

Investigation of the effects of different plant groups on surface runoff

Farklı bitki gruplarının yüzeysel akış üzerindeki etkilerinin incelenmesi

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Abstract

Urbanisation has been demonstrated to have a direct impact on the natural water cycle, particularly in urban areas and regions exhibiting high levels of human impact. This impact arises from the decrease in the infiltration of precipitation water into the soil, which is known as runoff. The objective of this study is to evaluate the effect of various plant groups, with a particular focus on tree and shrub cover, on runoff. In the case of the Sariyer district of Istanbul, the runoff amounts were calculated using the "Curve Number" method. NDVI data were utilised in this process. The findings demonstrate that the presence of tree cover has a reducing effect on runoff. The study emphasises the importance of prioritising tree groups in urban areas and protecting existing wooded areas for effective water management.

Özet

Kentleşmeye bağlı olarak, yağışla yeryüzüne düşen suyun toprağa sızmasının azalması sonucunda oluşan yüzeysel akış, özellikle kentsel alanlar ile insan etkisinin yoğun olduğu bölgelerde doğal su döngüsünü doğrudan etkilemektedir. Bu çalışma, çeşitli bitki gruplarının, özellikle de ağaç ve çalı örtüsünün yüzeysel akış üzerindeki etkisini değerlendirmeyi amaçlamaktadır. İstanbul'un Sariyer ilçesi örneğinde, yüzeysel akış miktarları "Eğri Numarası" yöntemi kullanılarak hesaplanmış ve bu süreçte NDVI verilerinden yararlanılmıştır. Elde edilen bulgular, ağaç örtüsünün varlığının yüzeysel akışı azaltıcı etkide bulunduğunu göstermektedir. Çalışma, etkin su yönetimi için kentsel alanlarda ağaç gruplarına öncelik verilmesi ve mevcut ağaçlık alanların korunmasının önemini vurgulamaktadır.

INTRODUCTION

Uncontrolled rapid urbanization that is far away from sustainability approaches, negatively impacts the natural systems of the Earth, which also interacts with climate change and has negative consequences. The most significant effects are visible on natural water cycle. Urbanisation leads to an increase in impervious surfaces, leading to a decrease in the infiltration rate of rainwater into the soil and an increase in surface runoff (Shao et al. 2019). Furthermore, climate change has led to a greater unpredictability in rainfall patterns, resulting in an increased frequency and severity of extreme weather events (Calvin et al. 2023). Consequently, when these two factors are considered together, flooding, infrastructure problems and related issues have become increasingly prevalent in urban environments.

Runoff is defined as the process that occurs when the volume of precipitation exceeds the infiltration capacity of the soil (Ramke 2018). In urbanised areas, this process disrupts the natural water cycle, precipitating various ecological and economic challenges. The most significant effects of runoff include a decrease in water quality (Jang et al. 2021), an increase in dissolved matter and pollutants (Xiao et al. 2016), and an increase in the frequency of erosion and flooding (Fullen 1991, Hao et al. 2019). In urban areas, runoff problems have become particularly pronounced, necessitating the implementation of appropriate management strategies.

The detection and analysis of surface runoff can be achieved through the implementation of both field studies and remote sensing methodologies. The utilisation of remote sensing methodologies confers numerous advantages, most notably its capacity to

furnish data at both high spatial and temporal resolution (Li et al. 2016, Zhao and Qu 2024). This facilitates the development of effective and timely decision-making mechanisms. Specifically, the utilisation of indices such as the NDVI (Normalised Difference Vegetation Index) enables a more refined analysis of the interactions between vegetation and water (Jain et al. 2011, Xue et al. 2022). These methods are used to reveal the water holding capacity and runoff characteristics of different surface types in the city (Huang et al. 2021).

A variety of methodologies are employed in the estimation of surface runoff. In urban areas, the approach adopted is contingent on the characteristics of the terrain and the objective of the study. A frequently employed method is the 'Rational Method', which facilitates expeditious calculation in compact regions (Young et al. 2009, Schärer et al. 2020). For a more comprehensive evaluation, the 'SCS-CN (Soil Conservation Service Curve Number) Method' is favoured, as it incorporates parameters such as soil type, land use, and precipitation data (USDA 1986, Verma et al. 2017). In the case of large and complex urban areas, the use of advanced modelling software such as HEC-HMS (Jin et al. 2015) and SWMM (US Environment Protection Agency 2024, Hossain et al. 2019) is recommended in order to analyse the effects of both runoff and green infrastructure. In addition, NDVI-based analyses are also performed to assess the effects of vegetation on runoff (Patton et al. 2022).

