

Groundwater and Population Dynamics: Examining the Relationship Between Aquifer Resources and Population Distribution in Kosovo

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Abstract

This paper examines the distribution of the population and settlements in relation to the aquifers in Kosovo. Due to the ease of groundwater extraction, the population is highly concentrated above aquifers with intergranular porosity and medium to high permeability, which are mainly located in the plains of the country: Dukagjini, Kosovo, Anamorava, Llapi and Drenica. Using the GIS/RS technique and statistical analysis, the relationship between the aquifers and population distribution was analysed and presented in the article. The analysis of settlement and population data, along with the distribution of aquifers, indicates that a large proportion of the population lives in areas overlying aquifers with intergranular porosity and low to very high permeability (sand, gravel, clay). These aquifers are home to 828 settlements (56.4% of all settlements) and a population of 1.34 million inhabitants, which corresponds to an increase from 66.8% (1948) to 85% (2024) of the country's population. The physical expansion of built-up areas, which cover 516 km², can lead to depletion (lowering of the water table) and overuse of groundwater resources, especially in dry periods. In addition, the expansion of agricultural activities on arable land adjacent to these aquifers, combined with the uncontrolled use of chemical fertilisers, has led to groundwater contamination.

Key words:
population density,
land cover changes,
built-up areas,
population migration

1 INTRODUCTION

Population distribution across the globe is very uneven and is determined by different natural and environmental conditions (Doignon et al., 2023). Geographical research has long sought to understand these patterns and the influence of physical factors. Access to water is an important determinant of population concentration, which often promotes the development of large urban centres (Tian et al., 2020). Consequently, regional differences in population density are evident and serve as indicators of settlement concentration.

Several interrelated factors influence population distribution, including climate, topography, soil quality, water availability, energy and mineral resources, proximity to coasts or rivers, cultural influences, political boundaries, government policies, economic activities (especially agriculture), transportation infrastructure, and social structures. Harsh climates and a lack of basic living conditions often lead to depopulation. No single factor can fully explain population distribution, but it is the result of complex interactions between different influences.

In the past, water resources have played a central role in settlement. Rivers, lakes and other surface waters have shaped settlement patterns and development. Today, groundwater, which accounts for 99% of the earth's freshwater (excluding ice and

snow), has become vital to human life (Glennon, 2002; Lerner & Harris, 2009). Studies show that population density tends to increase near freshwater sources, especially rivers (Kummu et al., 2011), while the relationship between people and water has evolved with changing physical, socio-economic and cultural conditions (Biswas, 1970). Urbanisation has further altered land surfaces, reducing rainfall infiltration and groundwater recharge and increasing pollution risks (Lerner & Harris, 2009).

Groundwater is stored in aquifers that have been shaped by geological, topographical and climatic factors, so that it is unevenly distributed. Nevertheless, it remains accessible and covers 50% of the world's population, 40% of irrigation and a third of industrial water demand (Ajami, 2021). Around 2.5 billion people depend on groundwater every day, making it a critical resource for social, economic and environmental sustainability (The United Nations World Water Development Report 2022). Kosovo lies within the aquifer system of the mountains of Central and Eastern Europe (IGRAC, 2022; Péntzes et al., 2023; Masný et al., 2023), with mainly isolated and some transboundary aquifers shared with neighbouring countries (Skoulikaris et al., 2021). These aquifers play a key role in the regional water cycle and socio-ecological dynamics (Huggins et al., 2025).

In Kosovo, population studies have examined demography (Islami, 2013; 2021), spatial distribution, ethnic composition, settlement typologies (Pushka, 2000; Ramadani, 2016) and altitudinal conditions. However, a comprehensive study integrating these aspects to investigate the relationship between population patterns and settlements at the national level is yet to be conducted. A holistic approach that considers demography, spatial organisation, environmental conditions and socio-economic factors is needed to support sustainable development.

Groundwater has had a decisive influence on the distribution of the population and the development of settlements in Kosovo. In the past, rural communities relied on individual sources such as wells. Settlements often developed near groundwater or surface water sources and were later extended by water infrastructure such as reservoirs (e.g. in Prishtina). Natural factors have influenced the connection between settlements and aquifers, although groundwater alone does not determine the population structure. Census data since 1948 show a strong link between water-rich aquifers and higher population density - a link that is likely to become stronger.

There are a number of aquifers in Kosovo. Those with greater storage capacity and faster recharge rates tend to offer higher population densities and more dynamic settlement patterns. However, these areas are also fraught with risks: aquifers with intergranular porosity are prone to contamination and settlements in river valleys are at risk of flooding (Di Baldassarre et al., 2013; Agaj et al., 2024).

Population growth and spatial distribution have led to changes in land cover and reshaped landscapes, especially in south-eastern Europe, faster than previously assumed (Feranec et al., 2016; Winkler et al., 2021). Urbanisation and the expansion of artificial surfaces have changed groundwater recharge patterns and increased water demand (Lerner & Harris, 2009). Studies in the Pakistani city of Mardan, for example, show how rapid population growth correlates with declining groundwater levels (Yar, 2020). Globally, groundwater overexploitation is a growing problem caused by land use change, climate change and population pressure (Ojeda Olivares et al., 2019; Gleeson et al., 2012).

In Kosovo, studies on land cover show different landscape changes. Studies in the Kosovo Plain, in hilly-mountainous regions and in watersheds at different altitudes (Bytyqi, Agaj & Ramadani, 2024; Bytyqi & Agaj, 2024b) show that agricultural areas are shrinking and settlements are increasing — especially in the plains where important aquifers are located.

This study examines the relationship between population dynamics and aquifers in Kosovo. Due to the different topography and hydrogeological conditions, the population in Kosovo has grown mainly in flat areas with aquifers of high to medium permeability. The analysis of CORINE Land Cover data shows that the pressure on groundwater is increasing due to the expansion of artificial areas and settlements.

2 MATERIAL AND METHODS

Aquifer types in Kosovo

Groundwater represents an important part of the country's water resources (Pllana, 2013). Groundwater is not a hidden element of the hydrosphere and not an invisible component of the terrestrial segment of the overall global cycle, but an essential and dynamic part of the lithosphere. The hydrogeological conditions for the presence and movement of groundwater are

characterised by two main aspects: the composition of the subsurface in terms of rock properties (especially porosity, fissuring, permeability, solubility) and the regional structures: thickness, lateral extent, depth of aquifers and other hydrogeological units. (Margat & Gun, 2013). The territory of Kosovo is characterised by a complex geological environment (Pruthi, 2013), where rocks of different types have been formed in terms of hydrogeological characteristics and where six types of aquifers are present, which are determined by the type of rocks as a determining factor of underground water circulation in the terrain (ICMM, 2006). The territory of Kosovo is characterised by a complex geological structure (Fig. 1b), in which rocks of different types have been formed in relation to hydrogeological features and in which 6 types of aquifers are present, which are determined by the type of rocks as a determining factor for underground water circulation in the terrain (Fig. 2).

The geological-tectonic features and landforms have resulted in Kosovo having adverse hydrogeological conditions, with magmatic and metamorphic rocks without considerable intergranular or fissured porosity ($K_f < 10^{-9}$) present in areas such as: Sharr, Blinajë-Golesh, Zhegoc, Bjeshkët e Nemuna (Accursed Mountains), between Gjilan-Novobërdë, Eastern Mountains, Drenica, Çiçavica, Kopaonik-Rogozna, etc., which cover 47.2% of the area of Kosovo (Tab.1, Nr. 6 and Fig. 1a).

