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Investigating the effects of various densities of predicted urban extents on flood hazard in Ayamama Watershed, Istanbul

*[1]Tewodros Assefa Nigussie, [2]Abdusselam Altunkaynak, [3]Farrokh Mahnamfar and [2]Yasin Abdollahzadeh moradi
[1]Hawassa University, Institute of Technology, Hawassa, Ethiopia
[2]Faculty of Engineering, Department of Civil Engineering Istanbul Technical University, Turkey
[3]Faculty of Engineering, Department of Civil Engineering Sakarya University, Turkey

Abstract

This study predicted the urban extent of Ayamama Watershed by the SLEUTH model and investigated its effect on flood hazard in the watershed by considering various densities of development. MIKE 21 FM was employed to generate flood inundation maps; the HEC-1 hydrological model was employed to develop the corresponding flood hydrographs. The result of the study showed that, with the opening of Esenler Military Zone for development, the flood inundation extent under 85% density of development was found to be significantly larger than the flood inundation extent determined by taking into consideration the current urban extent in the watershed. As opposed to this, the flood inundation extents under 50% density of development and the current urban extent in the watershed were not found to be considerably different. Thus, if further urbanization is allowed in the watershed, limiting the density of development under 50% is recommended.

Key words: Urbanization; flood hazard; inundation; density of development

1. Introduction

From hydrological point of view, urbanization is defined as the conversion of natural land cover into artificial land cover that result in the increase in the size of built-up areas and impervious surfaces altering the hydrological regime of a watershed [1]. A number of studies have indicated that urbanization can result in higher storm runoff peaks and may increase flood hazard. According to the World Meteorological Organization Global Water Partnership [2], flood hazard increases due to hydrological changes driven by urbanization.) Among the several factors (such as topographical and meteorological) that affect flooding, urbanization may be the most important factor as it results in considerable change on the hydrological processes [3]. The increase in artificial surfaces due to urbanization increases flooding frequency because of the resulting poor infiltration and reduction of flow resistance (due to faster concentration times) [4].

Flooding results in both short-term and long-term impacts in various parts of the world [5]. About 40% of all natural disasters worldwide are caused by flooding [6]. Next to earthquakes, flooding is the second important natural disaster in Turkey [7]. The report also added that, on average, 39 flood events take place in the country per year resulting in 25 deaths and property damages of about 60 million USD. In Istanbul, the largest city and the economic hub of Turkey, 59 flood events that claimed many lives and resulted in property damages were recorded between 1989 and 2009. The

*Corresponding author: Address: Faculty of Biosystems and Water Resources Engineering, Department of Hydraulics and Water Resources Engineering, Hawassa University, Hawassa ETHIOPIA. E-mail address: tewodrosas@hu.edu.et, Phone: +251925968979

flooding on 9 September 2009 appears to be the most damaging based on the number and level of damaged homes, workplaces and other properties. Only in Ayamama Watershed, in addition to the huge property damage, 31 people died and 50 people were injured. Though meteorological factors are also to be mentioned, the flooding in Istanbul is mainly attributed to rapid urbanization [8]. Recently, a controversial project termed as Project Canal Istanbul (PCI) has been proposed by the Turkish Government. The project leaves the northern part of Ayamama Watershed open for development [9]. Thus, more intense and frequent flooding events are likely to occur in the watershed with more urbanization unless appropriate actions are taken [10].

The solution to the detrimental effects of flooding is the design and implementation of proper measures that can preserve the natural hydrologic condition of a particular watershed [11]. However, addressing the impacts of flooding by making use of structural and/ or non-structural measures needs to be based on deep understanding of hazard conditions, described in spatial and/or temporal perspectives, and should produce information adequate to the needs of end-users [12]. In this regard, modelling the impacts of urbanization on flooding is essential to formulate policies on landuse planning and device measures that can be taken to cope up with the risk of flooding [13]. The implementation of effective adaptation measures can be realized only when the nature of the impact is well understood and, hence, the quantitative assessment of the increase of flood hazards from urbanization is essential [4]. This study was, therefore, undertaken to predict urbanization in Ayamama Watershed and analyze its effect on flood hazard by considering various densities of development as such a study has never been implemented in the watershed, to the best of our knowledge. The SLEUTH urban growth model, which is a recent adaptation of a Cellular Automata (CA) model and has been found to supply reasonable urban growth results [14] was used to predict urbanization and the two-dimensional flexible mesh model (MIKE 21 FM), which is identified as the most effective modelling tool for flood inundation mapping [15] was used for similar purpose in this study. Flood hazard maps were developed by taking into consideration rainfall amount of 500 year return period. The results of the study are believed to provide useful information to policy makers and other stakeholders in their efforts associated with proper urban planning and design and implementation of appropriate flood control measures.