Furthermore, the Curve Number (CN) method was selected for the calculation of runoff volume. The CN method has been shown to offer a simple, practical and reliable approach to estimating runoff, taking into account land use, soil properties and hydrographic conditions (USDA 1986). The primary reason for selecting this method is its capacity to analyse the effects of different vegetation types on runoff. Additionally, the CN method's extensive utilisation in the extant literature enhances the comparability of the results obtained with those from other studies.

Green infrastructure practices or natural-based solutions have been demonstrated to be highly effective in addressing runoff challenges (Woznicki et al. 2018, Yang

and Lee 2021). The implementation of permeable surfaces, biological filters, rain gardens and increased vegetation levels has been proven to contribute to reducing runoff and effectively managing stormwater (Alyaseri and Zhou 2016, Li et al. 2016, Kim et al. 2017, Coskun-Hepcan and Hepcan 2018). A comprehensive understanding of the effects of plant groups on runoff is of particular importance for urban planning and optimisation of ecosystem services (Maragno et al. 2018). The strategic integration of appropriate vegetation selection and the efficient design of infrastructure systems has the potential to significantly impact the water management capacity of urban areas.

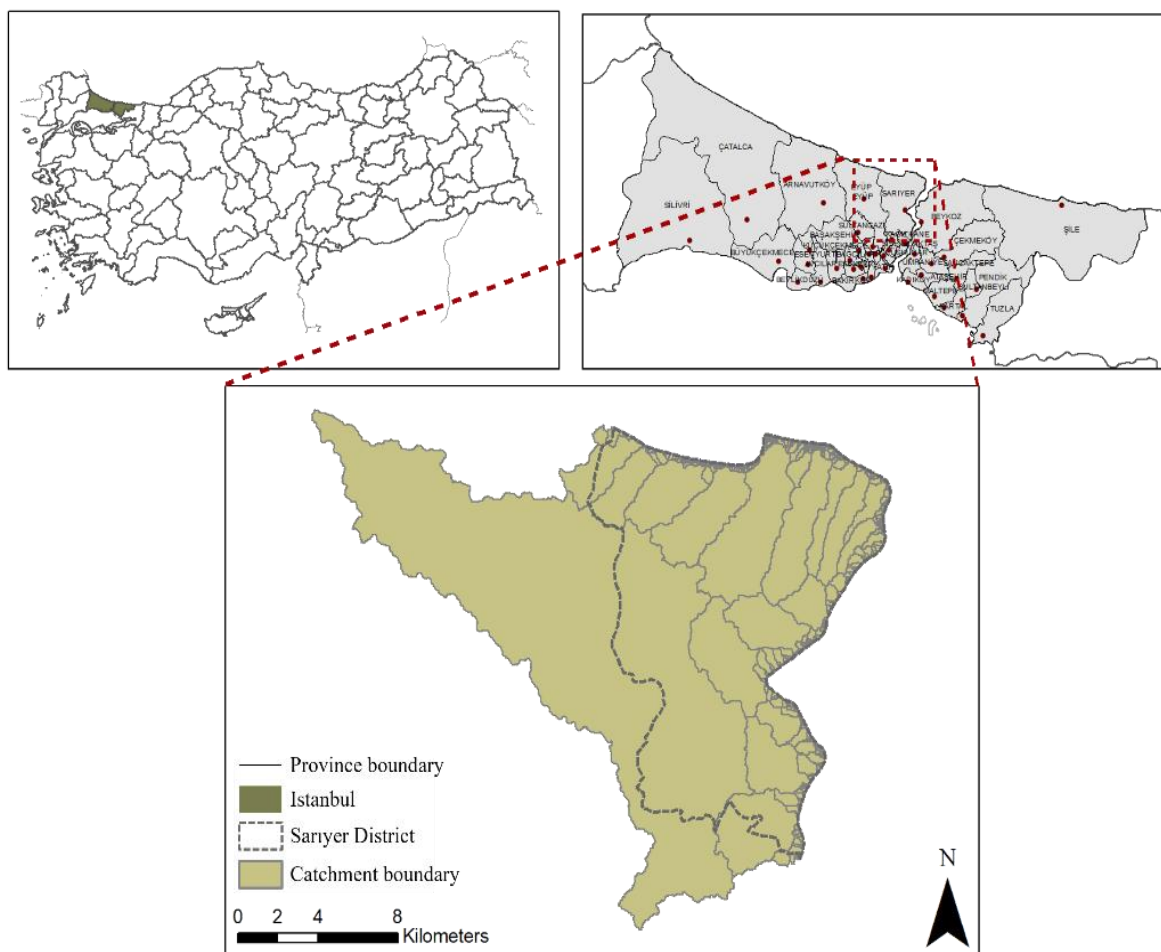
For instance, green corridors represent pivotal elements of green infrastructure, playing a crucial role in supporting ecosystem services and ensuring the continuity of biodiversity by establishing connections between natural and semi-natural areas (Beaugeard et al. 2021, Yan 2024). These corridors have been shown to reduce erosion and flood risk by decreasing surface runoff, thereby retaining water in the soil and slowing the flow rate of water (Coskun-Hepcan and Hepcan 2018) and they ensure the continuity of ecological processes by strengthening habitat connectivity (Zhang et al. 2019). Consequently, the establishment of green corridors is of critical importance for the conservation of water resources and the maintenance of a sustainable environment.