Fissured aquifers with medium to low fracture permeability are widespread (Tab.1, No. 4). Various igneous, metamorphic and sedimentary rocks, such as diabase, serpentinite, andesitic tuffs (Kopaonik and Rogozne), conglomerates, sandstones (Kamenica), marls, bentonites, trachytes, leucites (around Vitia), serpentinites (east of Drenica), marbles, quartzites around Gadima, etc, granites (Bjeshkët e Nemuna) represent aquifers with medium to low permeability ($K_f = 10^{-5} - 10^{-9}$), in which fissure type porosity dominates and which cover 6.7% of the total area of the country (ICMM, 2006).

In the western part of the country, large areas of limestone are found, distinguished by very high fracture permeability ($K_f = 10^{-5} - 10^{-9}$), mostly as large bodies of rocks compared to the eastern part (Tab. 1, No. 3), comprising 9.4% of the country's total area. The largest springs in Kosovo are located in these formations (Drini i Bardhë, Istogu, Vrella, Korisha, Poslishta, etc.).

Loose sediments consisting of sand and gravel of Quaternary or older (Tertiary) age form the most widespread and most exploited groundwater systems on Earth. Sand and gravel have a high porosity and permeability, are often interrupted by thin intermediate layers (intercalations), which are mixed with fine-textured sediments (clay and siltstone) and in some cases contain larger blocks of rock. Due to the geological-tectonic conditions, the general landforms of today's relief were formed in Kosovo, which later changed under the influence of external forces and reached their current state. The sediments of the Neogene-age lakes serve as an aquifer with low to medium permeability.

In Kosovo, the loose sediments are divided into two main groups with specific hydrogeological conditions, depending on their porosity and permeability:

- Intergranular porosity aquifers with very high to medium permeability ($K_f > 10^{-5}$) (e.g. sand, sand + gravel, sand + gravel + mud/silt) (Tab. 1, No. 1) are mainly represented by river alluvium (sand, gravel, clay), especially along the Drini i Bardhë River and its tributaries flowing through the Dukagjini Plain,

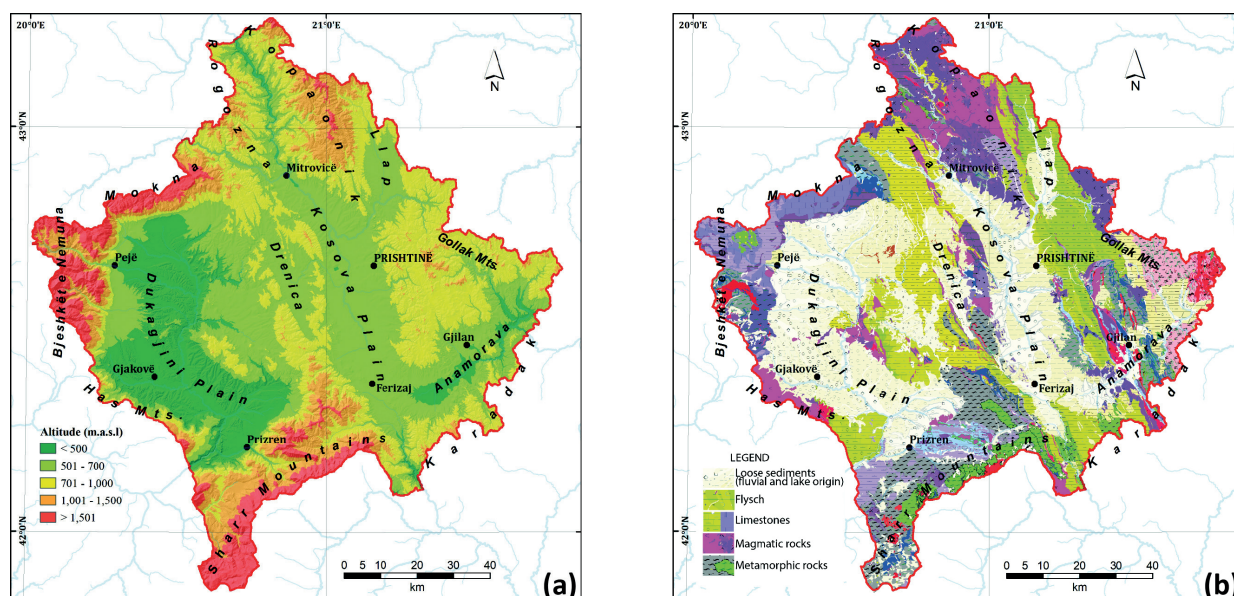


Fig. 1. Relief map of Kosovo (a), Geological map of Kosovo (b)
Source: (a) opendem.info, (b) Geological map of Kosova – ICM

Tab. 1. Types of aquifers in Kosovo.

No.*	Aquifer description	Area (km ²)	%	Number of settlements	% of settlements
1	Intergranular porosity aquifer with very high - medium permeability (e.g. sand, sand + gravel, sand + gravel + mud/silt)	2,161.5	19.8%	532	36.2%
2	Intergranular porosity aquifer with medium - low permeability (e.g. clay + sand + mud/silt)	1,843.9	16.9%	296	20.2%
3	Fissured and karstified porosity aquifer with strongly alternating, local, very high fracture permeability (e.g. limestone, marble)	1,022.1	9.4%	36	2.5%
4	Fissured porosity aquifer with medium - low fracture permeability (e.g. limestone, limestone/marlstone, marble, metamorphic rock, sandstone + conglomerate = limestone/marlstone, plutonic rock)	725.3	6.7%	74	5.0%
5	Double porosity aquifer with medium - low permeability (e.g. limestone)	1.2	0.0%	1	0.1%
6	Aquiclude without considerable intergranular or fissured porosity	5,151.2	47.2%	530	36.1%
		10,905.25	100.0%	1,469	100.0%

then along the Sitnica River (Kosova Plain), Morava e Binçës (Anamorava Plain) and smaller areas along the Llap and Drenica Rivers, covering a total of about 2,161 km² or about 19.8% of the country's area.

- Aquifers with intergranular porosity and medium to low permeability ($K_f=10^{-5}$ - 10^{-9}), e.g. clay, sand and mud/silt (Table 1, No. 2) are associated with lacustrine sediments and depositional processes on the slopes of the surrounding mountains. Geologically, these formations are of Pliocene age and contain coal layers. They cover an area of 1,844 km² or about 16.9% of the total area of the country.

Materials

Population and settlement data were obtained from the official website of the Kosovo Agency of Statistics (<https://askdata.rks-gov.net/pxweb/sq/ASKdata/>), which provides information from the official censuses of recent years. The distribution of groundwater resources in Kosovo has been described in detail in previous studies, which also include cartographic material such as the Hydrogeological Map of Kosovo (1:300,000 and 1:200,000).

