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Front cover photography: Vezeira, the traditional migration of livestock, from the village of Pincães (Montalegre, Portugal) to high-altitude pastures is a community event organized to revive pastoral traditions and involve younger generations (photograph: Joana Nogueira).
Fotografija na naslovnici: Vezeira, tradicionalna selitev živine iz vasi Pincães na Portugalskem na visokogorske pašnike, ki jo izvaja lokalna skupnost, je namenjena oživitvi pašnih tradicij in vključevanju mlajših generacij (fotografija: Joana Nogueira).

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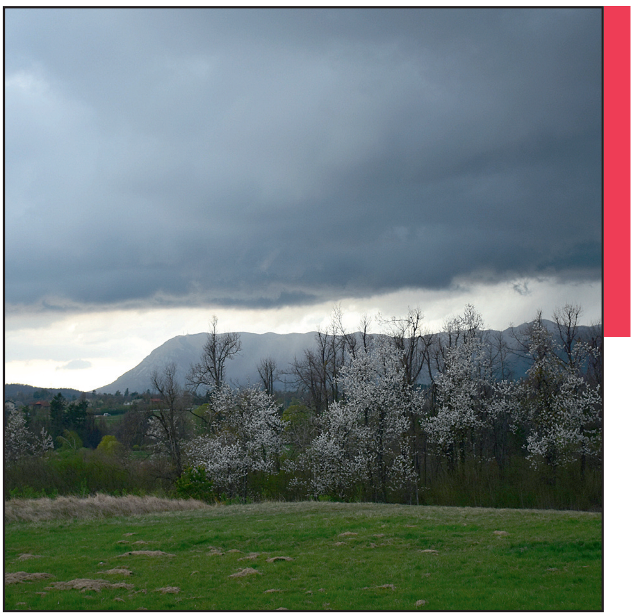
GROUNDWATER RECHARGE AS A BASIS FOR THE ASSESSMENT OF ECOSYSTEM SERVICES ON COMMON LAND: THE CASE OF THE PRIMORSKA REGION IN SLOVENIA

Nevenka Bogataj, Peter Frantar



The storm brings precipitation. A view of Nanos.

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Nevenka Bogataj[1], Peter Frantar[2]

Groundwater recharge as a basis for the assessment of ecosystem services on common land: The case of the Primorska region in Slovenia

ABSTRACT: The objective of this analysis is to assess groundwater ecosystem services and collect available data, with a particular focus on the supply side of their provision in common lands. The assessment of the state and trends of its recharge is conducted using the water balance model mGROWA. The study focuses on the period from 1972 to 2023 and the Primorska region due to the availability of both, spatial and temporal data for groundwater recharge and for forests on common lands. Based on the findings, we propose to recognise and support agrarian communities as large land proprietors practising the sustainable management of natural resources, underpinned by a benefit-sharing paradigm as stakeholders in groundwater management.

KEYWORDS: common lands, ecosystem services, groundwater, hydrology, Slovenia, Primorska region, drinking water

Napajanje podzemne vode kot osnova za ugotavljanje ekosistemskih storitev na skupnih zemljiščih: primer Primorske v Sloveniji

POVZETEK: Cilj te analize je opredeliti ekosistemske storitve podzemne vode in zbrati dostopne podatke s poudarkom na njenem zagotavljanju na zemljiščih, ki jih posedujejo agrarne skupnosti. Obseg in dinamika polnjenja podzemne vode sta ocenjena z modelom mGROWA. Spričo razpoložljivosti novejših prostorskih podatkov in trendov napajanja podzemne vode ter gospodarjenja z gozdovi smo se osredotočili na Primorsko in na obdobje med letoma 1972 in 2023. Na podlagi ugotovitev predlagamo, da se agrarne skupnosti kot lastnike velikih zemljišč z delujočo lokalno tradicijo njihovega trajnostnega upravljanja, ki temelji na paradigmi deljenih skupnih virov, upošteva kot deležnike v upravljanju s podzemno vodo.

