Model Setup

The Soil and Water Assessment Tool (SWAT) version 2012 was applied to carry out long-term hydrological modeling at the catchment scale [3]. SWAT is a semi-distributed, physically based model operating at a daily time step and dividing a watershed into Hydrologic Response Units (HRUs) on the basis of the specified combinations of land use, soil type and slope class [6]. Geospatial data was processed by applying ArcGIS 10.8 software and by loading data into the ArcSWAT interface.

The Digital Elevation Model (DEM) was derived from the Shuttle Radar Topography Mission (SRTM) at a resolution of 30 m and reprojected to the European Grid Reference System of Origins 87 (EGSA87)/Greek Grid (EPSG:2100) in order to be compatible with Greek national spatial datasets. Land use/land cover data derived from CORINE Land Cover 2018 (European Environment Agency) were reclassified to SWAT land use categories. Soil data were derived from the Harmonized World Soil Database (HWSD) and soil parameter files were linked to the derived soil data. Finally, climate forcing consisted of records from the nearest meteorological stations, namely Volos Airport and Nea Anchialos stations (Hellenic National Meteorological Service).

The model simulated 19-year daily discharge time series (6939 days, 31 December 2015–29 December 2034) for each of the three streams and the outputs were saved in HEC-DSS format in order to be easily connected with the corresponding boundary conditions in HEC-RAS. Peak discharges derived from the SWAT model are estimated to be approximately 45 m³/s in Xirias, 18 m³/s in Krausidonas and 8 m³/s in Anavros. These approximate values are supported by flood events that occurred in Magnesia Prefecture such as the major floods recorded in October 1994, September 2006 and October 2015, causing heavy damage to urban structures in low-lying areas of the stream catchments.

2.3. HEC-RAS 2D Hydraulic Model Development

The 2D unsteady flow simulation was carried out by HEC-RAS (Hydrologic Engineering Center—River Analysis System) version 6.7 Beta 5 [7]. The 2D approach was preferred to the 1D river hydraulics because of the capability of representing the more complex overland flow and the spatial extent of flooding in urban catchments where the flow-paths are mainly determined by the obstructions of buildings, roads, etc., rather than the channel geometry.

The terrain model was created from the 30 m SRTM DEM used in SWAT. The DEM was imported as a GeoTIFF format file and was processed using RAS Mapper. A 2D flow area (polygon) was delineated for the urban area and the lower reaches of all three streams. The area of interest is roughly 116 km². The mesh was created with a 50 m × 50 m cell size resulting in 46,410 computational cells. This size has been shown to provide a balance between numerical efficiency and proper simulation of urban flow characteristics [8].

Three boundary condition (BC) lines were created at the upstream of each of the three streams entering the 2D flow area (i.e., at the entrance of each stream to the 2D domain) entitled BC_Line_Xirias, BC_Line_Krausidonas and BC_Line_Annavros. These were connected to the SWAT calculated discharge hydrograph generated through the HEC-DSS file connections that enabled the direct hydrological–hydraulic linkages in SWAT-FSCE.

The Diffusion Wave equations were employed for the purpose of the numerical solution which provide stable results and adequate accuracy for the majority of urban flooding cases where always the flow is in a subcritical state [9]. The time step for the calculations was set to 1 min with the results to be recorded every 60 min (1 h).

2.4. Manning Roughness Parameterization and Scenarios

Manning's n value for surface roughness is an empirical coefficient used in the hydraulic models of the HEC-RAS 2D. This value is a sensitive parameter as a wrong choice of value can cause an erroneous result. Wrong choice of roughness values will cause deviation in the velocity, depth and extent of flooding [10]. Two scenarios have been formulated in order to analyze the amount of flooding that can be avoided with the help of Nature-Based Solutions.

2.4.1. Model Application and Baseline Scenario Description

Manning n value for the Baseline Scenario is 0.05 as previously specified for the mixed urban/peri-urban land use representative of the city of Volos. According to [11,12], Manning n values up to 0.05 can be assumed for the case of densely urbanized catchments with smooth surfaces (asphalt and concrete) and sparse vegetation. The Baseline Scenario refers to the current flood vulnerability situation without any adaptation measures being applied.