Methods

Using Geographic Information System techniques and ArcMap 10.8 software (esri.com), correlations between population density and aquifers were analysed, which enabled the identification of relationships between these factors through geovisualization. Data from the Kosovo Geoportal (<http://geoportal.rks-gov.net/>) were used to access official information from the Kosovo Cadastral Agency, including orthophotos from different years (2001, 2004, 2009, 2012, 2015 and 2018). These images enable the study of temporal and spatial changes in settlement patterns. In addition, topographic maps published by the authority were used to compare the extent of settlements over time within the aquifer areas. GIS techniques were also used to analyse the impact of the increase in artificial surfaces (built-up areas) on the aquifers and to study their distribution and associated consequences. In order to analyse the distribution of population in relation to aquifers in Kosovo, different statistical methods were applied, using data from the institutions responsible for data collection, processing and presentation. Regression analysis was applied to quantify the relationship between population growth, land cover changes and aquifer distribution.

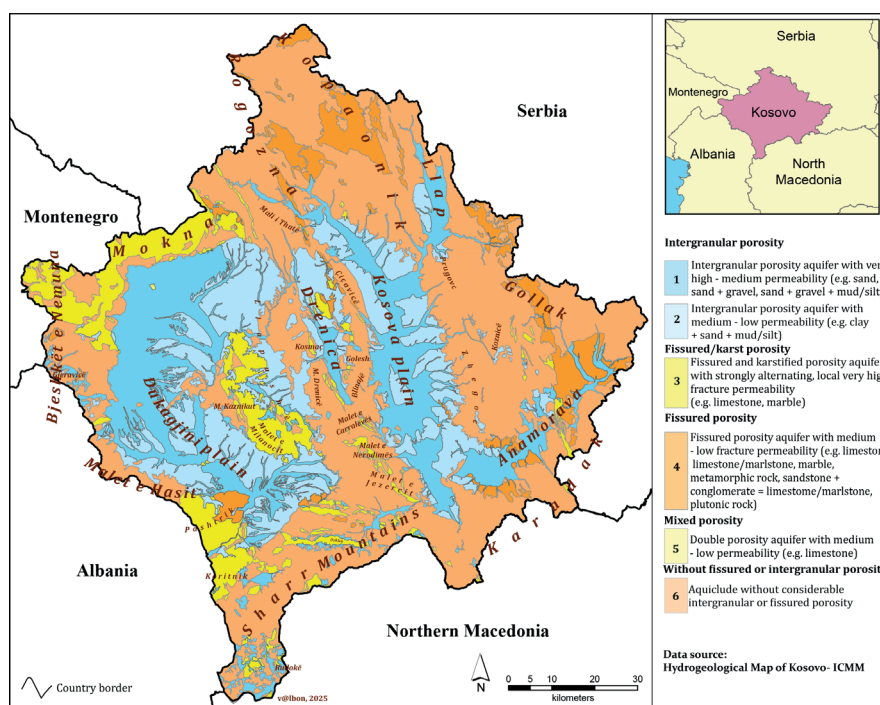


Fig. 2. Types of aquifers in Kosovo
Source: ICM - Hydrogeological Map of Kosova

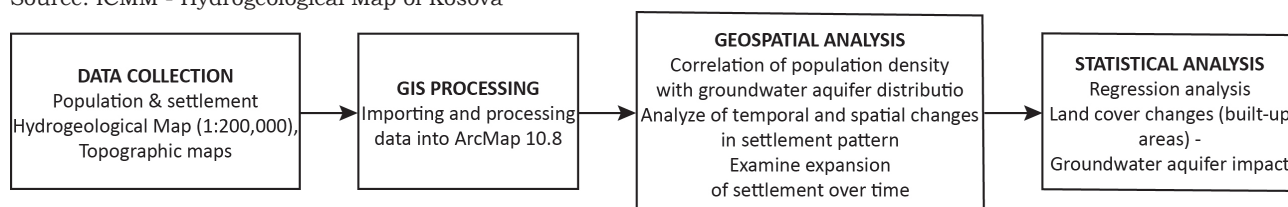


Fig. 3. Flow chart methodology

3 RESULTS

Distribution of population and settlements in Kosovo in relation to aquifers

Groundwater flows beneath the earth's surface and is very easy to extract. Easy access to groundwater has influenced the emergence of settlements and the development of life activities. The existence of water in aquifers has led to the continued existence of settlements and even an increase in population and other economic activities. Next, the number of settlements and the population ratio were analysed with the type of aquifers. Although there are a large number of settlements in Kosovo in the plains and foothills, the number of population and the density are analysed as a single point that represents the centre of the settlement. Through the official censuses in Kosovo, the number of settlements has increased, to 1,469 in 2024, based on the official censuses in Kosovo that were conducted after the Second World War until the last one (2011). Although aquifers were not the only pull factor for migration, access to drinking water and a secure supply were one of the reasons. The rise in living standards, especially in the years after the last war (1999), once again showed the changes that were taking place in the social and economic spheres, with water and its use being an indicator of living standards.

Of the 1,469 settlements in Kosovo, 56.4% of them are situated above aquifers with intergranular porosity, that are lithologically composed of loose sediments of recent geological age, with low to high permeability (depending on the composition of clay, sand, gravel) and high storage of groundwater,

which are located in Dukagjini, Kosova, Anamorava, Drenica and the Llap plain, as well as in the valleys of mountain rivers, where the deposition of loose sediments (alluvium) can be found in part (Lepenci, Ibri, Klina and small river tributaries coming from the hilly-mountainous terrain) or slope deposits (deluvium) and glacial sediments (moraine).

The number of settlements is related to the type of aquifer, while the number of population shows a stronger correlation with rich aquifers, especially those with intergranular porosity, which are found in the plains of the country. From the analysis of the number of settlements located on specific aquifers, it can be seen that about 2/3 of the settlements are located on aquifers with intergranular porosity with medium to high permeability (36.2%) and on terrains without significant intergranular porosity (36.1%).

Aquifers with intergranular porosity with medium to high permeability, consisting mainly of sand and gravel (type 1), are located beneath 532 settlements in Kosovo, where about 917,000 inhabitants live, which corresponds to 58.0% of the country's population. With a population density of around 424 people per km², this aquifer is three times more densely populated than the national average of 145 people per km² (2024). The high population concentration also has an impact on water quality, as wastewater discharges, industrial pollution and municipal waste pose a major threat to groundwater. This aquifer is home to 8 urban centres with more than 10,000 inhabitants, including Prishtina, Peja, Ferizaj, Gjakova, Vushtrria, Podujeva, Fushë-Kosova and Lipjan, as well as 14 larger settlements with 5,000 to 10,000 inhabitants, such as Suharekë, Skënderaj,

Kaçanik, Obiliq, Bresje, Shtime, Gllogoc, Zhabar i Poshtëm, Viti, Klinë, Istog, Kamenicë, Vitomiricë and Uglar. In the early phases of settlement development, groundwater served as the primary source of water, which contributed to positive demographic growth in these areas (Fig. 4).

In addition, 296 settlements (20.2%) are situated above aquifers characterised by intergranular porosity and low to medium permeability (type 2). These areas consist mainly of Neogene sediments such as sand, clay and silt and represent the lower layers of former lake beds. Due to the geological activity of the rivers, these areas are the higher parts of the plains, with low ridges separating the watercourses. The population density in these areas is relatively high due to agricultural activity. These settlements are generally located on both sides of the Dukagjin and the Kosovo Plain, as well as in the northern part of the Drenica. While 20.1% of the settlements are located in the area of these aquifers, the 2024 census showed that 27% of the population lived here, i.e. about 428,000 inhabitants, with an average population density of 232 persons per km². Several large urban centres, including Prizren, Gjiilan, Matičan, Rahovec, districts of Mitrovica, as well as other significant settlements such as Dushanovë, Hajvali, Mamushë, Lubizhdë, Damjan, Gjonaj, Komogllavë, Mazgit, Kçiq i Madh, Llashkadrenoc, Korishë, are located there. In total, there are 4 centres with more than 10,000 inhabitants and 23 settlements with a population between 2,000 and 10,000.