KLJUČNE BESEDE: agrarne skupnosti, ekosistemske storitve, podzemna voda, hidrologija, Slovenija, Primorska, pitna voda

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1 Introduction

Ecosystem services (ES) represent the relationship between human wellfare and ecosystems. The latest version of the internationally agreed categorization, European Union Common International Classification of Ecosystem Services (CICES), was provided by Haines-Young and Potshin (2018) who generally define ES as arising from living structures and processes, but acknowledging abiotic ecosystem outputs to stress their non-biomass base, and recognition of hydrological cycle as driven by geo-physical processes (see also MEA 2005, TEEB 2010). As we focus on groundwater as a basis for ecosystem services, we acknowledge the CICES definition, primarily classifying groundwater as a provisioning abiotic service used for drinking (4.2.2.1), non-drinking (4.2.2.2) or energy (4.2.2.3) purposes, as the regulation and maintenance of the biotic service (2.2.1.3) or the cultural biotic service (3.1.1.1) when it enables interactions with living systems (e.g., in wetlands or biodiversity). The conceptualization of groundwater ES, just recently edited by Iliopoulos and Damigos (2024), contributed to more nuanced understanding of the role groundwater plays in societies. The inherent value of these ES is inextricably linked to the quantity of groundwater, in addition to the ecological and social benefits that defy straightforward economic quantification.

Groundwater is formed by precipitation, is found beneath the land surface and is a part of the hydrological cycle, e.g., mitigating the impact of drought. As a resource it is characterised by availability which decreases with use (Ostrom 1990). Therefore, its management is challenging (Ehrman 2020). Based precisely on the case of water supply, Ostrom (1990) identified self-regulated institutions as an effective governance model. As demonstrated in the works of van Laerhoven et al. (2020) and Romanelli and Boschi (2019), numerous authors have examined and built upon Ostrom's contributions to the field and much of the international literature on collective groundwater management is based on Ostrom works, for instance local adaptations due to balancing of interests (Doneo and Conrad 2024) and local consideration of the social and cultural roles of groundwater (Smith 2002) without displacement of weaker stakeholders (e.g., farmers) where groundwater is considered a commodity. Solutions for sustainable groundwater management were sought in river basins in India and China (Shang et al. 2024; Vora 2024) and by analysing international agreements on water and other resources (Soliev and Thesfeld 2017). A shift from negotiation between conflicting actors to the identification of options for maximising co-benefits was suggested (Soliev and Thesfeld 2017) which is the way local collectives manage resources, including water. Italian constitutional law grants collective landowners rights on the basis that they have preserved natural resources despite having used them for centuries. Despite the absence of explicit mention of groundwater in this law, it can be presumed that it was meant as a natural resource.

The interdependence of groundwater with soils and surface ecosystems is a particularly sensitive issue in karst areas with water-permeable carbonate substrate. The Slovenian region of Primorska combines both, karst bedrock and climate regimes of the Alps and the Sub-Mediterranean region to which local collective resource management institutionally adapted. This typically represents small-scale benefit sharing local collectives that regularly monitor resources, and incorporate feedback into their utilisation. The fundamental reason for such an organization is the (eventual) scarcity of resources that might lead to tensions, conflicts and – in the case of water – the potential jeopardy of survival. In light of the interconnection between droughts and climate change, groundwater recharge and dynamic served as a motive for our analysis, drawing upon the reports of Vertačnik (2023) and European Mapping and Assessment of Ecosystems and their Services (European Commission … 2020).

In Slovenia, groundwater is owned by the state and according to the Act on water published in 2004 regarded a public good. The governance of water supply and water protection areas is overseen by the Water Directorate, while the management of local groundwater use falls under the responsibility of municipalities. In the Primorska region groundwater is also the subject of transboundary cooperation. Access to groundwater cannot be prevented and depends on the consent of the landowners on whose land boreholes and wells are located, and water may be abstracted for personal needs.

Primorska is an informal region in Slovenia, which includes two statistical regions, called *Goriška* and *Obalno-kraška*. The local water management culture of this region is described in the context of the Karst area (Crnko et al. 2015) exhibiting adaptations to occasional droughts by collective approach amongst its inhabitants. Furthermore, the significance of alterations in land cover has been recently documented for two main river catchments in the area, namely Rižana and Unica (Ravbar et al. 2023; Ravbar et al. 2024). There was a decline in effective precipitation of 49% in the Rižana catchment, attributable to climate change, and an increase in forest cover of 30% between 1965 and 2018 (Ravbar et al. 2023). Opposite, a 5% rise in effective precipitation has been documented for the Unica catchment, attributable to the combination of climate change and large-scale forest damage during the period 2014–2016 (Ravbar et al. 2024). These analyses do not take into account the management of land.