2. Materials and Method

2.1. Description of the study area

This study was conducted in Ayamama Watershed (Figure 1). The watershed extends between 28° 21’ 18” E and 28° 24’ 43” E longitudes and between 40° 58’ 14” N and 41° 08’ 12” N latitudes. The area of the watershed is 68.3 km^2 and the urban extent in the watershed grew from 15.86 km^2 in 1987 to 44 km^2 in 2015 [16]. The north-eastern part of the watershed is covered with vegetation as it falls within the Esenler military zone. However, based on the proposed zone for urbanization under a project called PCI, Esenler will be open for development. Thus, urban extent of the watershed is expected to increase in the future. The nearest meteorological station to the watershed is Olimpiyat Station and is located at 28º 46’ 4.3” E and 40º 6’ 21.7” N coordinates and at an altitude of 100 meters above sea level (Figure 1).

Figure 1. Ayamama Watershed, location of Olimpiyat Station and boundary of the PCI project.

2.2. Data collection and analysis

2.2.1. Data collection and analysis for predicting urbanization

SLEUTH requires at least four historical urban extents, at least two transportation network maps, an excluded area layer, a slope map, a hillshade map and, though it is not mandatory, a landuse map in GIF format. In this study, the slope and hillshade layers were from a Digital Elevation Model (DEM) of the study area (with 30 m resolution) downloaded from the Advanced Space-borne Thermal Emission and Reflection Radiometer Global Digital Elevation Model (ASTER-*GDEM*) website. In addition, four historical urban extent maps were developed from the 1987, 2000, 2009 and 2013 satellite images of the study area downloaded from the United States Geological Survey (USGS) Global Visualization Viewer (USGS-GVV) website. Moreover, two transportation maps developed from the 1987 and 2013 transportation maps and an additional transportation map of the study area developed from the 2023 Master Plan of Istanbul (a total of three transportation maps (developed by screen digitizing using ARCGIS 10.1) were used. It should be noted here that various roads were given various weights based on their types as given by Istanbul Metropolitan Municipality (IMM) [17] for different types of roads have different levels of effects on urbanization. Figures 2a, 2b and 2c depict the slope and hillshade layers, the urban extent layers (1987, 2000, 2009 and 2013) and the transportation layers (1987, 2013 and 2023), respectively, used as inputs in SLEUTH.

The excluded area layer fundamentally depicts lands that are excluded from development. However, various levels of protection could be given to various zones to represent various levels of protection. For instance, landuses such as water bodies are given a values of 100% to show that these landuses completely exclude from development. As opposed to this, areas zoned for development are given an exclusion value of 0% and this means that such areas are considered are open for development and, thus, they are considered as areas of attraction. Based on the level of exclusion (protection) or attraction, various landuses are given values between 0 and 100. In this study, based on available codes, actual conditions on the ground, future plans and expert views, the following scenario was developed to come up with the excluded area layer.

Trend under PCI (PCIT): this scenario represents the scenario with the implementation of PCI. In this regard, landuses (forests, parks, agricultural lands and military zones, with the exception of water bodies) that fall within this zone are assigned with exclusion values of 0%. Since the main objective of zoning is to restrict development in areas out of zones allocated development, landuses such as absolute and short water protection zones, ground water recharge areas, wildlife protection zones and parks (found out of the PCI zone) were completely excluded from future development. The remaining land was left neutral. Though the objective was to determine the urban extents in Ayamama Watershed under the above given scenario, after preparing the input data in the required format, SLEUTH was run up to 2050 to predict the urban extents of Istanbul as more reliable and accurate results are achieved when the model is run at more regional scale [18]. Thus, the urban extent in Ayamama Watershed were determined by sub-setting the predicted urban extent of Istanbul.

2.2.2. Input data preparation and setup of MIKE 21 FM

Before going further with the MIKE 21 FM model, the geometry of the study domain need to be represented by mesh that is developed from a bathymetry data. Accordingly, the bathymetry of the study area was obtained from ISKI and it was used to define the extent of the study domain by talking into consideration elevation differences. The mesh of the study domain was developed by using the mesh generator tool of MIKE 21 FM from 20,260 regular (squared) and irregular (triangular) elements and 16,433 nodes. Another primary input to MIKE 21 FM is hydrograph of a given return period. The hydrograph of a watershed determined with rainfall amount 500 yr return period is crucial because of its common use in flood mapping [14]. Thus, the 500 yr return period hydrographs of the watershed determined under the current urban extent and the predicted urban extent (by considering 85% 65% and 50% densities of development) were used in this study. As indicated earlier, the SCS Curve Number (CN) method was used for the development of these hydrographs.