There are 530 settlements overlying aquifers without significant intergranular or fissured porosity (type 6, Tab. 2). These aquifers are located in the hilly and mountainous regions of Kosovo and cover almost half of the country, but their population is about 6.9 times smaller than in areas with intergranular porosity. According to the 2024 census, about 196,000 inhabitants lived in these regions, with an average population density of about 38 people per km², which is about 3.8 times lower than the national average. These settlements are mainly located in the peripheral and central mountains of Kosovo, including the Sharr Mountains, Bjeshkët e Nemuna, Mokna, Kopaonik, Rogozna and Karadak, which are rich in surface water due to their altitude and mountain climate. However, other natural factors, such as the relief and remoteness from urban and municipal centres, have led to a lower population density in these areas. Some of these regions are even experiencing population decline. According to the 2011 census, 35 settlements have become depopulated, while in 2024 the number increased to 153. About 117 settlements in these aquifers are small, with less than 50 inhabitants, and another 46 have a population between 51 and 100 inhabitants. Despite the prevalence of smaller settlements, these aquifers are also home to larger settlements, such as parts of Mitrovica and other significant settlements, such as Pleshinë, Kolovicë, Tërstenik, Llapushnik, Bllacë, Bresalc, Petrovë, Seçishtë, which are located near water sources.

Aquifers with fissure porosity or karst terrains (type 3) are mainly found in limestone and marble rocks. These aquifers have distinct hydrogeological characteristics, including varying groundwater levels and limited surface hydrography. The dissolution of carbonate rocks has led to the formation of karst springs, which are powerful sources of water. Karst rocks in Kosovo are mainly found in regions such as the Pashtrik, Milanoc (Shkoza), Sharr, Mokna and Bjeshkët e Nemuna mountains, while the eastern

part of Kosovo has a more limited distribution and consists of small, lenticular formations. In these areas, there is often a discrepancy between the topographical and hydrogeological watersheds with underground horizons, from small to large, where water can be stored. Karst springs are characteristic of these areas and have played an important role in the development and growth of settlements. Many settlements in Kosovo are located near these springs, which eventually spread into the plains or river valleys (alluvium aquifers) as settlements expanded. Even though these settlements grew into the plains, the water sources remained crucial to their existence. A total of 36 settlements, or 2.5% of all settlements in Kosovo, are located in karst areas where springs were historically the main source of water supply. Of these, 5 settlements have more than 1,000 inhabitants, the largest of which are Zhur, Lubizhdë e Hasit, Samadrexhë, Gllarevë and Carravranë. Around 22,000 inhabitants live in these areas (2024) (Fig. 4).

Aquifers with fissured porosity (type 4), characterised by medium to low fracture permeability (such as limestone, limestone/marl, marble, metamorphic rock, volcanic rock, pyroclastic material and sandstone + conglomerate), host 74 settlements or 5 % of all settlements in Kosovo. These aquifers have very specific hydrogeological conditions and show karst features. Several large settlements are located in these regions, such as Kabash, Beguncë, Krajk, Tërpezë, Lubishtë, all of which have more than 1,000 inhabitants. Some of these settlements are located in the eastern part of Kosovo and extend in a meridional direction from Podujevë to Ranillug. Other settlements are located on the western side of Çiçavica as well as in Rogozna, Kopaonik and in the northern and southern parts of Vitia. Of the 74 settlements, 29 have a population of between 100 and 1,000 inhabitants, while 39 are small settlements with fewer than 100 inhabitants. Some settlements are connected to aquifers consisting of conglomerates or igneous and metamorphic rocks. However, these aquifers have different physical water properties than typical karst aquifers. According to the 2024 census, around 18,000 inhabitants live in these areas.

The Banja aquifer, located in the municipality of Istog and known as Banja e Pejës, is unique due to the nature of its function. It is formed on carbonate tufts and travertine (type 5) originating from the Banja thermal spring. Due to the healing and hospitality activities associated with the spring, the settlement has grown 8.6 times in a period of 60 years, according to Kosovo censuses (Tab. 2).

Typology of settlements according to aquifer type

The typology of settlements is based on an interdisciplinary approach that takes into account factors such as the activities taking place in the settlement, its origins, functions, structure and population size. Population size reflects the number and type of activities within a settlement, which in turn affects the pressure exerted on the aquifers. Population size determines the amount of water required per inhabitant, while the number of activities indicates the potential for the management and sustainable use of water resources.

The simplest classification of settlements is into villages and towns. Historically, villages served as a source of water for individual households and relied mainly on wells. In contrast, the foundation, existence and development of towns are based on a reliable water supply for the population. Although Kosovo's early cities were located near water sources,

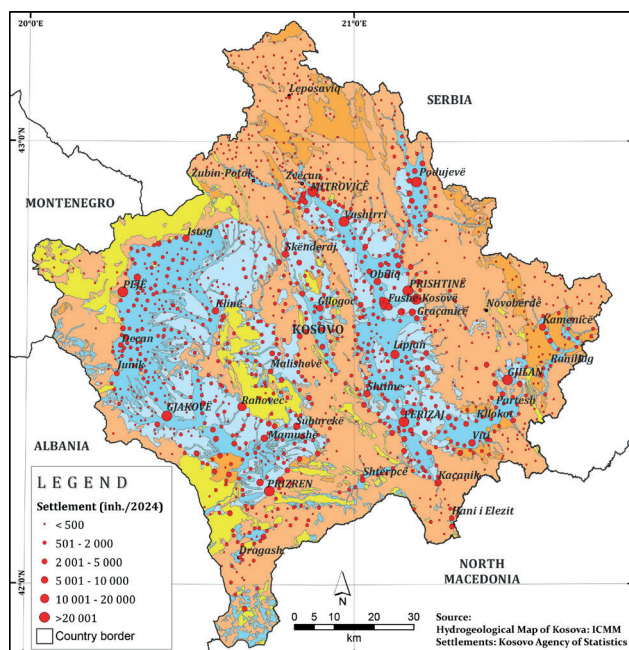


Fig. 4. Distribution of settlements on certain aquifers in Kosovo

their transformation into modern urban centres with communal housing was only possible after securing sufficient water resources. However, following the rapid growth of cities after the war (1999), especially the demographic expansion of cities (Islami, 2021), water capacity and infrastructure were not adequately planned to accommodate this growth. As a result, many cities experienced periodic water shortages, a problem that continues to this day (Bytyqi & Agaj, 2024a).

One approach to classifying settlements is by demographic size (Ramadani, 2016). Rural settlements are categorised as small (<500 inhabitants), medium (500-2,000 inhabitants), and large (>2,000 inhabitants) (Pushka, 2000). According to the 2024 census, there are 836 small settlements in Kosovo, 51% of which are located on aquiclude without significant intergranular or fissured porosity (type 6), predominantly in the hilly and mountainous areas. In recent years, many of these settlements have experienced population out-migration, and some have even been depopulated. This underlines the strong correlation between the size of settlements and aquifers in hilly mountainous regions.

