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Ecosystem Services Supply from Peri-Urban Watersheds in Greece: Soil Conservation and Water Retention

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Abstract: The main objective of this study is to investigate the supply of ecosystem services (ESs) within peri-urban watersheds (PUWs) across Greece, utilizing earth observation (EO) data and empirical models. To achieve these goals, several open-access geospatial datasets were utilized and processed within a GIS environment. Specifically, the supply of soil conservation and water retention services was assessed at the watershed scale. The results indicates that the supply soil conservation service withing the examined PUWs range from 44.41 t ha^{-1} y^{-1} to 441.33 t ha^{-1} y^{-1} with an average value of 161.99 t ha^{-1} y^{-1}. Water retention services vary from 35.09 to 154.63 mm within the PUWs, with an average of 91.45 mm. Additionally, the variation in ES values across distinct altitudinal zones and ecosystem types provides useful insights for implementing protection and management measures. It is evident from the analysis that the soil conservation service gradually increases with elevation, with alpine and subalpine areas exhibiting the highest values. Moreover, mountainous and semi-mountainous regions demonstrate higher values compared to the estimated average soil conservation services of the entire study area. Furthermore, the provision of water retention services varies across different altitudinal zones. Specifically, the mountainous and semi-mountainous areas exhibit the highest values, followed by the subalpine and hilly regions, while lower values are observed in the lowland and alpine regions. The analysis also reveals distinct patterns in ecosystem services across various ecosystem types within the PUWs. Woodland and forest, along with heathland and shrubs, demonstrate higher values in terms of both soil conservation and water retention services. Our findings contribute to understanding the dynamics of ESs in PUWs, highlighting their significance for sustainable land management, and informing policy decisions aimed at preserving ecosystem health and resilience.

Keywords: ecosystem services; watersheds; erosion; USLE; runoff; SCS-CN; earth observations

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1. Introduction

Since 2008, more than half of the global population has been living in urban regions, and this figure is expected to rise to 68% by 2050 according to average projections [1]. This unprecedented urban development witnessed over the last century and the forthcoming urbanization prospects in both developed and developing countries represent a phenomenon with profound economic, social, and environmental implications at regional to global scales [2]. While urbanization can positively influence economic development and productivity, the associated functional, morphological, and structural changes often impose increased pressure on adjacent natural resources, leading to adverse effects on environmental quality, ecosystem functions, and sustainability [2,3].

At the landscape level, the primary challenge lies in identifying the most effective approach to managing various land cover options [4]. The growth of urban regions leads to substantial changes in landscapes, transforming natural ecosystems into impermeable urban zones at an accelerated rate [5,6]. Despite the growing recognition of the environmental impacts of such transformations, unsustainable land-use practices persist. Land management decisions, influenced by policy and environmental planning, play a pivotal role in shaping land cover, and directly impact ecosystem services (ES) [7,8]. The Millennium Ecosystem Assessment (MEA), a major UN-sponsored effort to analyze the impact of human actions on ecosystems and human well-being, identified four major categories of ecosystem services: provisioning, regulating, cultural services, and supporting services [9].

Peri-urban landscapes, characterized by their adjacency to urban centers and the blending of urban and rural areas, face heightened vulnerability to the pressures of urban expansion and land-use alterations. The conversion of peri-urban regions from natural to anthropogenic landscapes not only compromises their ecological integrity but also undermines the provision of essential ESs crucial for human well-being and environmental sustainability. For a considerable period, the lack of awareness regarding the significance of ESs has led to numerous challenges, resulting in the excessive exploitation of natural resources, and affecting ecological security on the regional and global scales [10]. As urban sprawl encroaches upon these areas, the demand for green infrastructure, including peri-urban forests and open green spaces, intensifies.

Green infrastructures play a vital role in mitigating the adverse effects of urbanization by providing habitats for biodiversity, regulating microclimates, and enhancing the overall quality of life for residents [11–13]. Their significance spans from local to global scales, contributing substantially to the achievement of numerous Sustainable Development Goals outlined by the UN for 2030. They also offer a spectrum of material and non-material benefits to urban and peri-urban dwellers, encompassing carbon sequestration and climate regulation [14], atmospheric pollutant removal and air quality improvement [15,16], water flow regulation [17], purification [18], provision of wood and non-wood products [14], recreational and cultural opportunities [19], educational and science opportunities [20], renewable energy production [21], disaster risk reduction [22], and soil conservation [23]. Particularly noteworthy is their role in promoting physical and mental well-being, as evidenced during crises such as the COVID-19 pandemic [24,25].

Among these services, soil conservation and water retention capacity are of paramount importance, especially in the Mediterranean basin. This area is acknowledged as a focal point for both climate change and biodiversity [26,27], and it is anticipated to encounter heightened challenges in water-related services due to the climate crisis. The Food and Agricultural Organization (FAO) of the United Nations (UN) developed a comprehensive and practical international Forests and Water Agenda to guide future action [28]. While ESs are universally important, across all landscapes and at different scales, they are especially crucial in mountainous watersheds [29]. Moreover, water-related services should be studied at the watershed scale, following the trend of the EU directives (e.g., 2007/60/EC, 2000/60/EC) for integrated water resources management. Watershed areas are crucial units for studying ES dynamics due to their unique ecological, economic, and geographic characteristics. They provide a nuanced understanding of the supply and demand dynamics of ecosystem services, characterized by intricate interactions between natural processes and human activities. Scholars address these challenges by evaluating ecosystem services using watershed-scale approaches [30–32]. However, most studies are conducted as case studies rather than on a broader scale. In recent years, the expanding accessibility of earth observation (EO) data coupled with the widespread utilization of geospatial technologies enables the extensive evaluation of ESs on a large scale [33].

This study aims to evaluate the supply of soil conservation and water retention capacity ES in peri-urban watersheds (PUWs) across Greece using EO data. More specifically, this study provides insight into the following: (i) hotspot identification of the upstream PUWs for ES provision and (ii) exploration of the pattern between altitudinal zones and ecosystem

types with ES values. By delving into these complex dynamics within watershed contexts, the research contributes to a deeper understanding of sustainable land management practices and conservation strategies in peri-urban environments.

2. Materials and Methods

2.1. Study Area

The study was conduct in selected PUWs, located upstream of major cities across Greece. The location of these Greek cities can be found in Figure 1, while the characteristics of the PUWs are detailed in Table A1 (Appendix A). Specifically, the study examined 54 watersheds upstream of 14 cities.