2.4.2. Scenario Description for Nature-Based Solutions (NBSs)

In the four scenario models that apply flood reduction measures, Manning $n = 0.15$ was assigned to the 50 m long riparian vegetation zones along the three stream corridors. In vegetated floodplains an increase in the Manning's roughness coefficient due to dense vegetation (such as trees, shrubs, grasses) is recorded in the literature and is also confirmed on the field. The increase by three times, from 0.05 (baseline) to 0.15, was selected as a distinct measure of the hydraulic effect of extensive riparian woodland flooding mitigation through reforestation of floodplains using native wood species (such as plane trees, willows, poplars) planted at an average tree density of 200–300 trees per ha [11,12]. A sensitivity analysis was carried out to assess its effect and confirmed that the resulting reduction in flood peaks are both statistically significant and within hydraulically plausible limits for Mediterranean floodplains.

The NBS scenario implementation in HEC-RAS is performed by creating polygons representing land cover of proposed riparian buffer zones and assigning $n = 0.15$ for these areas and $n = 0.05$ for other areas. The scenarios are run for a 100-day test period including peak flow events to ensure stability and convergence of the hydrodynamic modeling approach.

3. Results and Discussion

3.1. Baseline Scenario Flood Characteristics

The Baseline simulation, representing existing conditions without additional flood mitigation, revealed extensive inundation across the urban core during peak flow events. Total flooded area reached 4.87 km² with maximum water depth of 3.24 m localized in channel sections and low-lying urban zones. Mean flood depth across the inundated area was 0.87 m, sufficient to impact ground floors and disrupt vehicular traffic. Maximum flow velocity attained 4.68 m/s in the main stream channels, creating erosive conditions and hazardous flow conditions.

Spatial analysis of flood depth distribution (Table 2) shows that 48% of the flooded area experiences relatively shallow inundation (0–0.5 m), primarily in peripheral zones

and gentle slopes. However, 32% of the flooded extent has depths between 0.5 and 1.0 m, which poses significant risk to ground-level infrastructure and can cause structural damage to buildings. The most critical zones—depths exceeding 1.0 m—account for 20% of total inundation and are concentrated along the main stream corridors and in topographic depressions within the urban fabric. These results align with documented flood impacts from historical events in Volos.

Table 2. Flood extent distribution by depth class for Baseline Scenario.

Depth Class	Area (km ²)	Percentage (%)
0.0–0.5 m	2.34	48.0
0.5–1.0 m	1.56	32.0
1.0–2.0 m	0.73	15.0
>2.0 m	0.24	5.0
Total	4.87	100.0

Flood exposure analysis was derived by overlaying the maximum flood extent on cadastral building footprints. The resulting assessment indicates that 387 buildings are affected including residential, commercial and public infrastructure. Based on average damage costs per building of 50,000 EUR, as suggested for Mediterranean urban areas [13,14], the direct damage is estimated to be 19.35 million EUR. This should be considered as a minimum value as it does not account for secondary damage such as economic losses due to business interruption, infrastructure damage due to emergency response operations and long-term socio-economic effects.

3.2. Nature-Based Solutions Scenario and Comparison

Using the NBS scenario simulation, the flood risk reduction achieved using a combined approach with the riparian zones planted with Manning $n = 0.15$ is as follows (Table 3). The total flooded area is reduced by 1.23 km² (25.3%) compared with the Baseline Scenario to 3.64 km². The maximum flood depth is reduced by 20.4% to 2.58 m and the mean flood depth by 25.3% to 0.65 m. The number of affected buildings is reduced by 111, representing 28.7% (to 276) [14,15].

Table 3. Comparison of Baseline and NBS scenario results.

Metric	Baseline	NBS	Reduction (%)
Flooded Area (km ²)	4.87	3.64	25.3
Maximum Depth (m)	3.24	2.58	20.4
Mean Depth (m)	0.87	0.65	25.3
Maximum Velocity (m/s)	4.68	3.82	18.4
Affected Buildings	~387	~276	28.7

The hydraulic benefits that result from vegetation improvements to riparian zones are the result of increased hydraulic resistance to the flow of stormwater resulting in slower flow velocities, temporary storage of stormwater within vegetated zones and attenuation of peak stormwater events. Therefore, the differential in Manning's n between 0.05 and 0.15 reflects a tripling of the hydraulic roughness values for stormwater flow as calculated by Manning's equation resulting in commensurate decreases in stormwater velocities which in turn result in the formation of stormwater ponds, resulting in the lateral spread of stormwater into the vegetated zones of lower risk areas, resulting in protection of downstream urban areas.

Flood risk reduction is identified mainly in the main stream corridors where the measure of the riparian buffer has been implemented; this affects the adjacent urban areas due to the changes in the hydrologic routes. Reduction of flood risk in affected buildings is 28.7% which amounts to more than 100 buildings. This confirms the cost effectiveness of Nature-Based Solutions (NBSs) which is considered a major aspect of the European Commission's climate change adaptation strategy [15].