Groundwater on common lands has not been addressed so far, although recently Pipan et al. (2023) presented water cooperatives (Lazarević et al. 2023). They have a different conception, history, purpose and functioning of collective management than agrarian communities (AC) as long-term land owners of common lands, documented as active and effective (Bogataj and Krč 2023). However, the intermediary role of AC is unclear and marginalized and it would appear that there is a dichotomy between private ownership of the land and state ownership (and management) of groundwater. Moreover, the issue is becoming increasingly important due to the climate change (European Commission … 2020; Vertačnik 2023) and changes in land cover. The simultaneous consideration of spatial and temporal variability in groundwater may, therefore, contribute to informed and consensual decision-making by all stakeholders regarding aquifers when considering any of the groundwater ES.

1.1 The national literature review on land commons related to groundwater

The concept of common pool resources was first introduced in Slovenia by Rodela (2012) and comparatively studied by Šmid Hribar et al. (2018), who also established the first link between common lands and ES in the country (Šmid Hribar et al. 2023). Dominated by forests and pastures (Kozorog and Leban 2023; Šmid Hribar et al. 2023), common lands are managed by self-regulated local institutions officially entitled AC and defined in 2015 by Agrarian Communities Act. Decade ago, AC owned 3.7% of Slovenia's surface area (Premrl 2013), but there is an overall lack of data on this issue, with the exception of Primorska, where they own four times more, 12% (Kozorog and Leban 2023), and Triglav National Park, where according to preliminary information approximately 20% of the land is under AC ownership.

The legal protection of AC was established after the denationalisation of the land by the Act on reestablishment of agricultural communities and restitution of their property and rights (sl. *Zakon o ponovni vzpostavitvi agrarnih skupnosti ter vrnitvi njihovega premoženja in pravic*) from 1994 and the Act on agrarian communities (sl. *Zakon o agrarnih skupnostih*) from 2015, and was characterised by numerous amendments, demanding procedures and costs. Their forest management is systematically monitored and rewarded by the Slovenian Forest Service (*Zavod za gozdove Slovenije,* SFS), which is the sole state institution that regularly selects AC for models of active sustainable management. Slovenian authors have considered AC from a variety of perspectives, including legal aspects (Hafner 2011; Cerar et al. 2016), historical development (Meden 2019; Kocijančič 2022), geographical characteristics (Šmid Hribar et al. 2023) and anthropology (Hrobat Virloget 2023; Beltrametti 2024). As Bavec and Bogataj (2021) demonstrate in publication with AC self-presentations, they are particularly active in Primorska in comparison to other regions, as a high proportion of cases from there (one third) are documented.

Šmid Hribar et al. (2023) conducted a study on commons from the perspective of their ES provision, but however, the eventual groundwater-related roles of AC were not addressed by the study. It is intriguing to note that an example of efficient response to natural extremes has been documented in the context of AC, e.g., fast and focused activation (Bogataj and Krč 2023). Groundwater recharge on common lands of AC in Primorska is a subject of contemporary concern due to a number of remarkable meteorological deviations there, including a particularly hot summer in 2003, several dry springs, followed by dry summers and an increased risk of fire, as well as an extreme fire event (Sandrin 2022) and unfavourable future projections (Vertačnik 2023).

1.2 Aims and scope

The scope of the paper is to identify groundwater recharge on common lands in the Primorska region as a potential source for the provision of groundwater ES as defined by Haines-Young and Potshin in CICES (2018) by codes 4.2.2.1, 4.2.2.2 and 4.2.2.3 and listed by Iliopoulos and Damigos (2024).

The following research questions were the subject of our analysis: which ES are provided by groundwater, at least in theory? What is the amount and dynamics of groundwater recharge as a basis for groundwater ES on common lands in the Primorska region? Are there any spatial differences in groundwater ES potential between Alpine and Sub-Mediterranean common lands?