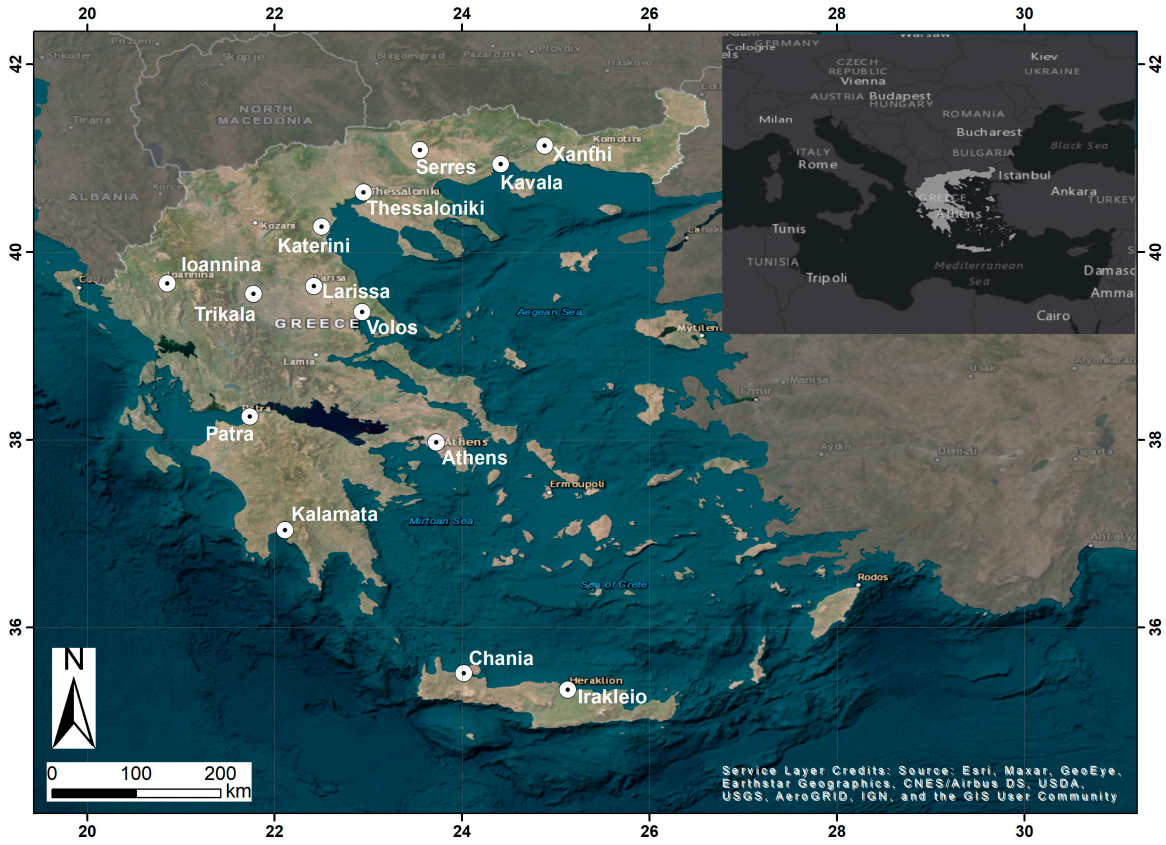


Figure 1. Location map of the major Greek cities.

To define the study area, a set of open-access geospatial data were utilized. Spatial boundaries of cities were derived from data provided by the Organisation for Economic Co-operation and Development (OECD), accessible at https://www.oecd.org/regional/regional-statistics/functional-urban-areas.htm (accessed on 10 January 2024). The OECD, in cooperation with the EU, has developed a harmonized definition of cities. According to this definition, a city is a grouping of local administrative units (LAUs) in European countries, such as municipalities or local authorities, where at least 50% of the population resides in an urban center. An urban area is defined by a grouping of adjacent grid cells covering a single square kilometer, with a population density of at least 1500 residents per square kilometer and a total population of no less than 50,000 individuals. To this end, fourteen cities were identified in Greece. Regarding the population data from the aforementioned source, two out of fourteen cities are characterized as metropolitan (with population more than 1 million inhabitants) named Athens and Thessaloniki, while the rest of the cities are rather smaller, and their population range from 46,800 to 156,000 inhabitants. The population of each city can be seen in detail in Table A1.

In terms of watershed, the thematic layers were retrieved from the Hellenic Ministry of the Environment and Energy (MEEN), accessible at https://geodata.gov.gr/en/dataset/oreines-lekanes-aporroes-2es-taxes (accessed on 10 January 2024). This dataset includes the mountainous watersheds of the Greek territory, as described in the torrent registry system compiled for the entire territory and used from local authorities as a basis for watershed management. Subsequently, the watersheds that intersect the borders of the cities were identified, thus determining PUWs that formed the study area of the present research (Table A1). The area of the PUWs included in this study ranged from 6.38 km^2 to 406.51 km^2.

2.2. Soil Conservation Service

The assessment of ecosystem services related to soil conservation relied upon the widely recognized empirical model of the Universal Soil Loss Equation (USLE) combined with some features of the updated model's revised form [34]. To accomplish this, potential and actual erosion rates were calculated using Equations (1) and (2), respectively. Furthermore, the soil conservation service, representing the disparity between potential and actual soil erosion rates was computed as detailed in Equation (3).

Potential soil erosion rate:

$$E_p = R \times K \times LS \quad (1)$$

Actual soil erosion rate:

$$E_a = R \times K \times LS \times C \times P \quad (2)$$

Soil conservation service:

$$E_c = E_P - E_a \quad (3)$$

where E_p and E_a represent the potential and actual rates of soil erosion, respectively (t ha^{-1} y^{-1}), while E_c denotes the soil conservation service (t ha^{-1} y^{-1}). The variable R stands for the rainfall erosivity factor (MJ mm ha h^{-1} y^{-1}), K denotes the soil's erodibility factor (t ha h ha^{-1} MJ^{-1} mm^{-1}), LS signifies the topographic factor (dimensionless), which is determined by slope length (L) and slope steepness (S), C indicates the cover management factor (dimensionless), and P represents the support practice factor (dimensionless).

The R factor, which serves as the model's climate component, was obtained from a newly created dataset by leveraging the Rainfall Erosivity Database at European Scale (REDES) in conjunction with UERRA regional reanalysis rainfall data spanning the period 1990–2018 [35]. This dataset, furnished by the European Soil Data Center (ESDAC) with spatial resolution 1 km, is accessible at https://esdac.jrc.ec.europa.eu/content/rainfall-erosivity-european-union-and-switzerland (accessed on 10 January 2024).

The soil erodibility (K-factor) represents the soil's resistance to the erosive effects of rainfall, influenced by various soil properties such as physical, chemical, and mineralogical characteristics, as well as their interactions. In this research, the soil erodibility factor is determined by employing following equation provided by Wischmeier and Smith [36]:

$$K = [\left(\frac{2.1 \times 10^{-4} M^{1.14}(12 - OM) + 3.25(s - 2) + 2.5(p - 3)}{100}\right) \times 0.1317] \quad (4)$$

where M represents the grain size parameter, OM denotes organic matter content (%), s represents soil structure, and p signifies permeability. The calculation of M relies on the on the percentages of the "silt + very fine sand" fraction (P_s%) and clay fraction (P_c%) as depicted in the equation below:

$$M = P_S(100 - P_C) \tag{5}$$

In this study, soil properties used in the calculations were obtained from SoilGrids, a state-of-the-art digital soil mapping system developed by the International Soil Reference and Information Centre (ISRIC—World Soil Information), accessible at https://soilgrids.org/ (accessed on 10 January 2024). SoilGrids employs advanced machine learning techniques along with a vast dataset comprising soil profile data (WoSIS) and environmental layers to provide precise, high-resolution soil property information at a resolution of 250 m [37]. This comprehensive resource enables the accurate characterization of soil attributes, including fractions of sand, silt, and clay, as well as organic matter content and descriptors related to soil structure and permeability.