In order to develop flood hazard maps, hydrographs of the study watershed are required. For this purpose, 30 years of daily rainfall data (1971-2000) of Olimpiyat Station was obtained from the Turkish General Directorate of Meteorology as this station is the closest station to Ayamama Watershed. The Peak-Over-Threshold (POT) method of extreme value analysis (EVA) was employed for frequency analysis. The results of the frequency analysis were used as inputs into the SCS Curve Number (CN) method to determine the hydrographs of the watershed. This is because the SCS-CN method is recommended for ungauged watersheds and/ watersheds with limited observed runoff data [19], [20], [21].

3. Results

3.1. Urban extent prediction results

As indicated earlier, after running SLEUTH, the current and predicted (under the PCIT scenario) urban extents of Ayamama Watershed were obtained by sub-setting the current and predicted urban extents of Istanbul (Figure 2). These images were further analyzed using ARCGIS 10.1 software and the current and predicted (for 2050) urban extents of the watershed were found to be 44 km^2 and 63 km^2.

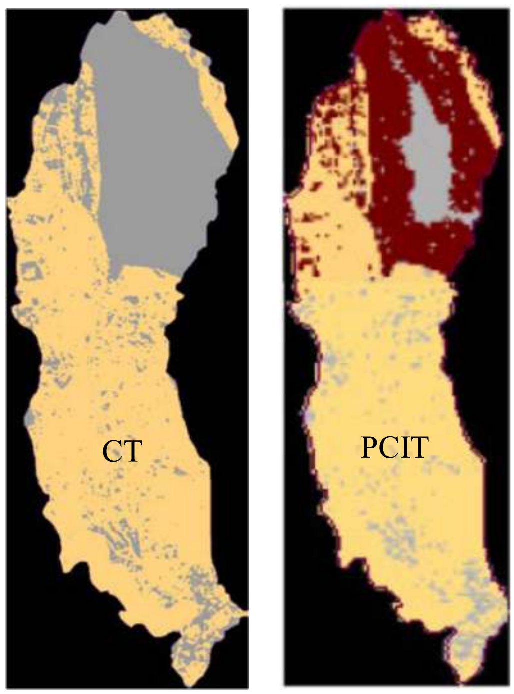

Figure 2. Urban extents under the CT (current) and PCIT scenarios.

3.2. The 500 yr return period rainfall amount and hydrographs

Based on the POT based extreme value analysis, the maximum 24 hr rainfall amount of the 500 yr return period was found to be 115. 36 mm. This rainfall amount was used in the SCC-CN method, together with the urban extents of the watershed under the current and the PCI trends and other geomorphological characteristics of the watershed, to develop these hydrographs. In this study, three levels of development (50% development-named here as low level, 65% development-named here as medium level and 85% development-named as dense level) were considered during the development of the hydrographs under PCIT. Table 1 depicts the peak discharges of the 500 yr return period hydrographs determined at the outlet of the project domain under the current and the three levels of urban developments under the PCIT scenario.

Table 1. Peak discharge values of the 500 yr return period hydrographs at the outlet of the study watershed.

Scenario	Peak discharge (m^3/s)
CT (without PCI)	429.6
PCIT-Low (50%)	468.6
PCIT-Medium (65%)	497.8
PCIT-Dense (85%)	662.9

3.3. Flood hazard (inundation) maps

The flood hazard (inundation) maps of the watershed resulting from the 500 yr return period hydrographs of the current level of urbanization and hydrographs of the dense, medium and low densities of development under the PCIT scenario are presented in Figure 3. The maps were further analyzed and the size of the inundated area (in km^2 and as percentages of the total area of the watershed) are presented in Table 2.

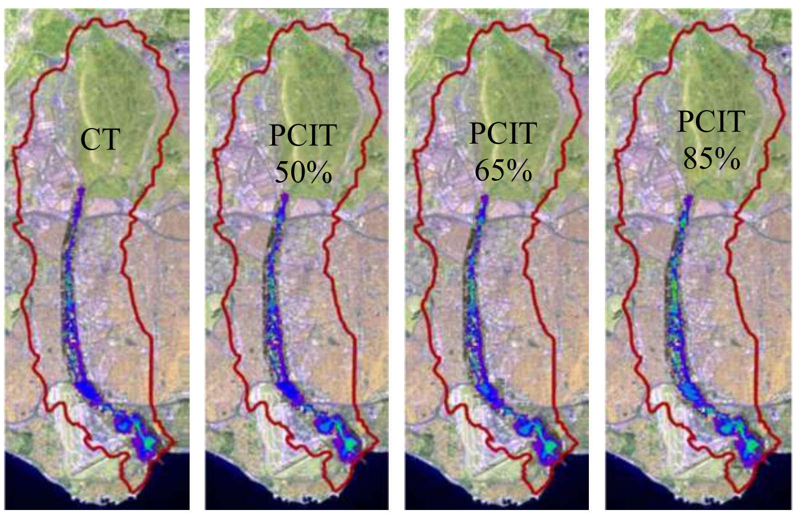

Figure 3. Flood innundation maps under the current (CT) and predicted (PCIT with 50%, 65% and 85% densities of development) scenarios.