The primary objective of this study is not to categorise or score services, but rather to establish a foundation for their future evaluation by focusing on the supply side of groundwater ES and unveiling the complex interactions between groundwater dynamics, climate and collective land use and management (Ostrom 1990; Meinzen-Dick and Bruns 2024) by examining numerical data (Booth et al. 2016; Shang et al. 2024). This approach aligns with contemporary research emphasizing the use of continuous data for nuanced interpretations of spatial and temporal trends while respecting landscape heterogeneity and avoiding potential oversimplifications (Smith 2002; Vora 2024).

2 Methods

A comprehensive review of the literature on groundwater ES was conducted, with a particular emphasis on the bibliography of Slovenian karst groundwater recharge in relation to the dominant land cover and the characteristics of AC management.

Iliopoulos and Damigos (2024) provided a detailed list of groundwater ES that are useful for the purpose of our analysis:

- provisioning final ES (drinkable water, irrigation water, livestock water, water for industrial use);
- intermediate provisioning ES in case of strategic water resources, storage capacity;
- regulating intermediate services ES for water purification, seawater intrusion control, flood control, subsidence control, carbon dioxide storage, hydraulic conductivity, maintenance or microclimate mitigation;
- fundamental or supporting intermediate ES for groundwater-dependent ecosystems, water cycle support and
- cultural ES (naturalist leisure activities, aesthetic enjoyment, spiritual well-being, education and research).

Their precise and consensually built classification and categorisation frame groundwater not only as a provisioning ES, but also as a regulating and cultural ES.

The estimation of groundwater recharge was conducted utilising the water balance model mGROWA (ger. *montatliches Großräumiges Wasserhaushaltsmodell*) for the period from 1991 to 2020 (Frantar et al. 2023) and comparison was made between the Alpine and Sub-Mediterranean group of common lands. An interdisciplinary approach was adopted to establish a comparison between the geographic data of the AC lands and the results obtained from the water balance model. The Primorska region was selected for analysis due to the largest amount of common lands there, their recent mapping and forest management analysis (Kozorog and Leban 2023), and the evidence of strict local rules regarding the use of resources (Kocijančič 2022; Juriševič and Medeot 2024) which may align with eventual risk perception (Ravbar and Kovačič 2010). Contrary to the general absence of data, these data enable diverse comparisons and a step towards complex analysis of groundwater ES. A measure of forest management intensity is an average cutting over the period from 2013 to 2023 (Kozorog and Leban 2023). In the context of comparisons between common lands and other spatial features, full correspondence is defined by 100% spatial correspondence, while substantial correspondence from 50% to 99%.

2.1 Study area

Kozorog and Leban (2023) described and mapped the AC of the Primorska region according to phytogeographical characteristics as a primary factor in the formation of two distinct groups: an Alpine and a Sub-Mediterranean group of common lands. Both groups face potential drinking water scarcity, because in the Sub-Mediterranean region karst bedrock prevents surface water courses, while the steep Alpine slopes cause rapid runoff. The Alpine group of common lands is located in the area of the Julian Alps and the high Dinaric Alps, while the Sub-Mediterranean part consists of coastal Koper area, the Brkini hills and the Karst region including a few lands of the Nanos area, despite them being part of the high Dinaric range. The total grid area of all common land units is 32.708 ha.