Settlements with an average population size (500-2,000 inhabitants) are mostly located in areas with intergranular aquifers with medium to high permeability (type 1), which contain abundant groundwater. These settlements account for 49.8% of the total number. Together with settlements

in areas with intergranular porosity and low to medium permeability (type 2), they account for 75.8% of settlements of average size in Kosovo. Larger settlements (both urban and rural) with more than 2,000 inhabitants are usually located in areas with intergranular porosity and medium to high permeability, where groundwater reserves are larger. In this category, 89.4% of settlements are located along alluvial and other loose sediments in the plains of Kosovo. The dominance of medium and large settlements overlying aquifers with medium to high permeability illustrates the significant relationship between population size and access to groundwater resources. However, population distribution in the plains of Kosovo is not solely determined by hydrogeological factors; it is also influenced by the presence of fertile alluvial soils, historical coal mining activity, well-developed transportation and energy infrastructure, as well as broader socio-economic and geographical conditions that collectively enhance the region's habitability and economic potential. These factors have also made the plains an attractive destination for internal migrants relocating from the more remote and less developed hilly and mountainous areas (Fig. 5).

Of the 13 urban centres in Kosovo that qualify as cities (Islami, 2018): Prishtina, Prizren, Gjiilan, Peja, Mitrovica, Ferizaj, Gjakova, Vushtrria, Podujeva, Rahovec, Fushë-Kosova, Suhareka and Kaçanik - all lie on aquifers with intergranular porosity that allow for greater groundwater accumulation. Although these urban centres are currently supplied with both groundwater and surface water, e.g. through artificial lakes and groundwater drawn from several kilometres away, the emergence and growth of these settlements are inextricably linked to the presence of groundwater.

The density of settlements in relation to aquifers also illustrates the relationship between human settlement and aquifers and the impact of human activities - agriculture, industry and private use - on water quality. Natural factors such as topography, geology, rivers and climate significantly influence the distribution of the population in Kosovo. As water is essential for survival, settlements have historically been established near water sources, which reinforces the strong correlation between settlement density and aquifer type.

In areas underlain by aquifers with intergranular porosity and medium to high permeability, where groundwater storage is greater, and the water table is closer to the surface, there is an average of 24.6 settlements per 100 km² (Tab. 3). These areas also have the highest settlement density, with an average of 1,709 inhabitants per settlement, and almost all settlements in these regions have experienced population growth and an increase in built-up area.

Tab. 2. Number of inhabitants, density and number of settlements based on the type of aquifers in Kosovo

Type of aquifer	Area of aquifer type (km ²)	1948	1991	2011	2024	% of inhab. (2024)	Density (inh./km ²) (2024)	Nr. of settle. (2024)	% of settlement
1	2,161.53	327,586	1,070,321	963,022	916,465	58.0	424	532	36.2
2	1,843.90	162,354	466,510	481,285	427,672	27.0	232	296	20.1
3	1,022.08	13,183	31,084	30,277	21,780	1.4	21	36	2.5
4	725.33	26,949	40,564	28,552	18,316	1.2	25	74	5.0
5	1.19	158	2,126	1,360	1,189	0.1	1,000	1	0.1
6	5,151.22	203,525	356,662	275,525	195,781	12.4	38	530	36.1
	10,905.25	733,755	1,967,267	1,780,021	1,581,203	100.0	145	1,469	100.0

Source: Population data from Kosovo Agency of Statistics (KAS); analysed by author.

The intergranular aquifers with medium to low permeability also have a high settlement density, with 16.1 settlements per 100 km² and an average settlement size of 1,467 inhabitants. As in the former areas, almost all settlements in these areas have experienced territorial and demographic expansion. Given the natural growth of settlements, especially rural ones, the potential for aquifer contamination is considerable. Pollutants from the surface, which are of anthropogenic origin, can penetrate and affect the groundwater.

Aquifers with fissured porosity or karst aquifers (type 3) are typically found in limestone and marble rocks and have a low settlement density of only 3.5 settlements per 100 km². There are few surface water sources in these areas, and the geographical extent of water-bearing rocks is small, so the probability of groundwater extraction is low. Consequently, the number of settlements in these aquifers is low. As settlements are often located close to karst springs, surface pollution can easily penetrate through cracks in the carbonate rock. The average population of settlements in these areas is 605 inhabitants.

Aquifers with fissured porosity (type 4) and low permeability of fractures (such as limestones, marls, marbles, metamorphic rocks, volcanic rocks, pyroclastics, sandstones and conglomerates) and terrains with very low porosity (type 6), which make up 53.9% of Kosovo's territory, have an average settlement density of 10.2 settlements per 100 km². This is lower than the general population density in Kosovo. In fissure-type aquifers (type 4), the average settlement size is 248 inhabitants in 74 settlements, while in soils with low porosity (type 6), the average settlement size is 370 inhabitants in 530 settlements. It is noteworthy that 336 of these settlements have a population of less than 200 inhabitants.

The number of settlements in certain aquifers is closely linked to population size and human activities. Factors such as industrial development, infrastructure, urban and municipal pollution, agricultural practices and the physical characteristics of the aquifers influence the quality of groundwater in these regions.

Population number through years classified based on the aquifers

Population distribution by aquifer serves as a key indicator of the importance of a secure water supply for the inhabitants. Migration and population growth tend to occur in areas with aquifers that have higher water storage and easier access to water sources. These factors make such areas attractive for both migration and natural population growth. Over the last century and into the present, population movements have favoured regions with more reliable

water sources, especially those in areas underlain by aquifers with intergranular porosity and medium to high permeability. This trend is reflected in the higher population density observed in these areas, and current population growth projections also indicate an increase in the regions with the richest water resources.

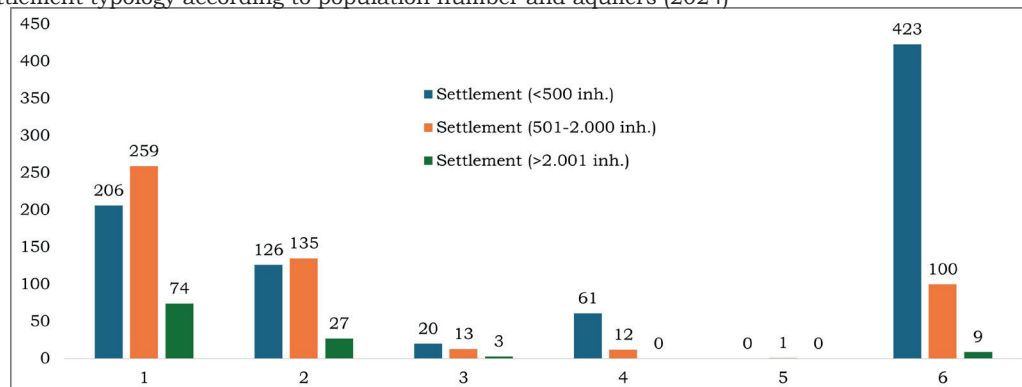
In 1948, the population of Kosovo was about 734,000 inhabitants, of which about 45% lived in settlements located above aquifers with intergranular porosity and medium to high permeability (type 1), mainly in the plains of the main basins, especially near rivers. These aquifers are characterised by rapid groundwater recharge, which makes them a primary source of water for the population. Due to their accessibility, these aquifers were attractive to the population in the past and still are today. Access to the water was usually via traditional wells, as the water table was relatively close to the surface, which facilitated extraction. These areas were less affected by migration trends (Bytyqi & Ramadani, 2018). Although they were generally close to surface water sources, agricultural activities, especially horticulture and vegetable farming, were not very pronounced in these regions.