The topographic factor (*LS*) is composed of individual factors, slope length (*L*) and steepness (*S*), which collectively describe their combined effect on soil loss. A crucial parameter for calculating the *LS*-factor is the digital elevation model (DEM). In this study, we utilized the newly developed Forest And Buildings removed DEM (FABDEM). FABDEM is a global elevation map that eliminates biases from building and tree heights in the Copernicus GLO-30 Digital Elevation Model (DEM) using machine learning techniques [38]. FABDEM emerges as the preferred choice due to its superior accuracy, particularly in areas with dense vegetation, presenting a significant enhancement over existing open-access DEM products with similar resolutions (30 m) [39].

The calculation of the LS-factor was conducted using advanced algorithms from the System for Automated Geoscientific Analyses (SAGA) within the latest version of QGIS (v3.22) software. This software package integrates the multiple flow algorithm, enabling comprehensive terrain analysis [40].

The formula introduced by McCool et al. [41] was utilized to derive the *S*-factor, relying on the slope gradient (ϑ) expressed in degrees:

$$S = \begin{cases} 10.8 \times sin\vartheta + 0.03, \vartheta < 0.09 \\ 16.8 \times sin\vartheta - 0.5, \vartheta > 0.09 \end{cases} \tag{6}$$

Furthermore, the *L*-factor was determined utilizing the recommended equation by Desmet and Govers [42], which has demonstrated reliability in regions characterized by intricate terrain [40]. This approach, incorporating the concept of unit-contributing area to account for variations in slope steepness across the area, is detailed by Equation (7):

$$L = \frac{\left(A_{i,j-} + D^2\right)^{m+1} - A_{i,j-in}^{m+1}}{D^{m+2} \times x_{i,j}^m \times 22.13^m} \tag{7}$$

In this method, $A_{i,j,-in}$ represents the contributing area (m^2) at the inlet of the grid pixel denoted by (*i*,*j*). D stands for the size of the grid pixel in meters. The variable $x_{i,j}$ denotes the combined sine and cosine values of the aspect direction ($\alpha_{i,j}$) of the grid pixel, calculated as $x_{i,j} = sin\ \alpha_{i,j} + cos\ \alpha_{i,j}$. The coefficient m is associated with the ratio β of rill to inter-rill erosion. Its values range from 0 to 1, while ϑ represents the slope angle in degrees. The m coefficient is calculated as follows:

$$m = \frac{\beta}{\beta + 1} \tag{8}$$

$$\beta = \frac{\frac{sin\vartheta}{0.0896}}{\left[0.56 + 3 \times sin\vartheta^{0.8}\right]} \tag{9}$$

The cover management factor (*C*) delineates the impact of land cover on erosion. Herein, the estimation of the *C*-factor relied on a national-scale ecosystem type product developed as a part of the LIFE-IP 4 Natura project [43], based on land use/cover (LULC) classification. This dataset, specifically tailored for ecosystem services mapping and assessment, served as the basis for our analysis and was supplied by the Natural Environment and Climate Change Agency (N.E.C.C.A.), the primary governmental body overseeing the National System of Governance of Protected Areas (PAs) in Greece. To determine the *C*-factor, appropriate values were assigned to each LULC based on the literature [44,45]).

Finally, the impact of support practices (*P*-factor), such as contour farming, stone walls, terracing, and grass margins on erosion mitigation, was evaluated using data retrieved from the European Soil Data Centre (ESDAC), accessible at https://esdac.jrc.ec.europa.eu/content/support-practices-factor-p-factor-eu (accessed on 10 January 2024), providing comprehensive coverage for the entire Europe [46].

The raster calculator tool was employed to combine various factors, resulting in the derivation of soil conservation service values, with the subsequent exportation of statistics at the watershed level per city. Additionally, zonal statistics were conducted to illustrate the outcomes across distinct altitudinal zones and ecosystem types.

2.3. Water Retention Service

The water storage capacity plays a pivotal role in hydrology, influencing both peak discharge and water supply. The assessment of water retention ecosystem service was based on the Soil Conservation Service-Curve Number (SCS-CN) approach [47], initially formulated by the SCS under the U.S. Department of Agriculture (now referred to as the Natural Resources Conservation Service—NRCS). According to this approach, the maximum water retention capacity (*S*) is directly influenced by the runoff coefficient (*CN*), as expressed by the following equation:

$$S = \frac{25400}{CN} - 254 \quad (10)$$

In the SCS-CN method, there is an inverse relationship between the maximum water retention capacity and the runoff coefficient. Soils with higher retention capacities exhibit lower runoff coefficients, while those with lower capacities generate runoff more rapidly.

To calculate this service, we estimated the maximum water retention capacity based on the current LULC (S_C) and compared it to a scenario without any vegetation (S_{noVeg}). This scenario typically excludes vegetation parameters from the Curve Number (*CN*) estimation, following the methodology of the erosion conservation service. Therefore, the water retention ES was defined as the difference between these two states. The empirical equation developed in the framework of the Deucalion Project [48] was used to calculate the *CN* for average humidity conditions. The updated evaluation of the *CN* parameter has improved the accuracy and spatial representation of *CN* across the entire watershed [49].

The *CN* value is determined by considering the predominant factors such as water permeability, land cover, and drainage capacity of the watershed, utilizing the following empirical equations [48,49]:

Current *CN*:

$$CN_C = 10 + 9 \times iPERM + 6 \times iVEG + 3 \times iSLOPE \quad (11)$$

CN without vegetation:

$$CN_{noVeg} = 10 + 9 \times iPERM + 30 + 3 \times iSLOPE \quad (12)$$

where *iPERM* represents water permeability, *iVEG* denotes vegetation density, and *iSLOPE* indicates drainage capability, each variable ranging from 1 to 5 based on literature [48,49].

To determine the *iPERM* values, the parent material of the studied Permeable Urban Watersheds (PUWs) was identified using the national scale soil map of Greece. The vector data of the parent material are accessible through the Hellenic Ministry of the Environment and Energy (MEEN) website at http://mapsportal.ypen.gr/maps/289 (accessed on 10 January 2024). Subsequently, each parent material was assigned an appropriate value based on the relevant literature [49]. A ranking system ranging from 1 to 5 was then employed, where an index of one corresponds to substrata with very high permeability (e.g., karst formations), while an index of five denotes substrata with very low permeability (e.g., dense rocks).

