Article

Estimation of Urban Imperviousness and its Impacts on Flashfloods in Gazipaşa, Turkey

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Abstract

The paper examines flooding issues under rapid urbanization in Gazipasa city during the past seven years 2013-2019. The Storm Water Management Model (SWMM) integrated with the satellite images representing temporal variation in the land use and land cover (LULC) characteristics of the city were used to determine the variation in the runoff generation capacity, flood volume, and associated risks. The Google Earth software together with GIS technology were utilized to create and handle spatial data required for SWMM simulation. Standard design storm intensity derived from the local intensity-duration-frequency curves was used as the stationary input parameter for SWMM simulation in both the past and current LULC conditions. The comparison between LULC maps showed that the extent of urban imperviousness area has been approximately increased by 80% in average. The SWMM simulations showed the peak flood value of 51.3 m^3/sec and 61.4 m^3/sec for the year 2013 and 2019, respectively. Moreover, under the same design storm, Rational Method has been applied and 39 m^3/sec of peak flow rate has been calculated by disregarding the urbanization activity. The results indicate that the LULC variation during the past seven years resulted in almost 20% (18%) increase in peak flow (flood volume).

Keywords: SWMM; urbanization; flooding; design storm; Gazıpaşa.

1. Introduction

Flash floods driven by intense storms are of natural disasters that negatively affects human life and their social activities, particularly in urban areas where serious infrastructural damages or loss of life and property may occur [1]. Many researchers have explored flash floods, their driving mechanism, and their simulation/prediction at both local or regional scales [2]–[7]. Focusing on the urban storm water management, a large number of lumped and distributed software packages were used to simulate rainfall-runoff process, propagate flood over the landscape, and design storm water drainage systems [6], [8]–[11]. Among various tools, the US Environmental Protection Agency's Storm Water Management Model (SWMM) is one of the most widely used software for planning, analysis, and design of green infrastructures, storm water, wastewater, and watershed management. Examples of the most recent (2015-2020) applications of the SWMM for storm water management include (but not limited to) [4]–[6], [12]–[18]. Using Sub-hourly hydro-meteorological data from the city of Espoo, (Finland), Guan et al. (2015) explored the hydrological change in the city due to urbanizing [14]. They calibrated SWMM using the data from a fully developed catchment and explored the hydrological changes at different development phases. The authors showed that the low-frequency flow rates had remarkably increased over the three-year period of 2004 to 2006 along with the increase of impervious areas. Khadka and Basnet (2019) applied SWMM to model storm floods at Lakeside catchment, Nepal with a total catchment area of 41 ha [5]. The authors concluded that the existing drainage system of Lakeside is inadequate to convey runoffs during intense rainfall events. More recently, Behrouz et al. (2020) developed an integrated OSTRICH-SWMM to automatically calibrate SWMM via the Optimization Software Tool for Research Involving Computational Heuristics (OSTRICH) [6]. The authors applied this hybrid model in a catchment in Buffalo, NY and showed that the model can be successfully used to minimize calibration error in simulated peak flow and total flow volume. During the recent decades similar studies have been accomplished to model rainfall-runoff processes in Turkish basins using SWMM [19], [20]. For instance, A parametric sensitivity analysis was carried out by Akdoğan and Güven (2016) to determine the most significant parameters affecting the SWMM outcomes [21]. A total of 55-year observed data was used for runoff prediction at Alibeyköy Reservoir Basin, Istanbul. The authors demonstrated that the sub-catchments area and slope are the most and least significant parameters, respectively. More recently, Gülbaz et al. (2019) applied SWMM to simulate depth and volume of September 2009 flood event at the Ayamama River Basin, Istanbul. The Watershed Modeling System (WMS) was used to draw flood hazard map [20]. The authors showed that flood depth raised up to 11 m in some critical regions such as Çoban-çeşme district. Comparing to GIS-based data entrance into WMS, the authors reported that the manual entrance of input data is a drawback of SWMM. Our review in the germane literature showed that SWMM has been used in both natural and built catchments ranging in size from 1 ha to 40000 km^2. Despite several studies on the application of SWMM in Turkey, rapid urbanization impacts on storm floods in Akdeniz basin catchments have not been explored yet. Likewise, no study on the application of SWMM in Antalya province does not carried out so far. In this study, we aimed at determining urbanization impact on peak flow and flood volume in eastern region of Gazipaşa district in Antalya province, Turkey using SWMM. To this end, the method of SCS Curve Number together with Horton Infiltration Curve were applied interactively to explore surface run-off variation in the region. The results were also compared with those of traditional Rational Method.