The objective of this study is to analyse the effects of different vegetation groups (i.e. shrubs and trees) on runoff in Istanbul, Sariyer region. Total rainfall data of Sariyer region for 2021 and the Curve Number (CN) method were utilised to determine the amount and distribution of runoff. In particular, by comparing the area sizes of shrub and tree groups and the amount of runoff per unit area, the water retention capacities of both plant groups were evaluated. The analysis is expected to provide a comprehensive understanding of the impact of vegetation diversity on hydrological processes, thereby offering valuable guidance for the planning and management of green infrastructure and water resources in urban settings.

MATERIAL AND METHOD

The study was conducted in Istanbul, Sariyer region. The study area is located between longitude 28°58'6" and 41°10'55" latitude. Sariyer is situated in the north-eastern part of Istanbul on the European side of the city (Figure

1). The northern part of the district is located along the Black Sea coast, while its eastern border is defined by the Bosphorus, which connects the Black Sea to the Sea of Marmara. The western and southern regions of the district are characterised by a predominantly urban landscape.



There are various basins within the administrative boundaries of the study area and these basin boundaries extends beyond the boundaries of administrative divisions. The administrative area of the Sariyer region was determined as the study area which covers 3.048.5 hectares. The main reasons for the selection of Sariyer region as the study area are (1) exhibits a wide variety of land uses and land covers (European Environment Agency 2020) (Figure 2), (2) the diversity of land use and cover is evident in the Istanbul district of Sariyer, which mirrors the city's overall structural characteristics, (3) a

considerable portion of the total area is covered with forest ecosystems, which serves to highlight the area's significant value and the necessity of its protection. However, despite the significant ecological value of the region, the presence of a highway in the north and the pressure of urbanisation in the south highlight the need to protect these natural areas and implement measures before problems such as surface runoff become unsolvable. This demonstrates that the ecological functionality of the region must be maintained through the implementation of sustainable management strategies.