Vegetation classes are delineated based on land characteristics such as retention mechanisms, soil roughness, and filtration capacity, influenced notably by root zone growth. Leveraging the LULC product and the associated ecosystem types established within the LIFE-IP 4 Natura project, as described above [45], the vegetation type within the designated area is first classified as dense, moderate, undergrowth, sparse, or absent. Then, a grading scale from 1 to 5 is implemented, with a score of 1 indicating regions with dense vegetation (e.g., evergreen forests), while an index of 5 indicates bare soil [49].

The initial classification of the drainage capability encompasses categories such as negligible, low, moderate, high, and very high, followed by the assignment of ranks ranging from 1 to 5. These rankings are determined solely by considering five terrain slope categories, as this information can be readily obtained through standard DEM processing. A rank of one is designated for nearly flat areas, while a rank of five corresponds to slopes exceeding 30% [49].

Similarly with the soil conservation, water retention service values were derived using raster calculator tool and then exported as statistics at the watershed level per city. Additionally, zonal statistics were conducted to visualize the outcomes across different altitudinal zones and ecosystem types.

2.4. Overall Workflow

Various geospatial datasets were acquired and processed to fulfill the objectives of this study, including topographic, climatic, land cover, pedological, and geomorphological data. With the aid of the open-source Quantum GIS (QGIS) software, the datasets were structured into GIS thematic layers. The study area was delineated, and factors influencing soil conservation and water retention were identified. The output pixel size for ecosystem service (ES) analysis was set to 100 m, with the coordinate system set as the standard European Coordinate Reference System, utilizing the European Terrestrial Reference System 1989 (ETRS89) datum and the Lambert Azimuthal Equal Area (LAEA) projection (EPSG: 3035). The selection of a 100 m pixel scale was considered optimal, allowing for the adjustment of the C-factor layer, which operates at a similar resolution, in response to policy interventions affecting land use, as highlighted in previous large-scale assessments [50]. In summary, the methodology's entire workflow is depicted in the accompanying figure (Figure 2).

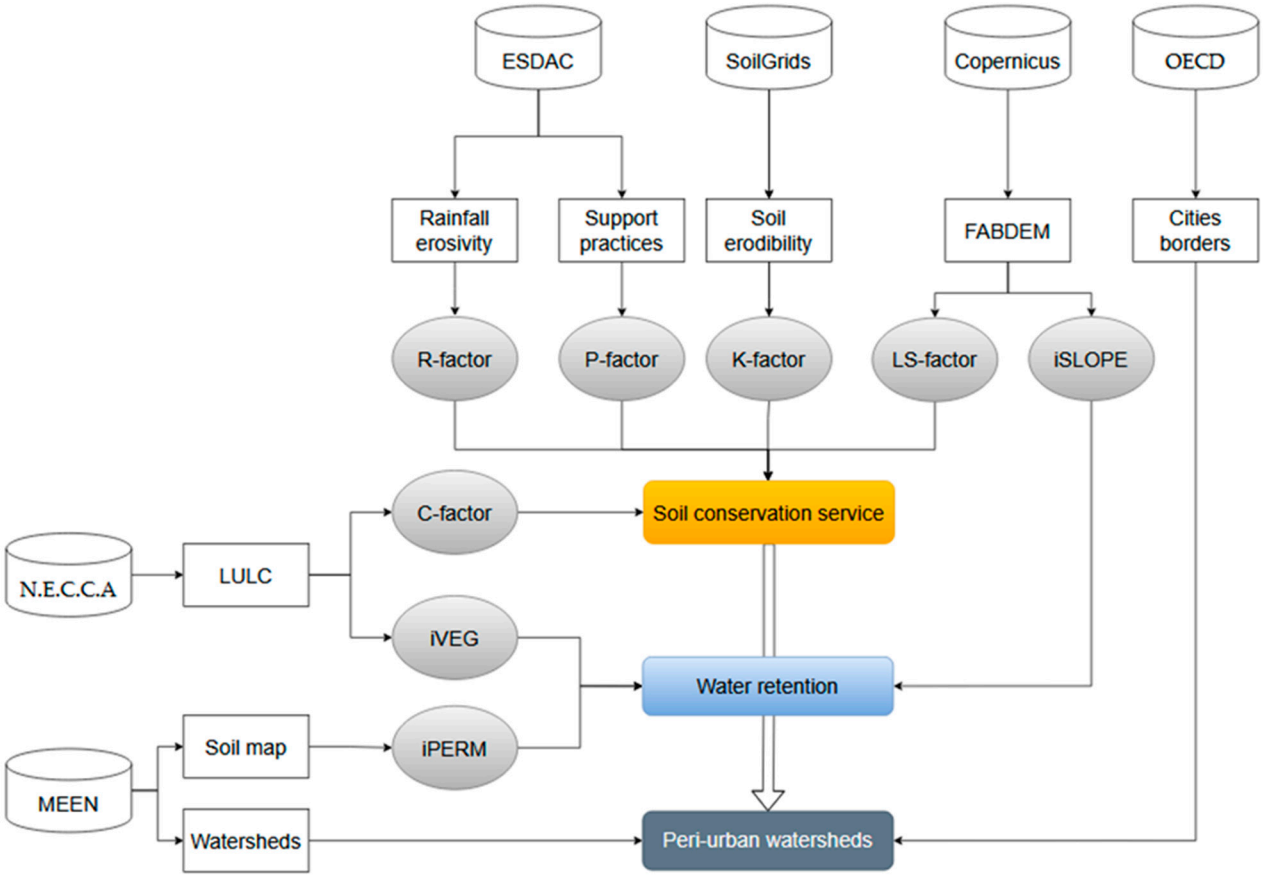


Figure 2. The overall workflow of the methodology.

3. Results

The results demonstrate the critical role of PUWs in providing ESs that contribute to sustainable development and human welfare. The average soil conservation supply in the PUWs located upstream of the examined cities in Greece was found to be 165.54 t ha^{-1} y^{-1} with a range from 44.41 t ha^{-1} y^{-1} in Dendropotamos watershed (Thessaloniki) to 441.33 t ha^{-1} y^{-1} in Nedonas watershed (Kalamata). Figure 3 depicts the average soil conservation service along with the standard deviation (SD) yielded by the PUWs for the studied cities.