2. Study area and data

The province of Antalya located in the Mediterranean coast of southern Turkey. It is one of the main destinations of the world's truism sector, a rapidly growing urban area. The population increased from 1.6 million inhabitants in 2005 to 2.55 million in 2020. The Gazipaşa (Figure 1), one of the oldest cities in Antalya Province, located in 180 km east of the city of Antalya. During the past few years, Gazipaşa has been urbanized quickly and a huge amount of its rural area was changed to impermeable built area. Thus, the analyses of potential flood hazard in the city is of special importance for the region.

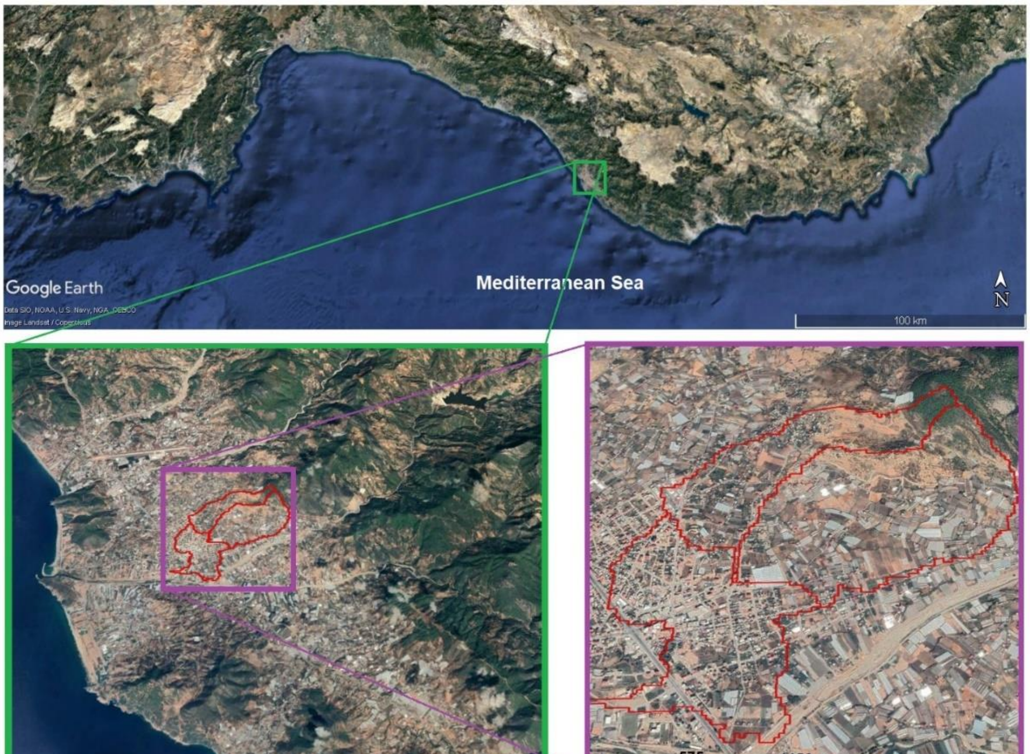

Figure 1. Study area, Gazipaşa, Turkey.