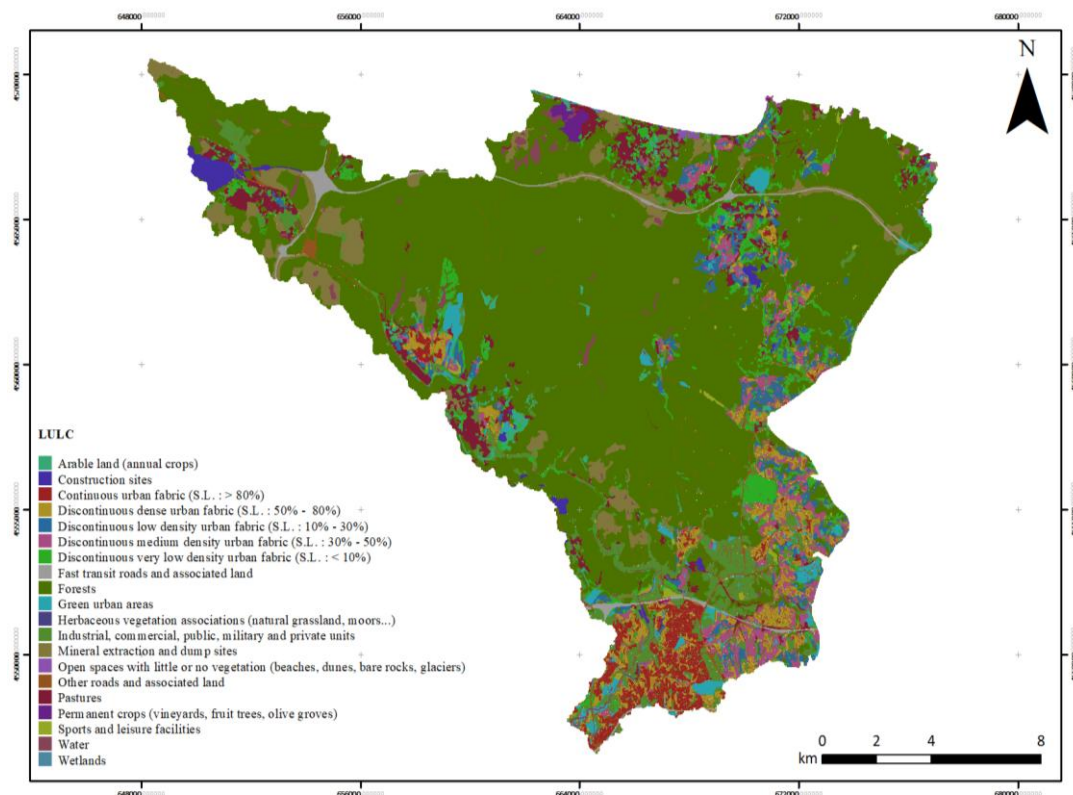


Figure 2. Land use and land cover of study area

A range of data sets were utilised to evaluate the effects of different plant groups on runoff. During surface runoff analysis, precipitation, slope, major soil groups (MSG), hydrologic soil groups (HSG), curve number (CN) values and water holding capacity were evaluated. The

integration of these data sets was undertaken to determine the impact of diverse plant communities on runoff phenomena. The data utilised within the scope of the study are delineated in the table below (Table 1).

Table 1. Dataset that was utilised in the study

Data type	Source	Resolution
LULC	Urban Atlas	-
NDVI	Sentinel-2 MSI Level-2A	10m
Precipitation	Official meteorological service	10m
Slope	Digital Terrain Model (DEM)	30x30
Soil structure	1/25000 Soil Maps	-
Curve number values	USDA National Engineering Handbook	-

Firstly, the Normalised Difference Vegetation Index (NDVI) data obtained from the "Sentinel-2 MSI, Level-2A" satellite images were utilised to ascertain the plant groups in the study area (Earth Resources Observation and Science Center 2017). Precipitation data were obtained from the Turkish State Meteorological Service for the year 2021 (Turkish State Meteorological Service 2021). The Digital Elevation Model (DEM) data was utilised to access the slope data of the study area (Farr et al. 2007). Finally, the necessary data for the calculation of

surface run-off was obtained. Specifically, soil structure data were obtained from (Republic of Türkiye Ministry of Agriculture and Forestry 2013), and CN values were obtained from United States Department of Agriculture (USDA 2004). The obtained data was used for the analyses and calculations related to surface runoff. All data analysis were conducted by using ArcGIS (ESRI 2011a) and Google Earth Engine (Gorelick et al. 2017) applications.

The Normalised Difference Vegetation Index (NDVI) is an index that measures the density and health of vegetation in an area using remote sensing methods. The NDVI ranges from '-1.0' to '1.0'. Negative values are reflected by clouds, water and snow, while values close to zero are mostly reflected by rocks and bare soil. Very low values of '0.1~' correspond to barren areas of rock, sand or snow. The range '0.2 - 0.3' is indicative of shrubland and grassland, while the range '0.6 - 0.8' is suggestive of temperate and tropical rainforest (ESRI 2011b).

Table 2. NDVI Values and Classification

NDVI value	Classification	Displaying value	Displaying color
(-1) – (0,2) Low NDVI	No vegetation	1	Red
(0,2) – (0,3) Medium NDVI	Shrubs	2	Yellow
(0,3) – (+1) High NDVI	Trees	3	Green

The images provided by the 'Sentinel-2 MSI, Level-2A' service were utilised within the scope of the study (Earth Resources Observation and Science Center 2017). The NDVI data was obtained by processing 'NIR (Band 8)' and 'Red (Band 4)' images using Google Earth Engine according to the following equation (1).

$$NDVI = \frac{(NIR - Red)}{(NIR + Red)} \quad (1)$$

NIR: Measured reflection value of near infrared band (Band 8)

Red: Measured reflection value of red band (Band 4)

Precipitation, the other parameter that directly affects surface runoff, was obtained using data provided by the Turkish State Meteorological Service (Turkish State Meteorological Service 2021). In order to undertake spatial analyses, the total precipitation data for 2021 were obtained by rearranging the historical precipitation distributions for the years 1970-2000 (Fick and Hijmans 2017). The slope information of the study area was determined using the 30-metre resolution Digital Elevation Model (DEM) obtained from Shuttle Radar Topography Mission (SRTM) data, and a slope classification was subsequently completed (Farr et al. 2007).