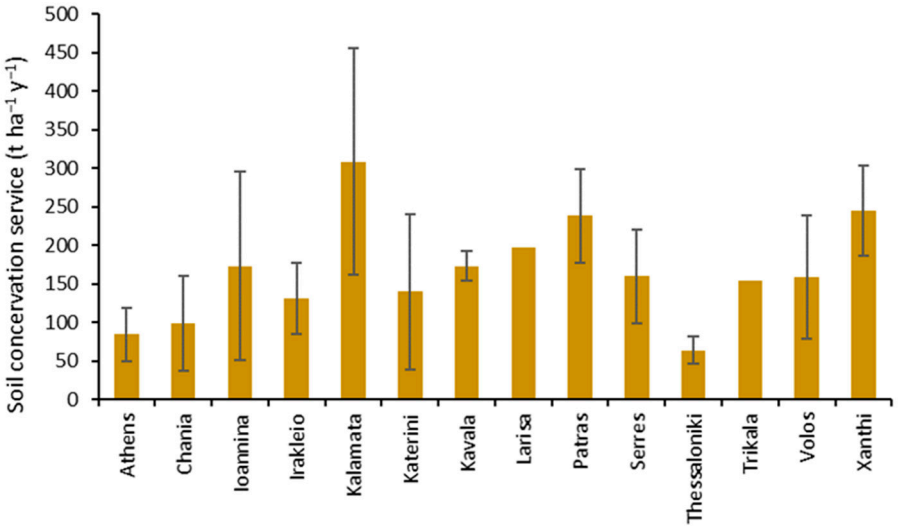


Figure 3. Average and SD values of soil conservation service provided by PUWs upstream of Greek cities.

The analysis identified the upstream PUWs of Kalamata (309.03 t ha^{-1} y^{-1}, SD: 146,37 t ha^{-1} y^{-1}), Ioannina (260.20 t ha^{-1} y^{-1}, SD: 122.42 t ha^{-1} y^{-1}), and Xanthi (245.84 t ha^{-1} y^{-1}, SD: 58.53 t ha^{-1} y^{-1}) as the top hotspots for soil conservation supply, while the PUWs upstream of Chania, Athens, and Thessaloniki were found to yield the lowest soil conservation services reaching 99.35 (62.00), 84.59 (SD: 34.75), and 64.19 (SD: 18.05) t ha^{-1} y^{-1}, respectively. The spatial distributions of the soil conservation service in selected PUWs are presented in the following figure (Figure 4).

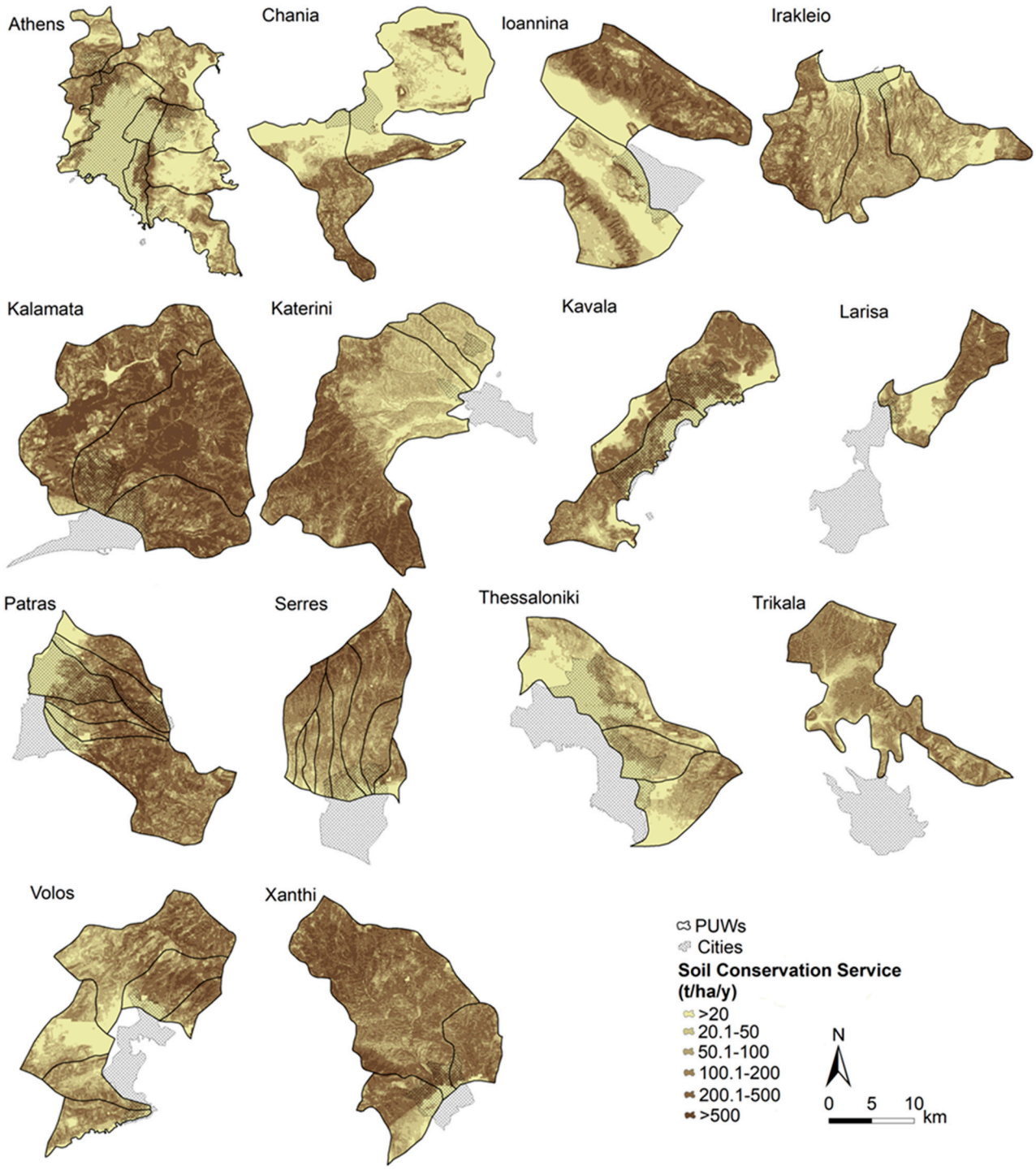


Figure 4. Spatial distribution of soil conservation service in the examined PUWs of Greece.

Moreover, the water retention service of the PUWs was assessed as an additional regulating ecosystem service within the PUWs, revealing a range from 35.09 mm in Vrilision watershed (Athens) to 155.48 mm in Xirila watershed (Kalamata), with an average of 91.45 mm. In detail, the average water retention supply along with the SD values of the PUWs upstream of the cities under study is illustrated in Figure 5, while their spatial distribution can be seen in Figure 6.

The PUWs demonstrated varying levels of water retention service across the examined cities. The higher amount of water retention service was provided by the PUWs over Kalamata (120.27 mm, SD: 40.35 mm), Trikala (112.3 mm), and Ioannina (103.23 mm, SD: 20.70 mm). On the contrary, the lowest values were found in the PWUs over Chania (82.1 mm, SD: 7.28 mm), Thessaloniki (76.41 mm, SD: 21.24 mm), and Irakleio (62.38 mm, SD: 11.93 mm). Figure 5 provides the spatial distribution of the water retention service within the selected PUWs.