Rapid development and land use change in this area resulted in increasing surface water runoff and inundation problems in recent years. Figure 2 exhibits the overflow of water from existing stormwater drainage system during a rainfall event on 06.01.2021 that turned streets into streams. Similar overflow problems are seen mostly in the Eastern side of the City next to İnceağrı River (see Figure 1) that has been considered as the case study location to be simulated in this study.

3. Methodology

The present study was carried out in three phases: 1) spatial data preparation, 2) SWMM simulation, and 3) comparison of the results. In the first phase, the Google Earth software together with GIS technology (ArcMap) were utilized to create and handle spatial data required to achieve the aims of the present study. The LULC maps as well as the digital elevation model (DEM) of the study area are the required spatial data that was prepared in this phase. While the formers were retrieved from Google Earth images for the years of 2013 and 2019, the latter was downloaded from ASTER Global Digital Elevation Map provided by the Ministry of Economy, Trade, and Industry (METI) of Japan and the United States National Aeronautics and Space Administration (NASA) jointly and has the resolution of 30 m which is considered suitable for this study. To calculate spatial characteristics of the study area and encompassing sub-basins, the ArcGIS (Archydro plugin) was used in this phase. While delineating watershed, it was assumed that an area of 1 km^2 would create a runoff. The reason for this is that the Mehmet Oğuz boulevard (see Figure 2), which is the focus of the study, and the area that brought the flood to the boulevard are better represented.

Figure 2. Flash flood event at Gazipaşa town (City Center, 06.01.2021).

Drainage fields under three hydrologically created sub-basins were determined considering the land use and the roads around it. Totally 25 drainage fields have been created and the same areas are used in comparison for the 2013 and 2019 models. Surface slope and drainage field areas calculated using DEM. Impervious areas have been calculated according to the satellite images taken from 2013 and 2019, separately. Building areas, industrial areas and greenhouse areas were included in the impermeable area calculations in both years. In order to determine hydrological soil groups for sub-basins, NASA's 250 m grid dataset has been used [22]. Drainage fields 23, 24, and 25 located in the south of the basin are classified as hydrological soil group D (high run-off potential), and all remaining drainage areas are classified as type C (mid to high run-off potential). USDA's 1986 report Urban Hydrology for Small Watersheds was used to determine the curve numbers together with hydrological soil groups.

In the second phase, i.e., modelling phase, the spatial data is imported to the SWMM 5.1 and the model is executed for the past (2013) and current (2019) conditions, separately. It is worth mentioning that the model was run with the same storm hyetograph derived from local 25 years recurrence intensity-duration-frequency (IDF) curves. Even though 5- or 10-year return period is usually considered to design of sewer systems in Turkey, 25-year storm was used in the present study as it is commonly used for similar applications worldwide. The associated cumulative storm hyetograph was illustrated in Figure 3.