A significant proportion of the population, namely 22.1%, was concentrated above aquifers with intergranular porosity and medium to low permeability (type 2), which had a higher proportion of inhabitants than the aquifers mentioned above. The remaining aquifers (types 3, 4 and 5) contained only a small proportion of the population, namely only 5.5% of the total population of Kosovo.

The population migrations that took place in the 1960s and afterwards led to significant changes in population distribution, especially in the settlements in the hills and mountains (depopulated areas) and in the plains (host areas) (Islami, 2013; Bytyqi & Ramadani, 2018). As a result, the percentage of Kosovo's total population living in areas without fissured or porous aquifers, where population growth occurred primarily through natural growth rather than migration, decreased. In 2024, approximately 196,000 inhabitants lived in these aquifers (type 6), representing only 12.4% of Kosovo's total population, a decrease from 27.7% in 1948.

Settlements situated above aquifers characterised by intergranular porosity and varying degrees of permeability—ranging from low to high (types 1 and 2) have generally experienced consistent population growth over time. This trend reflects the crucial role of groundwater availability in supporting sustainable settlement development, particularly in regions where surface water resources are limited. Furthermore, such areas often coincide with favourable environmental and socio-economic conditions, which

Fig. 5. Settlement typology according to population number and aquifers (2024)



Tab. 3. Distribution of population and settlements according to aquifers

Type of aquifer	Area of aquifer type (km ²)	% of Kosovo's area	Inhabitants (2024)	% of inhabitants (2024)	Density (2024) (inh./km ²)	Nr. of settlements (2024)	% of settlements	Density of settlements (100 km ²)
1	2,161.53	19.8	916,465	58.0	424	532	36.2	24.6
2	1,843.90	16.9	427,672	27.0	232	296	20.2	16.1
3	1,022.08	9.4	21,780	1.4	21	36	2.5	3.5
4	725.33	6.7	18,316	1.2	25	74	5.0	10.2
5	1.19	0.0	1,189	0.1	1,000	1	0.1	1.0
6	5,151.22	47.2	195,781	12.4	38	530	36.1	10.3
	10,905.25	100.0	1,581,203	100.0	145	1,469	100.0	13.5

Source: Population data from Kosovo Agency of Statistics (KAS); analysed by author.

further reinforce their capacity to attract and sustain growing populations (Fig. 6). The population in these areas has increased steadily since 1948, with the exception of the 2011 census, which was criticised for its methodology and exclusion of the Albanian population living outside Kosovo (Islami, 2021). In 1948, approximately 327,000 inhabitants lived above aquifers with medium and high permeability (type 1), which accounted for 44.6% of Kosovo's total population. By 2024, this number had risen to 916,000 or 58.0% of Kosovo's resident population. In the 76 years between the two censuses, the population in these areas has tripled, but it is lower than in 2011, which is now due to migration abroad. According to statistical projections, population growth in these aquifers is expected to continue, increasing pressure on groundwater resources and potentially leading to environmental problems related to various forms of pollution. Low R² values belong to settlements in the hilly uplands, which have experienced population migration towards type 1 and 2 settlements and will tend to experience population decline as shown in the 2024 census.

A similar threefold population increase was observed in areas overlying aquifers with intergranular porosity and medium to low permeability (type 2). In 1948, approximately 162,000 inhabitants lived in these areas, but by 2024, this number had increased to around 428,000. This growth in population is due to the improvement in water supply, as most settlements now have access to public water. Although these aquifers do not accumulate large amounts of water, the reliability of the water supply is high. The larger settlements in this category are mostly rural communities that have taken on urban characteristics and are located near large regional centers such as Prishtina, Prizren and Mitrovica. Examples are: Matičani, Hajvalia, Çagllavica, Arbana (Dushanova), Lubizhda and Korisha. Some settlements experienced particularly strong population growth: the population of Hajvalia increased 17-fold, from 436 inhabitants in 1948 to 7,702 in 2024, while the population of Arbana (Dushanova) increased from 231 in 1948 to 7,870 in 2024. In both aquifers (types 1 and 2), 91% of the population growth is attributed to the availability of groundwater resources (Fig. 7).

The fissured and karstified aquifers (type 3) have not seen any significant population growth due to the physical and hydrological characteristics of the limestone rocks. From around 13,000 inhabitants in 1948, the population grew to around 22,000 by 2024. These settlements were largely out-migration areas, which led to stagnation or even a decline in population. The settlements in the fissured aquifers (type 4) also recorded only minimal population growth, with their numbers remaining almost the same as in 1948. 26,000 people lived in these settlements in

1948, which had risen only slightly to about 18,000 by 2024. If one compares the percentages of the total population, 3.7% of the total population of Kosovo lived in this aquifer in 1948, but only 1.2% in 2024.

Population density according to the type of aquifer

Population density by aquifer reflects the concentration of people in relation to groundwater resources. Each aquifer is characterised by its extent, which is influenced by the physical and geographical characteristics of the terrain. In addition to population growth in certain areas, population density has also risen, which increases the pressure on groundwater-rich aquifers.

In Kosovo, population density has increased over the years in parallel with the growth. In some areas, population density has been higher than the national average due to the natural features of the terrain, especially the abundance of groundwater. In 1948, the average population density in Kosovo was around 67 inhabitants per km². Aquifers with intergranular porosity and permeability ranging from low (type 2) to high (type 1) had densities above this average. The alluvial aquifer, for example, had a density of 153 inhabitants per km², about 2.2 times higher. At the time of the last census in Kosovo (2024), the average population density had risen to 145 inhabitants per km², while the density in groundwater-rich aquifers ranged from 232 inhabitants per km² in the aquifer (type 2) to 424 inhabitants per km² in the aquifer (type 1).

When comparing the aquifer with intergranular porosity and medium to high permeability (type 1), the population density increased from 151 inhabitants per km² in 1948 to 424 inhabitants per km² in 2024, an increase of 2.8 times. This growth rate was higher than the total population increase in Kosovo, which was 2.2 times (Fig. 8). Therefore, the groundwater-rich aquifers have a higher population density than the national average. The higher population density also reflects the impact of human activities, including urban, municipal, agricultural and industrial pollution. In addition, the high population density in water-rich aquifers is associated with fertile agricultural soils where dense settlements have developed and grown the most.