Subsequently, an investigation was carried out to discern the diverse values of ecosystem services across distinct altitudinal zones and ecosystem types. The analysis of the altitudinal zones revealed a significant dominance of lowland areas (0–200 m) and hilly areas (201–500 m) within the PUWs, accounting for 34.3% and 32.4% of the total area, respectively. As the elevation increased, there was a gradual decrease in coverage. Semi-mountainous areas (501–1000 m) represented 21.8% of the total area, while mountainous areas (1001–1500 m) comprised 9.2%. In contrast, subalpine and alpine areas presented relatively small percentages (<2%) in the overall landscape. The average soil conservation and water retention capacity services in each altitudinal are presented in Figure 7.

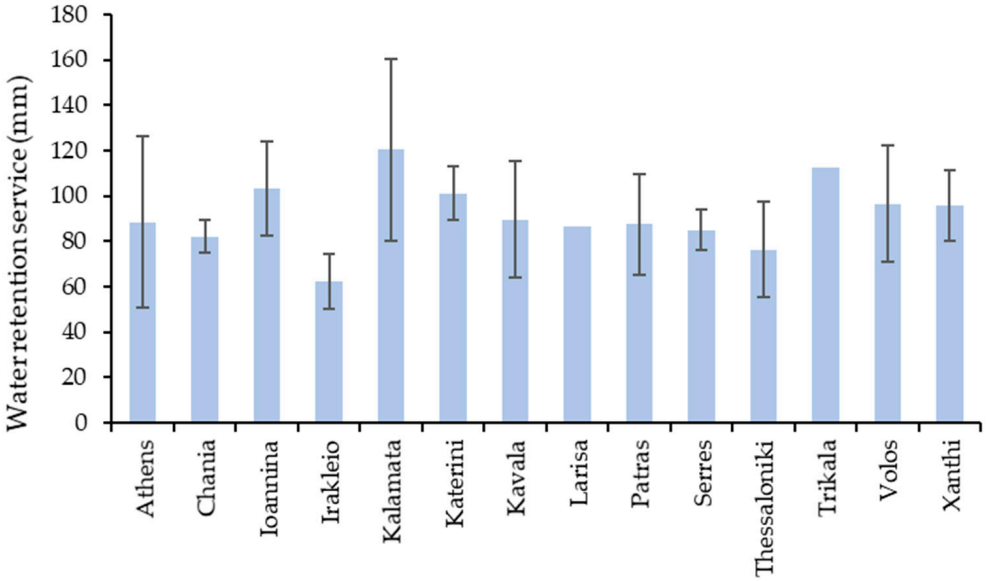


Figure 5. Average and SD values of the water retention service provided by PUWs upstream of Greek cities.

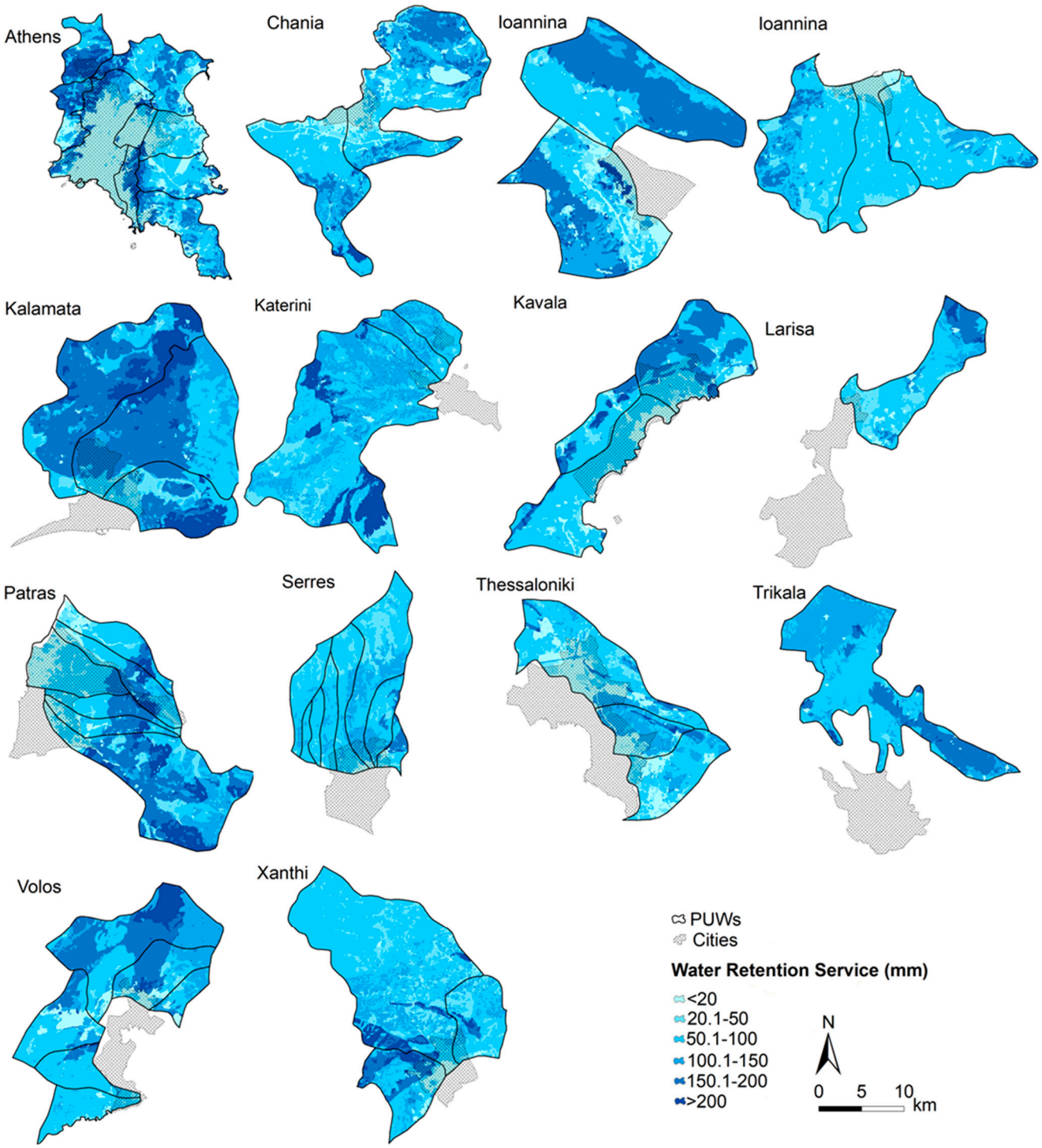


Figure 6. Spatial distribution of water retention service in the examined PUWs of Greece.