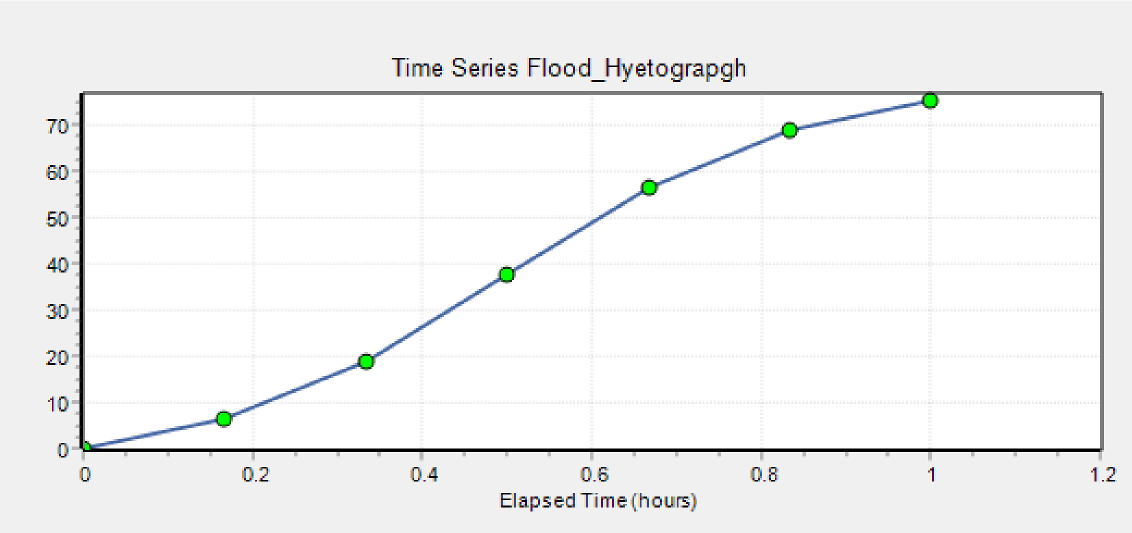

Figure 3. 25-year cumulative storm hyetograph having with 1-hour duration.

The information obtained using GIS was processed into SWMM software and two separate models of the field was created for 2013 and 2019. These models consist of 25 drainage fields, 8 junction points, 1 outlet point, and 8 channels in total (Figure 4). All the channels that connect the junction points are designed to have 10 m wide and 2 m depth. Although all the features of the mentioned hydraulic elements are the same, the only difference between the two models is the percentage of impermeable area and curve numbers. To achieve low continuity error on both models, five minutes initial computational time step was chosen and gradually decreased to figure the lowest point out. Considering the 1-hour total storm duration, 5 minutes of reporting time steps was found reasonable. As a result, both models were run with 10 seconds of computational and 5 minutes of reporting time steps. Drainage field discharge points are determined according to the slope of each field. Drainage fields located Northern side of the basin discharges are set to the drainage fields located at the downstream fields by considering the slopes due to the underdeveloped and being agriculture-focused lands.

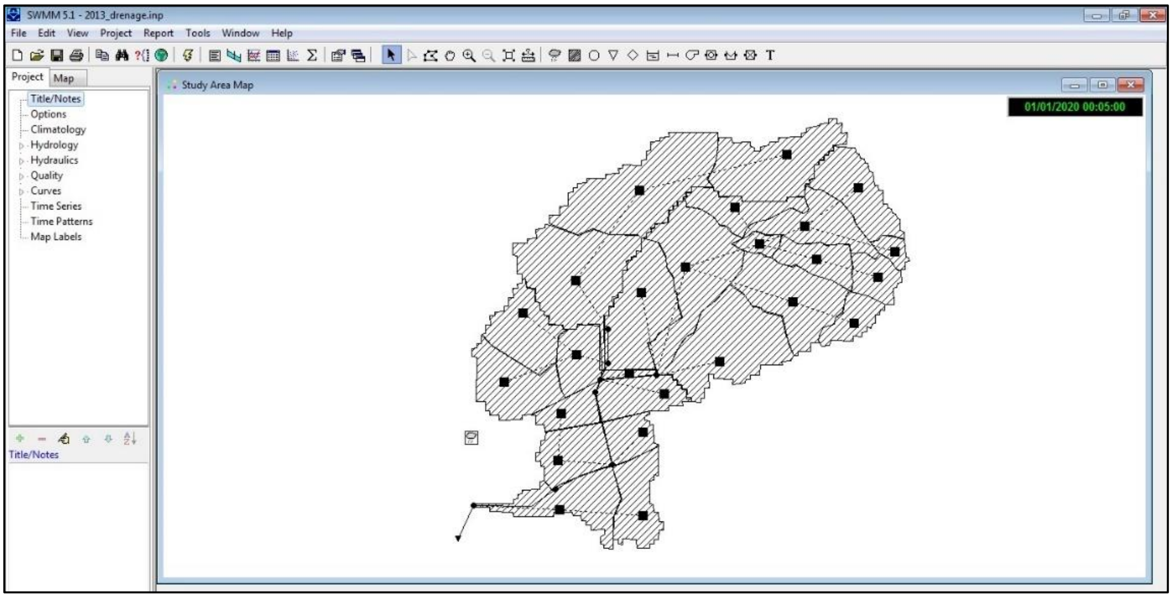

Figure 4. Model interface shows study area in 2013 and 2019.