Table 2. Inundated area (in km^2 and as percentages of the total area of the watershed) under the various levels of urbanization and the hydrographs of 500 yr return periods.

Scenario	Inundated area	
	km^2	%
CT (without PCI)	4.89	7.1
PCIT-Low (50%)	5.19	7.5
PCIT-Medium (65%)	5.29	7.7
PCIT-Dense (85%)	5.75	8.4

4. Discussion

4.1. Urbanization urban extent prediction

The change in the urban extent of the watershed from the current 44 km^2 to 63 km^2 by 2050 is a considerable increase (46% increase in urban extent). This is expected to result in major changes in the hydrologic response of the watershed. These results were further considered for modifying the characteristics of the watershed and develop corresponding hydrographs as input in MIKE 21 FM.

4.2. The 500 yr return period rainfall amount and hydrographs

As presented in Table 1, the peak discharges of the 500 yr return period hydrographs of the CT scenario was found to be 429.6 m^3/s. This peak discharge is larger than the corresponding peak discharge of the watershed determined by the Disaster Coordination Center of Turkey, abbreviated as AKOM in Turkish (253.8 m^3/s) [19]. This is because, despite the use of the SCS-CN method, the rainfall data used in the study by AKOM was taken from Aksaray Station, a station that cannot represent the rainfall in Ayamama Watershed as it is located relatively far from the watershed. A Thiessen Polygon method based analysis showed that Aksaray Station affects only 8% of the precipitation in Ayamama Watershed [22]. Moreover, the rainfall amount observed at Aksaray Station is smaller than the one observed at Olimpiyat Station. For example, the rainfall amount observed at Olimpiyat Station on 9 September 2009 was 175.2 mm while the amount recorded at Aksaray Station was 10.6 mm [23]. In addition, the Log Pearson III distribution, which is not recommended for frequency analysis, was employed in the study by AKOM [24]. Above all, however, the runoff flow pattern of Ayamama Watershed follows the rainfall pattern at Olimpiyat Station more than any other station in the region [25]. The peak discharge values obtained in this study are, thus, more reliable. Table 1 also depicts that the peak discharges of the 500 yr return period hydrographs of the dense, medium and low levels of development under the PCIT scenario were found as 468.6 m^3/s, 497.8 m^3/s and 662.9 m^3/s, respectively.

4.3. Flood hazard (inundation) maps

It can be seen from the hazard maps that the size of inundated areas increased with increasing level of urbanization. It can also be clearly seen from the maps that, even under the current level of urbanization, the 500 yr return period hydrograph results in significant level of flooding. This result agrees with the comment given by [24], which stated that even peak discharge value of 25 yr return period is capable of causing flooding in the Ayamama Watershed because of the poor drainage capacity.

As presented in Table 2, the size of the flood map resulting from the 500 yr return period hydrograph and under the current urban extent in the watershed is 4.89 km^2 (covering 7.1% of the watershed). This size is predicted to reach 5.19 km^2 (7.5%), 5.29 km^2 (7.7%) and 5.75 km^2 (8.4%) under the low, medium and dense densities of development of the PCIT scenario, respectively. It can be seen from these results that the level of inundation under the current urban extent is not considerably different from the inundation extent under the low density of development of the PCIT scenario (1.06 times larger). Thus, the best option for the watershed is to not allow further development and improve the drainage capacity of the watershed. However, if further development with the implementation of PCI is inevitable, keeping the level of development in the currently undeveloped areas below 50% is recommended.

Conclusions

This study predicted the urban extent of Ayamama Watershed using SLEUTH and investigated the effects of various densities of urbanization on flood hazard in the watershed using MIKE 21 FM. The following points could be concluded from the results of the study.

- Allowing dense development in the watershed with the implementation of PCI (PCIT) will leave considerably large area inundated when compared to the flood inundation under the current urban extent (CT).
- Though not allowing further development is a better option, limiting the level of development in the presently non-urban landuses to less that 50% and not altering the hydrological regime of the watershed could limit the increase in flood hazard.

However, even without further development, it was seen that the watershed could be susceptible to flooding from rainfall amounts of higher return periods. Therefore, improving the drainage of the watershed and coming up with effective flooding control measures are recommended.

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