The Curve Number (CN) method was utilised to calculate surface runoff. This method involves a series of operations to ascertain the volume of water flowing

In the context of this study, the classification of plant groups within the study area was facilitated by the utilisation of NDVI values, as derived from remote sensing methodologies (Table 2). All analyses were completed for areas with NDVI values of '2' and '3'. Given the consideration of catchment characteristics, the results of analyses other than precipitation and slope data will be evaluated within the present context.

during rainfall over a given land area. It was observed that as the CN value increases, the surface runoff also increases, and as the value decreases, the runoff decreases (USDA 2004). Within the scope of the present study, the method was executed in four phases and is described in detail below.

Phase 1: In order to calculate surface runoff, it is necessary to determine the 'Hydrological Soil Groups' of the study area. Accordingly, the study area was firstly classified within the scope of 'Major Soil Groups (MSG)'. The HSG classification was made according to the combination of MSG and soil properties (Ozturk et al. 2011).

Phase 2: CN values were determined according to the tree and shrub groups in the study area and HSG data. In accordance with the information obtained from the literature (USDA 1986), CN values determined for tree and shrub groups are given in Table 3.

Table 3. CN values for plant groups

	HSG			
	A	B	C	D
Shrubs	-	71	81	89
Trees	36	60	73	79

The argument has been made that slope should be considered in surface runoff calculation. Consequently, the CN values should be determined according to the

slope for areas where the slope exceeds 5% (2) (Huang et al. 2006).

$$CN_2 = \frac{CN * [322,29 + 15,63(\alpha)]}{(\alpha + 323,52)} \quad (2)$$

CN₂: CN value adjusted according to slope

CN: First CN value

α : Slope value (Percent rise)

Phase 3: Following the acquisition of the CN values, it is imperative to compute the potential water holding capacity of the designated study area. The subsequent equation is employed for this calculation (3).

$$S = \left(\frac{25400}{CN_2} \right) - 254 \quad (3)$$

Phase 4: The resulting potential water holding capacity value was processed in combination with the precipitation data in accordance with the following

equation (4), and the amount of water entering the surface runoff of the study area was obtained.

$$Q = \frac{[P - (0,2 * S)]^2}{[P + (0,8 * S)]} \quad (4)$$

P: Precipitation

S: Potential water holding capacity

RESULTS

In order to achieve the objective of the study, the location and context of green areas were specified, and NDVI analysis was conducted during the study. The findings of the study indicated the presence of areas with NDVI values of '1 (low)', '2 (medium)' and '3 (high)' within the study area (Figure 3). According to the NDVI values, the total area of each value within the study area is presented in the following table (Table 4).