The middle and southern side of the basin discharges were set to the junction points as the corresponding areas are more developed and suitable to establish a drainage network. Finally, the flood hydrographs on Junction 3 which is located on Mehmet Oğuz Boulevard, were compared to distinguish the differences in the hydrologic response of the study area to this rapid urbanizing.

3.1. Overview of SWMM

The SWMM is a dynamic rainfall-runoff simulation model based on momentum, mass, and energy conservation laws. This model is used in the design, analysis, and planning of drainage systems as well as for the simulation of runoff quality and quantity in urban areas [23]. SWMM is capable of calculating parameters such as surface evaporation, snow accumulation and melting, infiltration, percolation, and interflow between groundwater and drainage system. Although the software can use the kinematic wave equation and dynamic wave equation for hydraulic routing, the kinematic wave equation has been chosen in this study as it is less resource demanding. Since this article focuses on changes in flood volume and peak flow due to human activity, we focused on the relationship between rainfall and runoff rather than channel routing. The model describes the rainfall run-off with the SCS Curve Number method. In addition, the amount of water that needs to be collected on the surface during the transition of rainfall to surface flow is called depression storage and varies according to surface coverage (Table 1). Parameters such as the drying time of the soil in successive rainfall events as well as evaporation from depression storage have been ignored due to the focus on a single storm event.

Table 1. Depression Storages [24].

Surface Coverage	Depression storage (inches)	Depression storage (mm)	Chosen values (mm)
Impervious surfaces	0.05 - 0.10	1.27 - 2.54	1.905
Lawns	0.10 - 0.20	2.54 - 5.08	3.81
Pasture	0.2	5.08	5.08
Forest litter	0.3	7.62	7.62

3.2. Overview of rational method

Rational Method (Eq. 1) is frequently used in the design of drainage infrastructures of small urban areas [25]. The method has been used in the design of numerous urban drainage systems. As the area constraint of the method varies from organization to organization, it is common consensus that small basins up to 5 km² area are suitable for application. Rational Method calculates the peak flow rate regarding a runoff coefficient together with the precipitation intensity and the application area.

$$Q_p = C \times i \times A \tag{1}$$

where *C* is dimensionless flow coefficient, *i* is precipitation intensity (m/s), and *A* represents contribution area (m²).

4. Results and discussion

As previously mentioned SWMM was used in this study to detect the impact of the rapid LULC change in Gazipasa during the period of 2013-2019. Figure 5 compares the past (2013) and the current (2019) LULC map of the study area. The area has the extent of 4.4 km^2 including 25 drainage fields that are distinguished on the basis of their land use and established roads around them.