Land Cover changes: impact of increase in population

Groundwater recharge, which is influenced by the extent of the lithosphere, is affected by natural factors that are essential for maintaining a sustainable water supply. Both the surface water cycle and groundwater recharge depend on land cover, which is influenced by human activities and climate change (Wang et al., 2018). Urbanisation changes the way a catchment responds to precipitation by reducing infiltration and

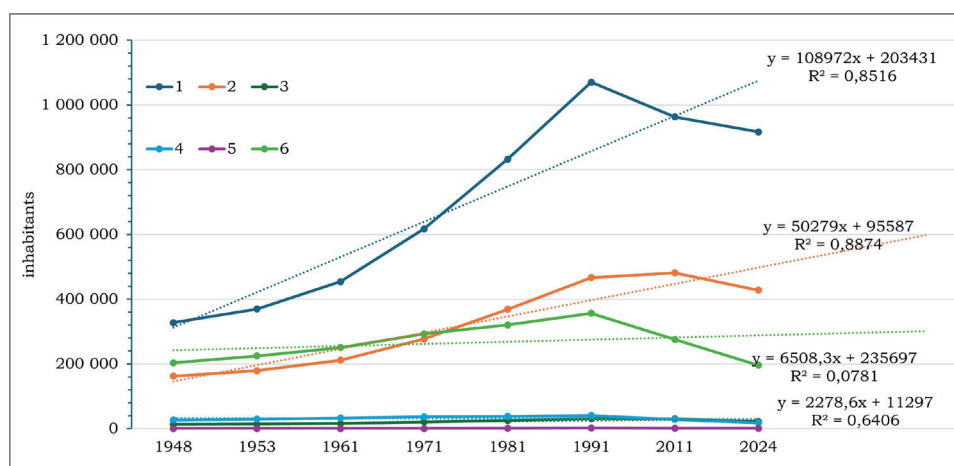


Fig. 6. Number of inhabitants over the years according to aquifers

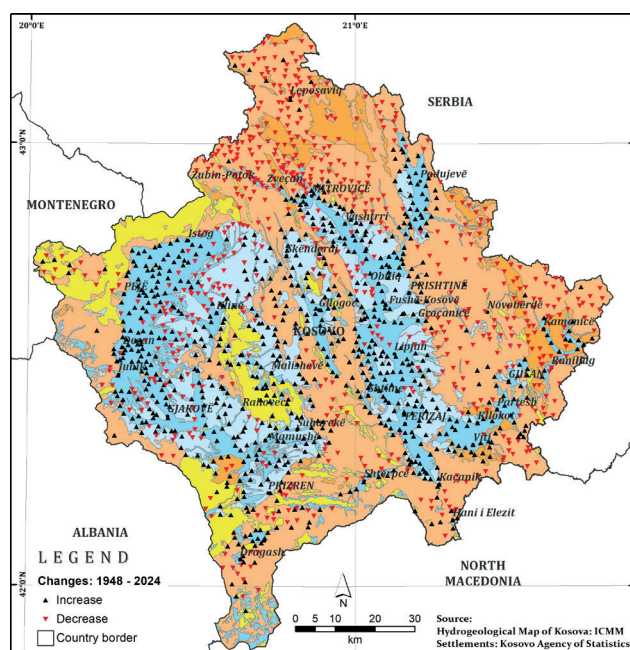


Fig. 7. Population changes in settlements (1948-2024) according to aquifer type

increasing runoff, while increasing the volume and velocity of water flow (Wakode et al., 2018). Land use and land cover (LULC) includes natural and man-made elements on the Earth's surface, such as vegetation, water bodies and human structures.

Land use and land cover change (LULC) affects groundwater systems by disrupting various components of the water balance (Poelmans et al., 2010). This often leads to overexploitation of natural resources and contributes to environmental degradation (Younes et al., 2023) and leads to landscape change (Hyka et al., 2022).

In Kosovo, land cover has been mapped using data from topographic maps showing the extent of artificial areas such as cities, villages and infrastructure. Studies have shown that urbanised areas reduce the potential for groundwater recharge (Siddik et al., 2022).

Over the years, Kosovo's urban population has increased, leading to a greater concentration in urban and municipal centres, which are mostly located on type 1 and 2 aquifers. In 1953, the share of the urban population in Kosovo was 15.6%, while in 1981 it had increased to 32.4% (Ramadani & Bytyqi, 2018). The last two censuses show a further increase, from 38.03% in 2011 to 50.18% in 2024 (Population and Housing

Census in Kosovo 2024 - First Final Results, 2024). The preliminary results of the 2024 census indicate a decrease in the population in the hilly-mountainous settlements, mostly associated with aquicludes, and an increase in the population in the settlements in the plain, characterised by intergranular porosity. The migration of the population from areas with low porosity or no porosity to the more permeable plains was accompanied by an increase in built-up areas. The expansion of settlements and infrastructure has led to an increase in artificial land cover. An analysis of topographic maps shows that settlements covered about 24,800 hectares in 1990, while the built-up area had grown to about 67,000 hectares by 2020, an increase of 270% (Fig. 8). This growth reflects the increase in population and population density.

Urban expansion has also affected aquifers with intergranular porosity, both with medium to high permeability (type 1) and with low to medium permeability (type 2). The built-up area in the aquifer with medium to high permeability (type 1) grew from 12,694 hectares to 33,821 hectares and in the type 2 aquifer from 5,699 hectares to 17,823 hectares. In 2020, the built-up area in these two aquifers together amounted to 51,645 hectares (516 km²), corresponding to 828 settlements in Kosovo, including urban centres and many large settlements in the plains of Kosovo, which account for 56.4% of all settlements in the country. In contrast, settlements in areas without fissured or intergranular porosity, which comprise 529 settlements (36.1% of the total), have a built-up area of about 12,500 hectares (Fig. 9).

In the past, human activities have had a drastic impact on the terrestrial biosphere, particularly through the conversion of forests and shrublands to agricultural land (Scanlon et al., 2005). In recent decades, urbanisation has accelerated both in Kosovo (Bytyqi, Qevani & Agaj, 2024) and globally, affecting the hydrological cycle, especially the relationship between precipitation and infiltration. Most urban areas have become impermeable, reducing the area available for rainwater infiltration (Agaj et al., 2024) and thus reducing the potential for groundwater recharge. The growth in artificial surfaces, especially in urban and rural settlements, has contributed to urban flooding or pluvial flooding. Water runoff from impermeable surfaces and urban development has significantly increased the risk of flooding. GIS/RS analyses in Kosovo show the change in natural landscapes due to urban growth. Especially in the post-war period (after 1999), the lack of adequate planning, together with rapid settlement growth, has increased the frequency of flooding.

The limitations of this study include several factors that could affect the accuracy and completeness of the results. While the study focuses on Kosovo and provides useful insights into the region, the results may not be fully transferable to other areas with different hydrogeologic conditions, land use patterns, or population dynamics. In addition, population distribution and groundwater use are influenced by a variety of interrelated factors, such as economic, cultural, and political conditions. Although the study attempts to account for many of these factors, it may be difficult to quantify or fully integrate some factors into the analysis. Groundwater recharge is a complex process that is influenced by geological, climatic and human factors. The study may simplify or generalise these dynamics, leading to a less nuanced understanding of the impact of specific aquifer types on population density and settlement patterns. In addition, the interpretation of the land use and settlement data could be biased, especially if assumptions are made about the causes and effects of the observed changes without sufficient evidence or consideration of other influencing factors. While the study considers physical factors such as water availability and aquifer characteristics, it may not take into account all relevant socio-economic dynamics, such as migration trends, economic growth or local policies that could also influence population distribution and land cover changes.