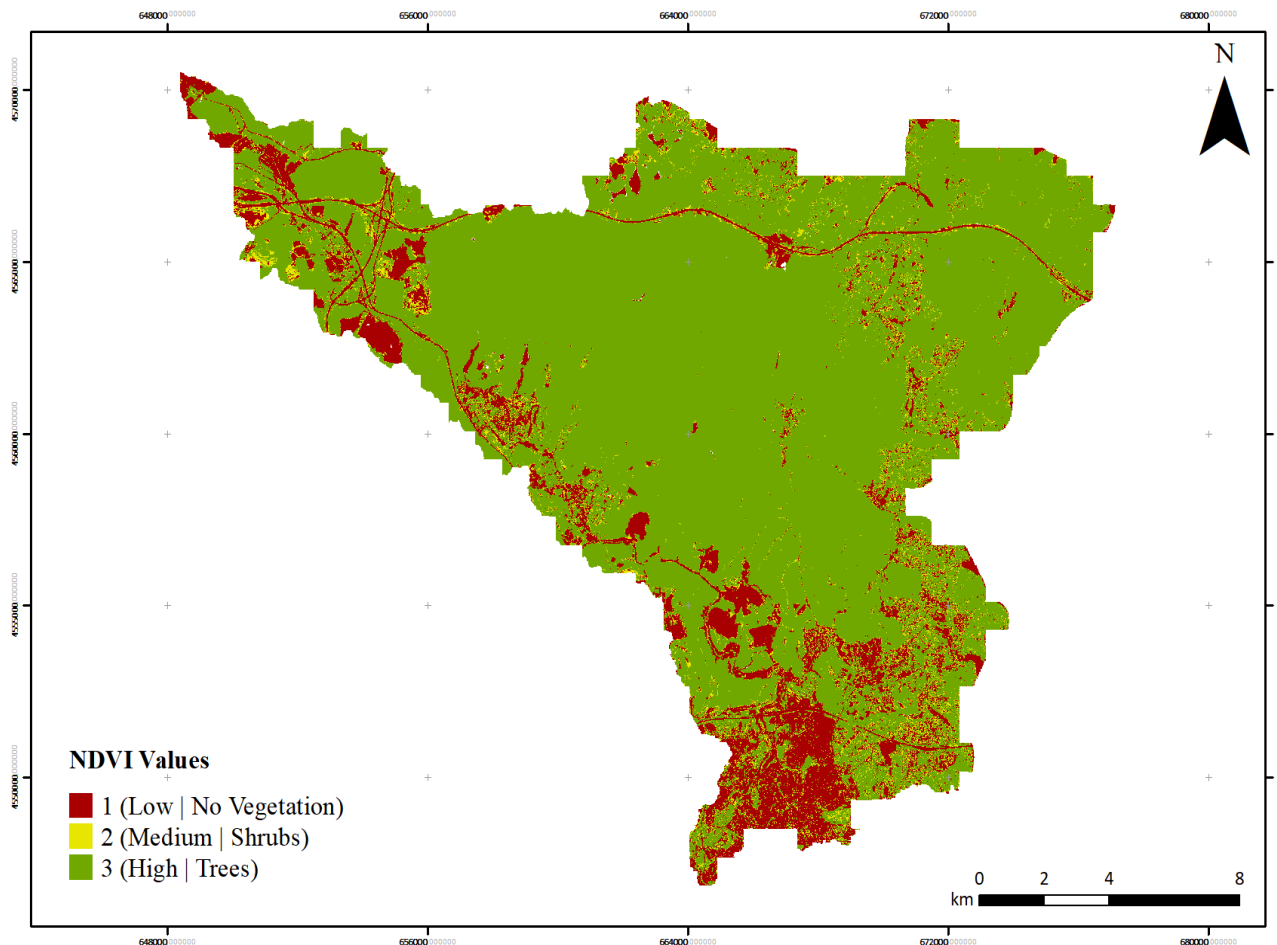
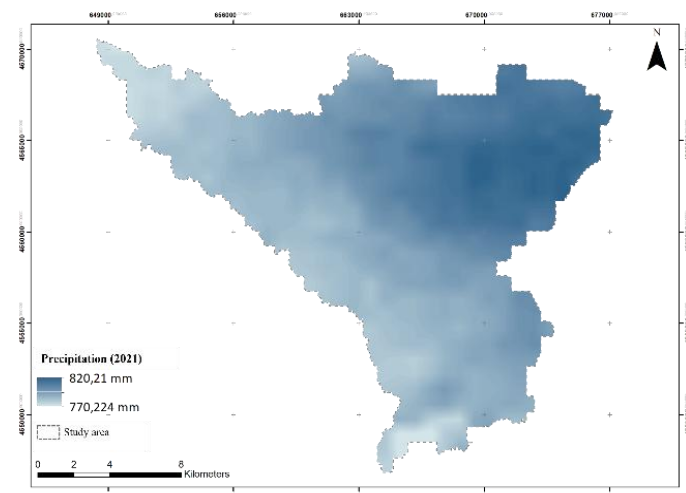


Figure 3. Spatial analysis of NDVI values in the study area

Table 4. Total areas of NDVI value classification

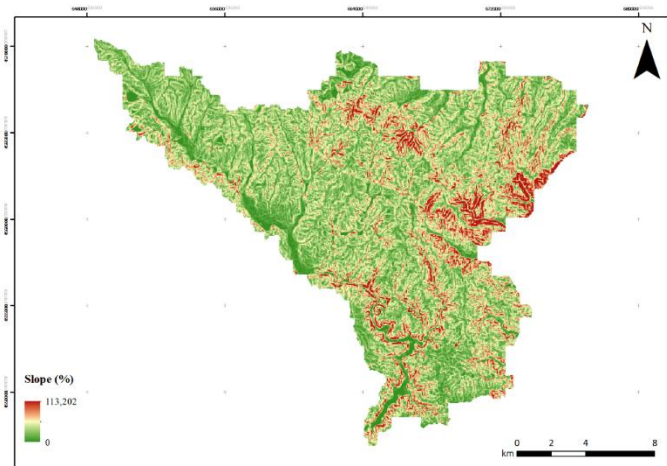
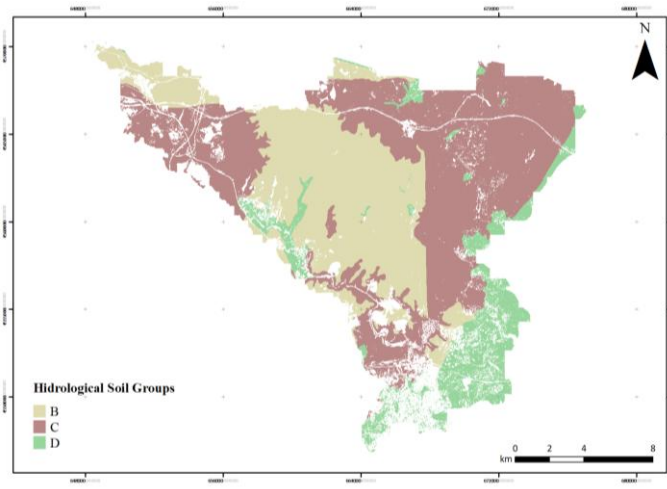
NDVI value	Area (ha)
2 (shrub)	1575.47
3 (tree)	24267.4