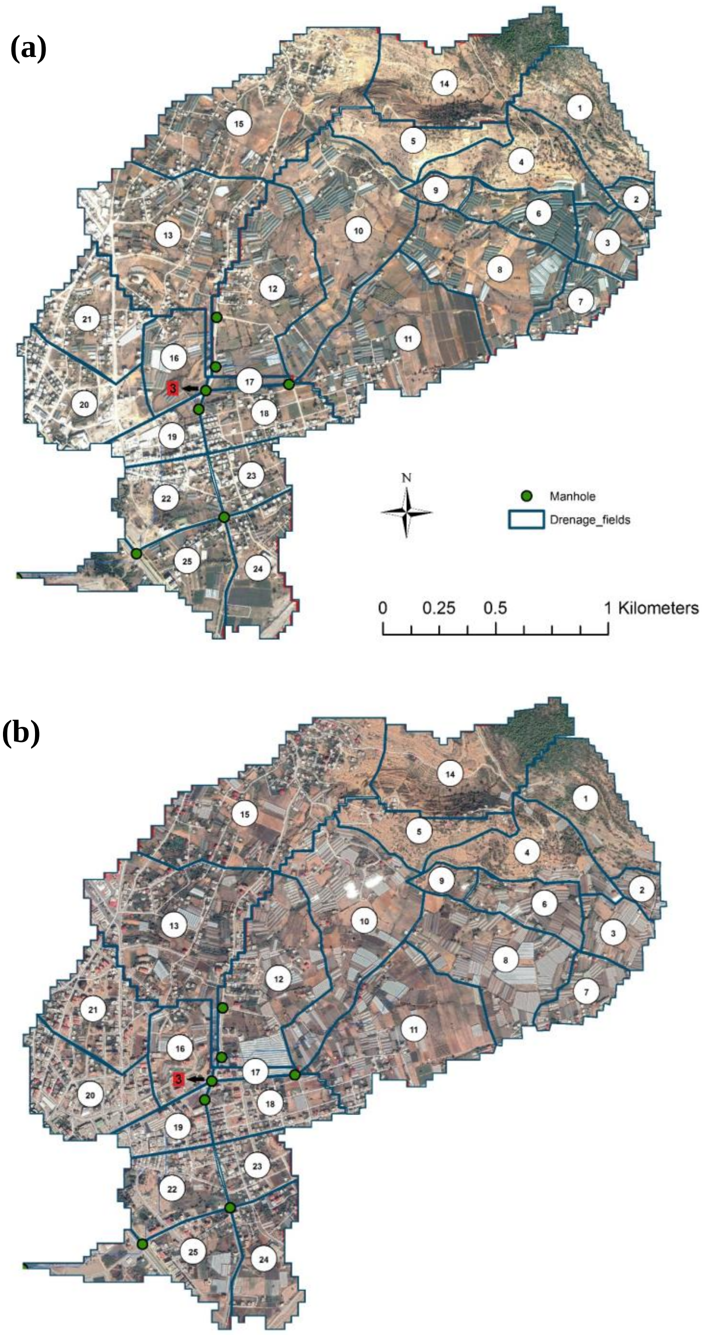

Figure 5. The LULC map of the study area in 2013 (a) and 2019 (b).

According to LULC maps, 14.16 and 25.44 % of the total basin area was covered with impermeable areas in 2013 and 2019, respectively. This increment corresponds to an 80 per cent increase in impermeable areas over seven years. Figures 6, 7 and 8 summarized the sub-catchment characteristics of the study at the past and current conditions.

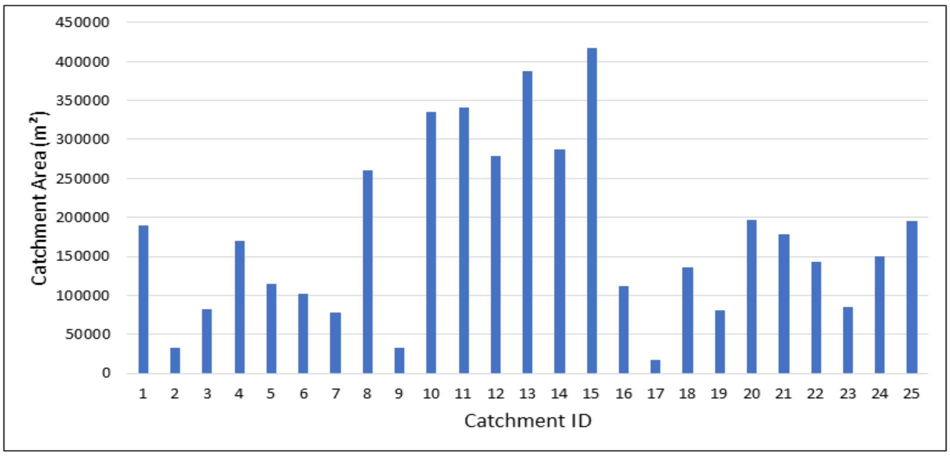

Figure 6. Total sub-catchment areas.