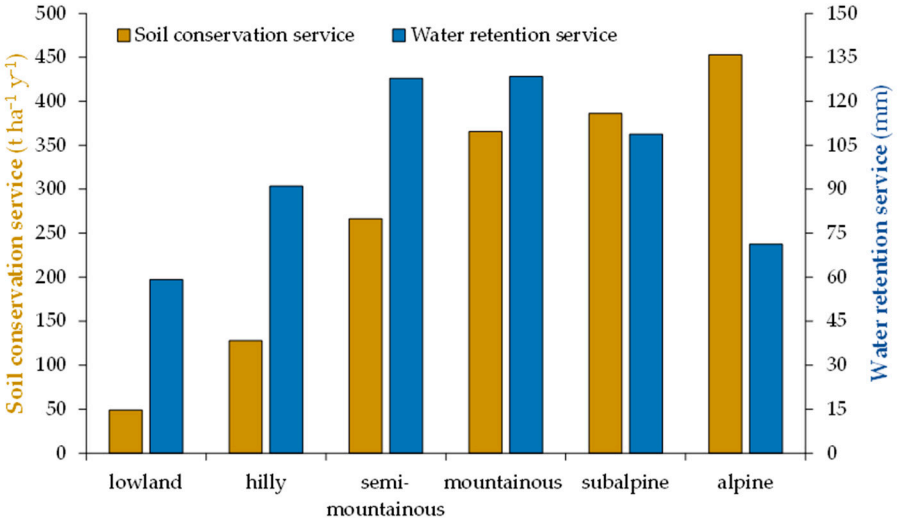


Figure 7. Average ES supply per altitudinal zone.

Based on the above graph, it is evident that the soil conservation service gradually increases as elevation increases. The alpine and subalpine areas exhibit the highest values, while the mountainous and semi-mountainous regions demonstrate higher values in contrast to the calculated mean soil conservation services across the entirety of the study region. Additionally, the provision of water retention services varies across different altitudinal zones. Specifically, the mountainous and semi-mountainous areas exhibit the highest values, followed by the subalpine and hilly regions. Conversely, lower values are observed in the lowland and alpine regions.

Afterwards, the variation in ecosystem service supply between different terrestrial ecosystem types were examined based on the classification scheme for the ecosystem type mapping and assessment (MAES) level 2 [51]. Croplands, heathland and shrubs, and woodland and forest occupy roughly equal percentages (about 30%) in the research area, while grasslands and sparsely vegetated areas occupy rather smaller percentages, 5.2% and 1.9%, respectively. Also, the percentage coverage of wetlands is negligible (0.11%). The graphical representation of the average soil conservation and water retention services within each MAES category is depicted in the figure below (Figure 8).

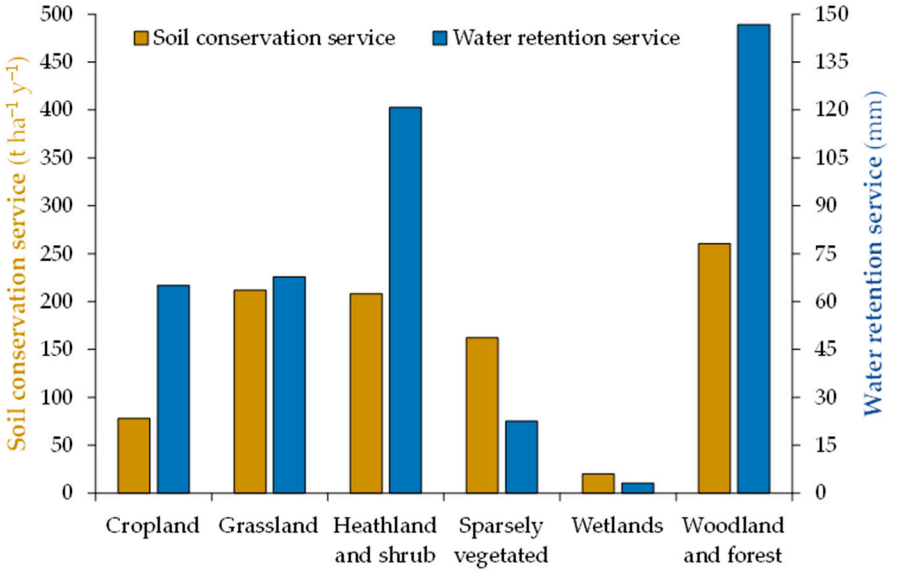


Figure 8. Average ES supply per MAES category.

The analysis of the provided data reveals distinct patterns in ecosystem services across various ecosystem types within the PUWs. Woodland and forest, along with heathland and shrubs, demonstrate higher values in terms of both soil conservation and water retention services. In contrast, croplands and wetlands exhibit lower values in these services. It is worth mentioning that grasslands and areas with sparse vegetation surpass the anticipated average soil conservation services of the study region.

4. Discussion

The ES concept was developed with the intention of integrating it into decisionmakers' agendas, employing various methods focused on environmental and natural resource management. However, its limited incorporation thus far can be attributed to the absence of institutional capacity and the credibility of the generated information [52]. Due to the ongoing increase in the availability of EO data, the established utilization of geospatial technologies, and the use of empirical models, conducting the large-scale assessments of ES has become feasible [33,53]. In pursuit of this objective, national-scale approaches have been employed to evaluate the provision of numerous ecosystem services for conservation planning [51,54].

In recent decades, demographic trends and urban development have intensified the pressures on ecosystems near city boundaries, thereby presenting challenges in estimating ESs for both urban and peri-urban landscapes. This direct linkage between ecosystem services and the advancement in implementing the United Nations Sustainable Development Goals (SDGs) underscores the significance of comprehending and managing these dynamic relationships [55,56]. Nevertheless, limited studies have been carried out on the scale of peri-urban watersheds. As a part of such an approach, An et al. [33] evaluated temporal changes in soil conservation services across four large basins worldwide, providing a valuable conceptual framework.

This research utilized the SCS-CN and RUSLE modeling approaches to estimate the ESs provided by the Greek PUWs. Both models have been widely applied, especially in ungauged watersheds. However, their uncertainties need to be acknowledged to contextualize the findings appropriately. For instance, both methods rely on parameters like land cover, topography, and soil properties, which are derived from Earth Observation (EO) data. However, EO data come with inherent limitations in spatial resolution and temporal coverage, which can impact the accuracy of soil conservation and water retention estimates. Moreover, these parameters might not capture site-specific conditions accurately. In particular, the largest uncertainties in the SCS-SN model, regarding maximum water capacity, arise from the lack of knowledge about the previous soil moisture conditions [57]. On the other hand, when it comes to erosion estimation, the uncertainties in the RUSLE model stem from the fact that critical processes, such as sediment transport, deposition, and routing within hydrographic networks, are not considered [58]. Nonetheless, comparing erosion rates and maximum water retention capacity between the current LULC and a scenario without vegetation effectively quantifies the supply of the related ESs.