The analysis of precipitation and slope data was conducted to calculate surface runoff. Consequently, the total precipitation in the study area ranged between 820.21 mm and 770.224 mm, in the north-south direction, respectively (Figure 4). This change in precipitation levels is evident in the spatial distribution across the study area.

**Figure 4.** Precipitation data

The distribution of slopes in the study area varies between 0% and 113.20% (Figure 5). This finding indicates that the topographic diversity in the region is high. The presence of low-slope areas, characterised by their flatter topography, suggests enhanced potential for water infiltration. This variation may have important implications for water management and green infrastructure practices in the area.

In order to ascertain the curve number (CN) values, the soil structure of the area was analysed. Following the determination of the major soil groups (MSG), the hydrological soil groups (HSG) of the study area were determined. The analysis revealed that the study area did not contain any areas belonging to the 'A' group, but it did contain areas belonging to the 'B', 'C' and 'D' hydrological soil groups (Figure 6).

**Figure 5.** Slope data**Figure 6.** Hidrological soil groups of the study area

By adjusting the CN values assigned to the shrub and tree groups according to the slope, new CN (CN₂) values were obtained for the calculation of surface runoff (Table 5).

Table 5. CN₂ values adapted to slope

HSG	Tree		Shrub	
	CN	CN ₂	CN	CN ₂
A	36	-	-	-
B	60	60.55	71	71.22
C	73	73.16	81	81.65
D	79	90.16	89	89.68

The mean runoff amount of the shrub groups with NDVI value '2' in the study area was determined as 732.40 mm, and the mean runoff amount of the tree groups with NDVI value '3' was determined to be 677.78 mm (Table 6).

Table 6. Runoff quantities of shrub and tree groups

NDVI value	Area (ha)	Mean (mm)	Sum (mm)
2 (shrub)	1575.47	732.40	10440377.76
3 (tree)	24267.4	677.78	180242903.6

DISCUSSION AND CONCLUSION

The present study has been conducted for the purpose of determining the effects of tree and shrub communities on runoff, a problem which is particularly pertinent in urban areas. The utilisation of remote sensing methodologies is intended to provide a comprehensive explanation of the interaction between these plant communities and the runoff problem. Data pertaining to plant communities has been obtained through the utilisation of NDVI images, a metric of plant health. Additionally, the Curve Number method, a key component in the calculation of surface runoff, has been employed. The study's objective is twofold: firstly, to collect pertinent information regarding the runoff, which is a contemporary urban problem, and secondly, to propose solutions that mitigate the adverse effects of this problem to the highest possible extent.

In the study area, the shrub group has an area of 1575.47 hectares, while the tree groups have an area of 24.267.4 hectares. The effects of these two plant groups on runoff were analysed in terms of runoff per unit area and total runoff values. Upon examination of the findings obtained from the data, it is evident that the tree group exhibits a higher proportion within the total runoff amounts of each plant group. This difference can be attributed to the fact that the area covered by the tree group is 15 times larger than that of the shrub group. Consequently, when comparing the runoff amounts of the two groups, it would be more efficient to discuss the differences in unit area instead of total amounts.

The mean runoff per unit area of the shrub group was 732.40 mm, whereas this value was 677.78 mm for the tree group. These findings indicate that tree groups maintain a reduced level of runoff per unit area and thereby facilitate more effective water retention in the soil.

The findings demonstrated that tree groups exhibited a beneficial effect on runoff problems in comparison to shrub groups. In accordance with the research conducted by Armson et al. (2013) and Grey et al. (2018), the positive contribution of tree groups to water management is apparent, as evidenced by their dense root systems, diverse foliage types, and stand effects. In contrast, shrub

groups appear to demonstrate comparatively diminished capacity to influence runoff in analogous contexts (Rahman et al. 2023). Meanwhile, the impact of diverse plant communities on runoff may be different depending on their leaf characteristics. Forests comprising a high density of coniferous trees have been shown to increase evapotranspiration and reduce runoff relative to deciduous groups (Kim and Kim 2004). As can be seen from the forest cover in the study area, mixed stands have significantly lower runoff (Rahman et al. 2023).