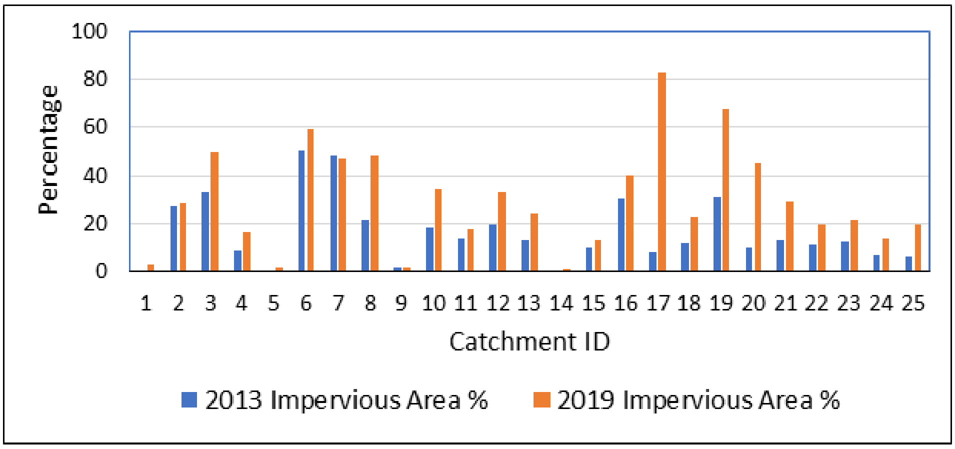

Figure 7. Impervious area percentages.

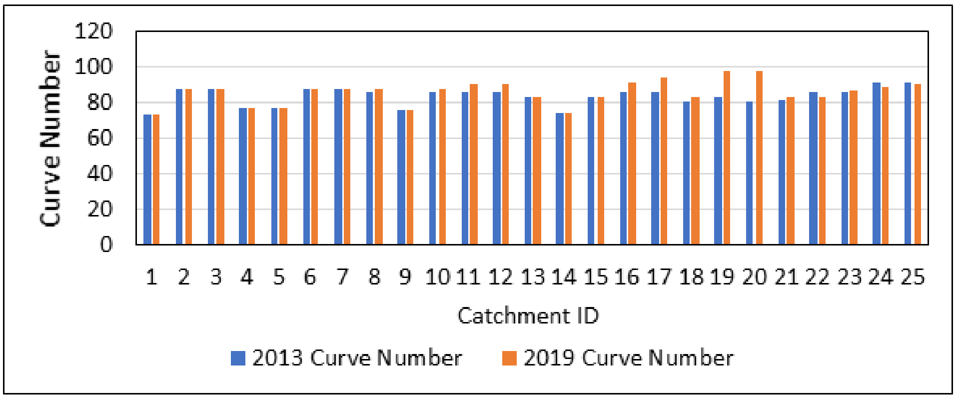

Figure 8. Sub-catchment Curve Numbers.

Intensity of 25-year storm having one-hour duration is equal to 75 mm/h. The value was considered as a new design storm for the city. The SWMM results for the corresponding storm was shown in Figure 9. As can be seen from Figure 5, the junction #3 located in the central part of the basin was chosen for flood hydrograph comparison. The simulation results showed a peak flow of 51.31 m^3/sec in 2013. Similarly, a peak flow rate of 61.40 m^3/sec was estimated under the same design rainfall in 2019. This result indicates that peak flow in the city center has been increased by 20%. Such an augment in flood peak is the consequence of 75% rise in the extent of impermeable area contributing to this point over the past seven years. The volumetric analysis between flood hydrographs revealed that the flood volume has approximately increased by 17.5% over the study period.