4 CONCLUSIONS

The size, distribution and other characteristics of aquifers in Kosovo are influenced by geological, morphological and climatic conditions, which also play a crucial role in settlement patterns and population distribution. An analysis of population and settlement data in relation to aquifers shows that a significant concentration of settlements is located in the vicinity of aquifers with abundant water resources. There are 1,469 settlements in Kosovo, a large proportion of which are located above aquifers with intergranular porosity and medium to high permeability. In these aquifers, about 916,000 inhabitants (58.0%) live in 532 settlements (36.2%) with a population density of about 424 people per km² - the highest density compared to other aquifers (2024). The statistical analysis, in particular the coefficient of determination (R^2), indicates that the population and the extent of artificial areas in these aquifers will continue to increase in the future. The aquifers with intergranular porosity and high to low permeability,

which are mainly located in the plains of Kosovo, have experienced the largest population growth due to the availability of groundwater. According to the 2024 census, 1.34 million inhabitants (85.0% of Kosovo's population) lived in these two aquifers.

Water is a vital factor for life on Earth and crucial for the establishment and growth of settlements and cities. The construction of artificial lakes and water reservoirs has facilitated the development of settlements even in areas with limited natural water resources that rely on water supply systems instead. The growth in these groundwater-rich aquifers, especially since the second half of the 20th century, has resulted in 85.0% of Kosovo's population being concentrated in these regions. However, the uncontrolled and unplanned expansion of both urban and rural settlements has led to a proliferation of artificial areas that disrupt the natural water cycle.

As the population and man-made areas have increased, there has been an overuse of groundwater, especially in dry periods, which has led to falling water levels. The growing population and the expansion of built-up areas hinder the natural infiltration of atmospheric and surface water into the aquifers. In addition, agricultural activities on groundwater-rich soils combined with the excessive use of chemical fertilizers have led to contamination of groundwater, which is slow to regenerate and purify.

Studies have shown that 21 of the world's 37 major aquifers are depleted by human activities (Richey et al., 2015), and the same risk exists for Kosovo's aquifers. In order to protect these valuable water resources from further damage, it is imperative that protective measures are taken, as the consequences of neglect could be severe.

Based on these analyses, the highest population concentrations occur around aquifers with abundant groundwater, where not only the largest settlements are located, but also where the majority of Kosovo's total population lives. The availability of groundwater remains a very important factor influencing population dynamics, while other key determinants include the presence of fertile soils, coal mining activity, access to transportation and energy infrastructure, favourable topographical conditions, and proximity to urban centres. Together, these elements shape patterns of settlement development and migration, particularly in the lowland regions of Kosovo.

Urban and settlement planning should prioritise the protection of aquifers by enforcing strict land use regulations that restrict building in sensitive recharge zones and promote compact, sustainable development

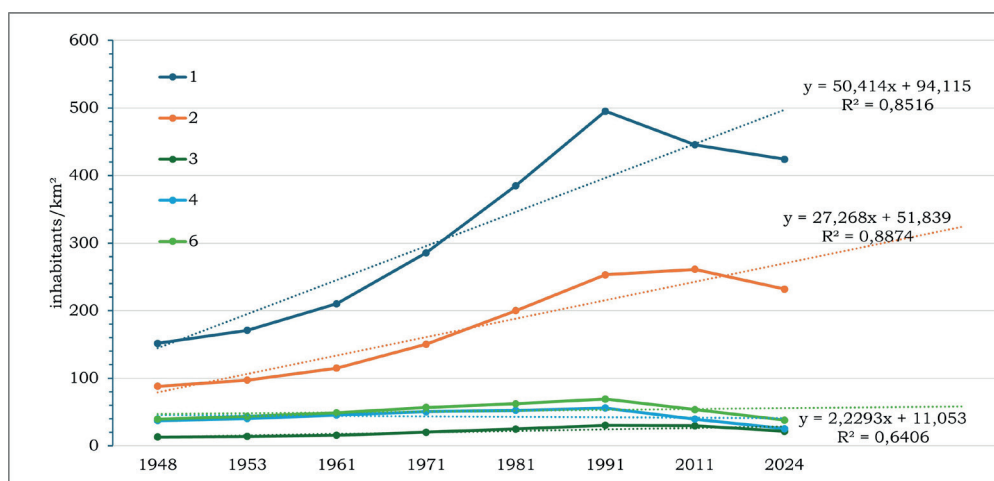


Fig. 8. Population density according to the aquifer and changes over the years

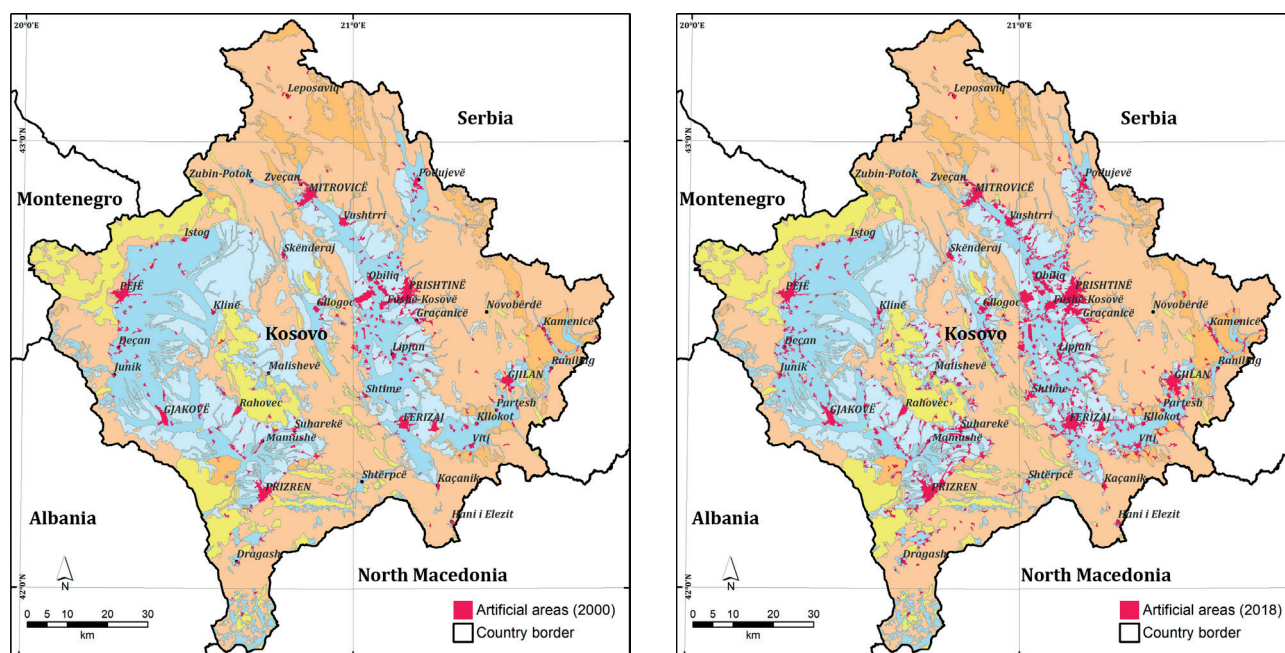


Fig. 9. Artificial areas in the year 2000 and 2018

patterns that minimise the spread of artificial surfaces. In addition, planning frameworks must incorporate groundwater vulnerability assessments into decision-making processes, establish buffer zones around critical aquifers, and ensure that agricultural and industrial activities near these areas are carefully monitored and regulated to prevent contamination and over-abstraction.

Acknowledgements:

I would like to extend my sincere gratitude to the Academy of Sciences and Arts of Kosovo for funding the project “Water and Population in Kosovo”.

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Article first received: 22 August 2025
Article accepted: 1 December 2025