Runoff constitutes a significant problem for urban areas for a number of reasons. A range of approaches have been developed to address this issue. Green infrastructure and nature-based solutions can be regarded as systems that facilitate the integration of soil and water (Li et al. 2020a). Of particular note is the establishment of systems capable of coping with the increase in both the frequency and intensity of precipitation, a phenomenon attributable in part to climate change (Zhang et al. 2023). Such systems have the potential to support cities ecologically, whilst also reducing disaster risks (Liu et al. 2014). Moreover, green infrastructure solutions have been shown to offer effective solutions at a lower cost compared to traditional methods within the scope of the sustainability principle (Li et al. 2020b). The analysis of the effect of tree groups on runoff, for example, serves to emphasise the importance of green infrastructure elements such as green corridors within the city. An evaluation of the Sariyer district reveals the potential for the establishment of green corridors. Specifically, the establishment of a green corridor along the Bosphorus coast in the eastern part of the district has the potential to enhance surface runoff in this area. Moreover, it has the capacity to prevent the transport of pollutants into the sea water as a result of excessive precipitation, such as that caused by vehicle roads. It is evident that the motorway situated in the northern portion of the site, which segment the forest habitat, has the capacity to contaminate the soil through surface runoff. Therefore, in addition to the establishment of green corridors, the incorporation of green infrastructure elements such as bioswales within the design of these areas has the potential to reduce surface runoff and facilitate relatively cleaner infiltration.

When Istanbul is considered in general, it is thought that coastal areas can be evaluated within the scope of green corridors in a similar way as in Sariyer district. Furthermore, the integration of forest habitats within the city, which have been fragmented due to urban expansion, is expected to mitigate the aforementioned challenges.

The forest area within the Sariyer district's borders is of significant importance. It is an ecological structure with the potential to resolve the problems created by urban areas, not only surface runoff. Consequently, in regions experiencing high levels of urban pressure, the preservation of these areas is of paramount importance. Forest ecosystems characterised by dense tree cover have been shown to significantly reduce surface runoff by increasing water infiltration into the soil and encouraging evaporation (Kuehler et al. 2017). However, it can be argued that such areas within urban settings, which initially demonstrate a positive effect in terms of surface runoff management, can ultimately exhibit a negative impact due to their utilisation for recreational purposes. Intensive recreational use can result in the compaction of forest soil structures (Foti et al. 2021), thereby reducing water infiltration and increasing surface runoff. It is evident that certain regions of the forest area within the defined study area are utilised for recreational purposes (URL-1, URL-2). In order to mitigate the consequences of anthropogenic interactions and prevent the runoff in the forest area from becoming a more significant problem, it is recommended that the pressure brought by recreational use is mitigated. In this context, the implementation of a controlled and limited form of recreation may be recommended. Consequently, it may be considered misleading to conclude that tree groups alone reduce runoff based on these data alone.

In the context of the study, surface runoff was calculated by remote sensing methods. The utilisation of higher-resolution data, such as satellite imagery, a benefit of the method, has the potential to yield more accurate results. Furthermore, the findings can be supported by field studies to reach more precise conclusions, since the NDVI data is not sufficiently informative about the stands.

Subsequent studies may undertake a comparative evaluation of the effects of diverse plant species (e.g. ground cover plants, mixed plant communities) on runoff. Furthermore, conducting such analyses with long-term precipitation data and taking into account seasonal changes in vegetation cover may increase the scope of the findings. However, it is clear that the use of design rainfall data can provide more specific and reliable results, especially in infrastructure and flood management studies, and will greatly contribute and guide planning studies within the scope of future scenarios. A more detailed examination of the effects of vegetation on hydrological processes, using various modelling and statistical analyses to support consistency between data, will provide more comprehensive information for green infrastructure planning.

The results of the study demonstrated that green areas have a significant impact on water management. Diverse structures such as forest ecosystems, shrub and tree groups, play a pivotal role in the management of surface runoff, as well as in the resolution of numerous environmental issues in urban areas. Green areas in the urban environments are important green infrastructures which provide ecosystem services such as water management, erosion control and biodiversity conservation by acting as repositories for water absorption and storage.

This study provides significant findings for understanding the effects of vegetation types on runoff. In particular, it emphasises that tree groups should be prioritised within green corridors as a green infrastructure element within the scope of water management. The effectiveness of tree groups in reducing runoff and supporting the natural cycling of water is further supported by the findings of similar studies in the literature (Alves and Formiga 2019, Downton et al. 2023, Wu et al. 2024).

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