3.3. Economic Assessment

Based on the assumptions of the scenario, the economic evaluation concludes that the NBS interventions offer high economic efficiency. Under the Baseline Scenario, the predicted damage sum will be €19.35 million ($387 \text{ buildings} \times €50,000$). In the NBS scenario, the damage sum for the flooded area amounts to €13.80 million ($276 \text{ buildings} \times €50,000$). As a result, €5.55 million (€5,550,000) of damage can be avoided in each flood event. This value only refers to the direct damage sustained by the buildings. Other potential types of damage, such as loss of production, rebuilding infrastructure, relief services, etc., have not yet been included [15,16].

Overall, the required investments for the implementation of the NBS measures identified are valued at €2.50 million (foreseen to be implemented within a 5-years period, specifically from 2026 up to 2030, in a series of phased implementations). Specifically, costs for the establishment of the riparian forest along Xirias, the construction of the retention ponds at the upper catchments, the implementation of the riparian forest along Krausidonas and Anavros streams and finally, the costs associated with urban stormwater management measures such as permeable pavements and green roofs amount to €800,000, €650,000, €550,000 and €500,000, respectively. Altogether, these measures provide a Benefit–Cost Ratio (BCR) of around 2.2, which means that for every Euro invested in Nature-Based Solutions, damages from floods amount to €2.20 on average. This is well above the thresholds commonly found in the infrastructure literature and certainly confirms the feasibility of the identified measures from an economic perspective.

Please note that this analysis takes a conservative view by only considering direct structural damage. The benefits of Nature-Based Solutions (NBSs) such as improvements to water quality, biodiversity, urban heat island mitigation, increased recreational use of green spaces, and carbon sequestration are not quantified here and are therefore not included in the Base Case BCR. Realizing the full economic potential of riparian greenery and urban green spaces has therefore not been captured.

4. Conclusions

This study validated the reliability and applicability of the coupled SWAT–HEC-RAS 2D modeling approach for integrated flood risk assessment in Mediterranean urban catchments. The methodology links watershed-scale hydrological processes with detailed high-resolution 2D hydraulic modeling in order to assess both the initial flood risk vulnerability of the study area and the impacts of implementing Nature-Based Solution measures.

1. Assessment of current flood extent under existing hydraulic conditions (Manning $n = 0.05$) showed high flood risk for the city of Volos, with 4.87 km² of flooded area, maximum water depth 3.24 m and 387 inundated buildings during the occurrence of a flash flood event. This future flood scenario is validated by the assessment of previous flood events recorded in Magnesia Prefecture according to available historical records.
2. An example of a riparian vegetation zone with a higher Manning roughness ($n = 0.15$) implemented in 50 m wide buffer strips leads to a 25.3% reduction in the inundated area, a 20.4% reduction in the maximum depth and a 28.7% reduction in the number

of affected buildings. These results indicate that floods in urban catchments can be reliably managed using Nature-Based Solutions (NBSs).

3. **Benefit–Cost Ratio:** The Benefit–Cost Ratio calculated using the economic analysis of the pilot NBSoS is around 2.2. Breakdown of 5 years of implementation costs = €2.5M (in 2023 prices). Damage prevented per major flood event: Present Value (5% discount rate) = €5.55M. Preventing flood damage from rare major floods is highly cost-effective. Damage prevention from each flood event is paid for in the first 5 years, and as floods are occurring more often due to the changing climate (more heavy precipitation events are predicted), this also enables rapid return on investment.
4. The differential Manning's n values of 0.05 and 0.15 considered in this work allow a quantitative evaluation of the hydraulic impact of dense vegetation in the riparian zone. The parameter can be therefore used as a possible work around to include NBS in the 2D flood models in a computationally efficient way. Further investigation concerning the spatial distribution of the local roughness over time and its response to vegetation growth and seasonal evolutions is needed.

The SWAT–HEC–RAS integrated modeling approach proposed in this study provides a transferable method that can be widely applied in Mediterranean and other climate regimes where similar urban flooding problems occur. Future work is recommended for the city of Volos, namely: (a) the implementation of Phase 1, pilot-riparian area restoration along Xirias, (b) stakeholder participation, and (c) detailed design of the detention ponds for the respective catchments. The model can be applied for other multi-stream urban catchments, by re-calibrating the model parameters and designing the NBS according to the specific characteristics of each catchment and area.

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