Our analysis was performed in the upstream watersheds of the largest Greek cities. It delves into the pivotal role of PUWs in Greece as key contributors to essential ecosystem services, focusing on soil conservation and water retention capacity. These services play a critical role in fostering sustainable urban development and enhancing human well-being. The spatial distribution of soil conservation and water retention services highlights distinct hotspots and areas with lower contributions. The findings reveal the varying degrees of soil conservation and water retention services provided by different PUWs across Greek cities. Soil conservation services, crucial for preventing soil erosion and sedimentation, exhibit substantial spatial disparities. Noteworthy is the identification of Kalamata, Ioannina, and Xanthi as hotspots for robust soil conservation supply, offering potential models for effective soil preservation strategies. Conversely, regions like Athens, Thessaloniki, and Chania face challenges in soil conservation, underlining the complexities associated with urbanized landscapes. Water retention capacity, crucial for urban resilience against flooding and water

scarcity, also varies across PUWs. Kalamata, Trikala, and Ioannina emerge as leaders in this regard, indicating their potential to manage stormwater runoff and mitigate flood risks. On the other hand, areas like Chania, Thessaloniki, and Irakleio demonstrate lower water retention services, underscoring their vulnerability to water-related urban challenges.

Altitudinal analysis elucidates the relationship between elevation and ecosystem services, revealing how higher elevations tend to enhance soil conservation and water retention capacities. This emphasizes the importance of alpine and subalpine areas as valuable contributors to erosion control and flood management. The relationship between average soil conservation services and elevation has been evaluated in similar studies. It was found that these services increase with elevation up to 1000 m, but decrease for higher altitudes, despite the non-linear behavior observed in the latter case [33]. The investigation into different terrestrial ecosystem types reveals significant variations in service supply. Woodland and forest, along with heathland and shrubs, emerge as prominent contributors to both soil conservation and water retention. These findings align with established ecological principles, as vegetation cover and root systems in forests and shrublands play a pivotal role in stabilizing soils and regulating water flow [59]. In contrast, croplands and wetlands display relatively lower levels of these ecosystem services, necessitating context-specific management interventions to enhance their contributions. The study accentuates the need for integrating green infrastructure and sustainable land management practices into urban planning to optimize ecosystem services.

The insights gained from this study have far-reaching implications for urban planning and policy development. By recognizing and leveraging the varying capacities of different PUWs, cities can formulate site-based strategies in an effort to improve ES supply. Despite the importance of the soil conservation and water retention ESs, they are closely linked to other regulating services, such as carbon sequestration and climate regulation. By preventing soil erosion, these services help maintain soil fertility and structure, which in turn supports plant growth and carbon storage. This interconnection highlights the role of PUWs in mitigating climate change and enhancing ecosystem resilience. Moreover, the preservation of soil and water resources contributes to provisioning services by sustaining agricultural productivity and ensuring a stable water supply. Healthy soils and efficient water retention are essential for crop growth, which directly supports food security and local economies. These services also reduce the need for artificial fertilizers and irrigation, leading to more sustainable agricultural practices.

Incorporating these findings into urban development plans can lead to more sustainable land use, improved disaster risk reduction, and enhanced urban livability. While this study provides a comprehensive analysis of soil conservation and water retention capacity in Greek PUWs, there are avenues for further research. Studying the economic value of these ESs can offer a deeper insight into their tangible benefits for society. Moreover, exploring the potential synergies and trade-offs among different ESs within PUWs could provide valuable guidance for making more holistic land-use decisions.

5. Conclusions

In conclusion, this study underscores the critical importance of PUWs as essential suppliers of ESs that contribute to sustainable urban development and human well-being. The analysis of soil conservation and water retention capacity across diverse landscapes and urban contexts offers valuable insights into the potential of these natural systems to enhance urban resilience.

By recognizing the spatial disparities in ES supply, cities can strategically allocate resources and prioritize conservation efforts. The identification of hotspots and areas with lower contributions provides a roadmap for targeted interventions that can maximize the benefits of ecosystem services for both current and future generations.

The integration of ecosystem service considerations into urban planning and policy can pave the way for more resilient and livable cities. Embracing the principles of sustainable land management, green infrastructure, and nature-based solutions can facilitate a

harmonious coexistence between urbanization and ecological functioning. As cities continue to grapple with the challenges of rapid urbanization, the findings of this study offer valuable guidance for decisionmakers, planners, and researchers seeking to create urban environments that are both sustainable and supportive of human well-being. By harnessing the potential of peri-urban watersheds and their ecosystem services, we can build cities that thrive in the face of environmental uncertainties while fostering a healthier and more vibrant urban future. Hence, there is a necessity for a unified directive that addresses the management of watersheds and the services they offer, particularly in areas adjacent to urban and peri-urban zones.

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Appendix A

Table A1. Upstream watersheds for the fourteen cities under study.

Id	City	Population	Watershed Name	Watershed Area (km^2)
1	Athens	3,608,000	Asopou	150.56
2			Filis	113.08
3			Group of Gullies East Hymettus	197.35
4			Group of Gullies West Hymettus	82.31
5			Kifissou	406.51
6			Lauriou	251.69
7			Martathonos	293.63
8			Rafinas	161.74
9			Prelesion	71.56
10	Chania	62,040	Chanion	91.90
11			Soudas	156.44
12	Ioannina	64,500	Kranoulas	67.90
13			Marmaron	58.08
14	Irakleio	138,600	Gazanou	294.79
15			Giofiriou	175.12
16			Karterou	230.66
17	Kalamata	52,500	Eleochoriou	54.53
18			Nedona	132.18
19			Xirila	114.54
20	Katerini	57,200	Gerakari	55.48
21			Mavroneriou	613.29
22			Tsiamanti	45.75
23	Kavala	46,800	Chalkerou	56.47
24			Group of torrents between Iraklitsa-Kavala	54.19
25			Kokkinoxomatos	22.32

Table A1. *Cont.*

Id	City	Population	Watershed Name	Watershed Area (km^2)
26	Larisa	144,000	Sikouriou	99.90
27	Patras	156,000	Charadrou	20.54
28			Elekistrtas	12.90
29			Finikos	127.84
30			Glafkou	76.75
31			Milichou	25.83
32			Romanou	12.80
33			Selemnou	17.75
34	Serres	57,000	Agion Anargiron	80.63
35			Anatolikou Christou	6.38
36			Anatolikou Lefkonos	21.21
37			Ditikou Christou	27.45
38			Ditikou Lefkonos	10.90
39			Eleonos	26.76
40			Eptamilon	11.79
41			Kamenikion	38.23
42	Thessaloniki	1,062,000	Dendropotamou	99.66
43			Pilaias	34.64
44			Thermis	51.52
45	Trikala	51,000	Lithaiou	211.28
46	Volos	77,000	Aligaroremato s	20.07
47			Anavrou	10.40
48			Arkoudoremato s	19.77
49			Krausidona	30.52
50			Seskouliti	32.97
51			Xiria	73.95
52	Xanthi	60,000	Kimerion	48.62
53			Kosinthou	240.63
54			Laspopotamou	53.09

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