As previously mentioned, the Rational Method was used to estimate peak flood flow at the location of Junction 3 (Eq. 2). Due to majorly agricultural nature of the field contributing to Junction 3, the flow coefficient equals 0.5 was considered in this study [26]. Area contributing to Junction 3 has already been calculated as 3.75 km². The results showed the peak flow rate approximately equals 39 m^3/s.

$$Q_p = 0.5 \times (2.08 \times 10^{-5}) \times 3752134 = 39.08\, m^3/s \quad (2)$$

As can be seen from Eq. (2), the design rainfall 75 mm/s has been converted to $2.08{\times}10^{-5}$ m/sec and the basin area been converted to m^2 to achieve the desired output dimension.

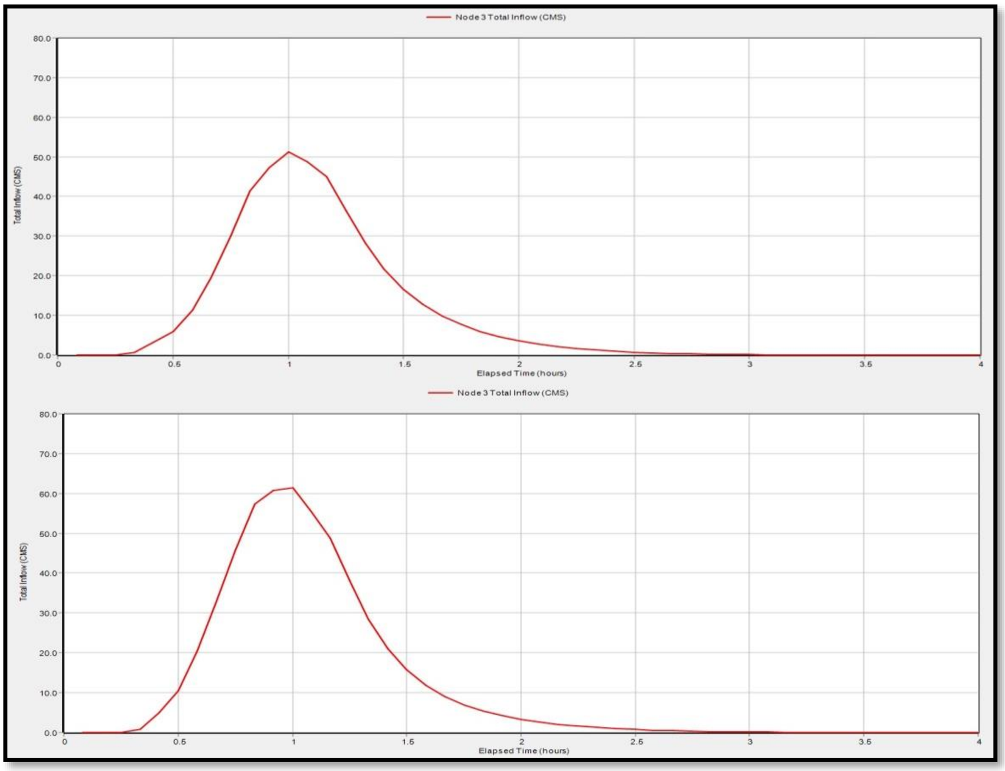

Figure 9. Flood hydrograph at Mehmet Oğuz boulevard junction in 2013 (Upper panel) and 2019 (Lower panel).

5. Conclusion

The impermeable areas determined within the study area are not classified according to the area of use. However, it's easy to tell that source of the impervious area increase from 2013 to 2019 within the drainage fields contributing to the control point is not only the residential areas but also industrial regions. Even it is not classified greenhouse land increase between 2013 and 2019 is significant. Rapid variation in LULC resulted in a 20% increase in peak flow and an 18% increase in flood volume in Gazipaşa, Turkey. This implies the importance of potential flood hazards and risk of mortality in rare storms having a return period of 25-year or higher. Thus, optimization of the existing stormwater drainage system must be considered by the relevant authorities. Our study was limited to a single design storm and 1only covers the Gazipaşa city partially. Future studies may include flood simulation of the entire city considering the tidal effects of the Mediterranean Sea on flood routing along the İnceağrı River.

Conflict of Interest: The author states that there are no conflicts of interest.

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