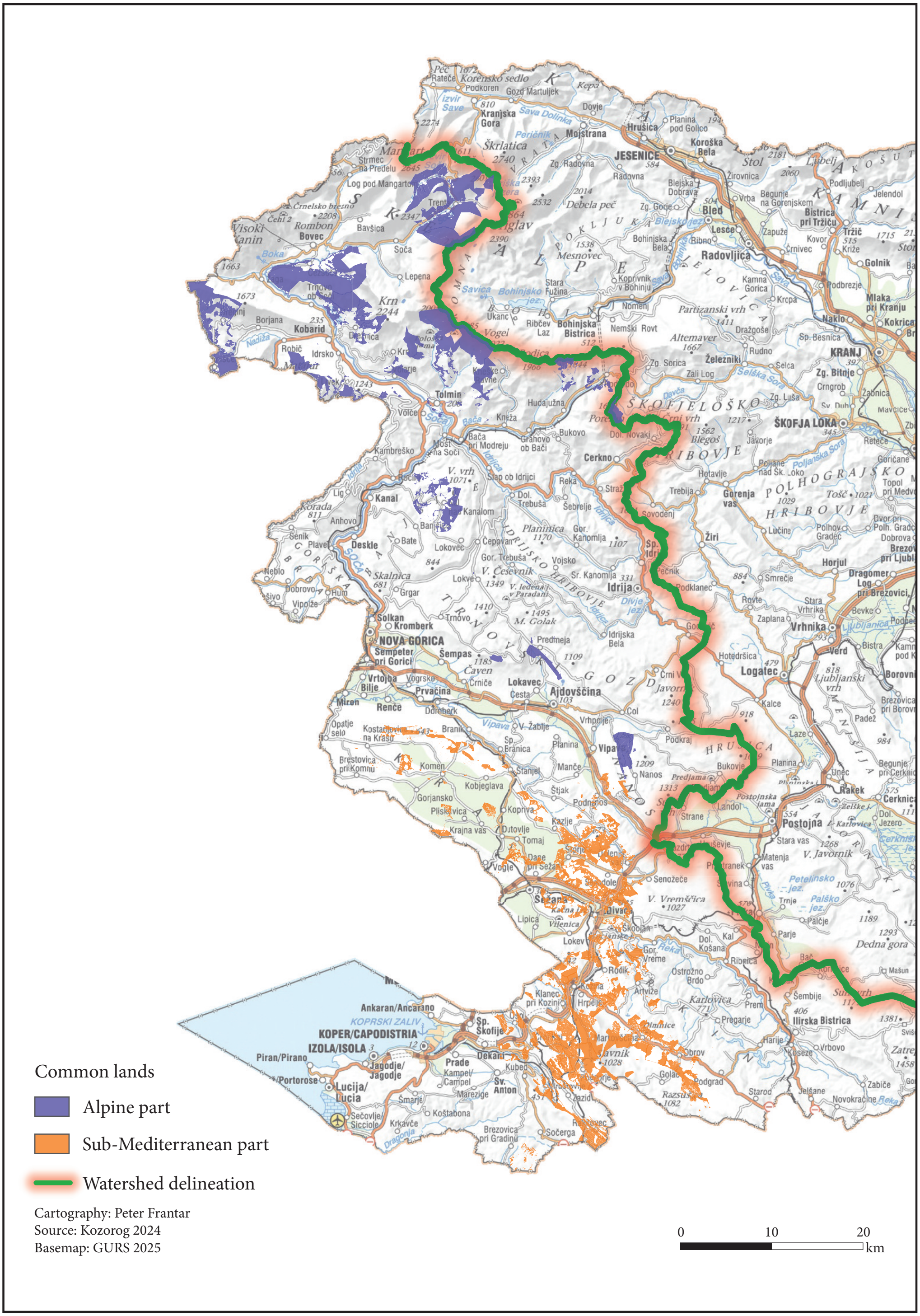


Figure 1: Common land grouped into Alpine and Sub-Mediterranean (Kozorog 2024).

2.2 Data sources

2.2.1 Agrarian Communities (AC)

An agrarian communities' layer is a polygon dataset representing lands defined and used as common lands owned by the AC. The geocoded data layer on AC was obtained from the SFS (Kozorog 2024) and analysed by Kozorog and Leban (2023) for their forest management. The layer includes merged polygons of 93 AC divided into the Alpine group in the north, and the Sub-Mediterranean group in the south.

2.2.2 The CORINE land cover layer

We used data from Coordination of Information on the Environment (CORINE). CORINE Land Cover (CLC) is general land cover layer in vector format. The coverage, definition and nomenclature of land cover classes are standardised (Bossard et al. 2000; Copernicus 2024). The mGROWA model used the CLC2006 layer to analyse the water balance across different land cover types. The main CLC categories are combined with hydro-pedological characteristics and soil water modelling. All that provides the model basis for the impact of land cover on the water balance. This also influences runoff and groundwater recharge. The model assumes constant land cover throughout the period 1991–2020, based on the CLC2006 layer.

2.2.3 Water protection zones

A water protection zone is defined as a designated area established to safeguard a water body used for or intended for public drinking water supply. There are two major water protection zone designations, namely of the state and of the municipality. Both have been joined into one layer and used as an indicator of land protection for groundwater ES. The data layer of water protection zones (version 2024) was provided by the Slovenian Water Agency.

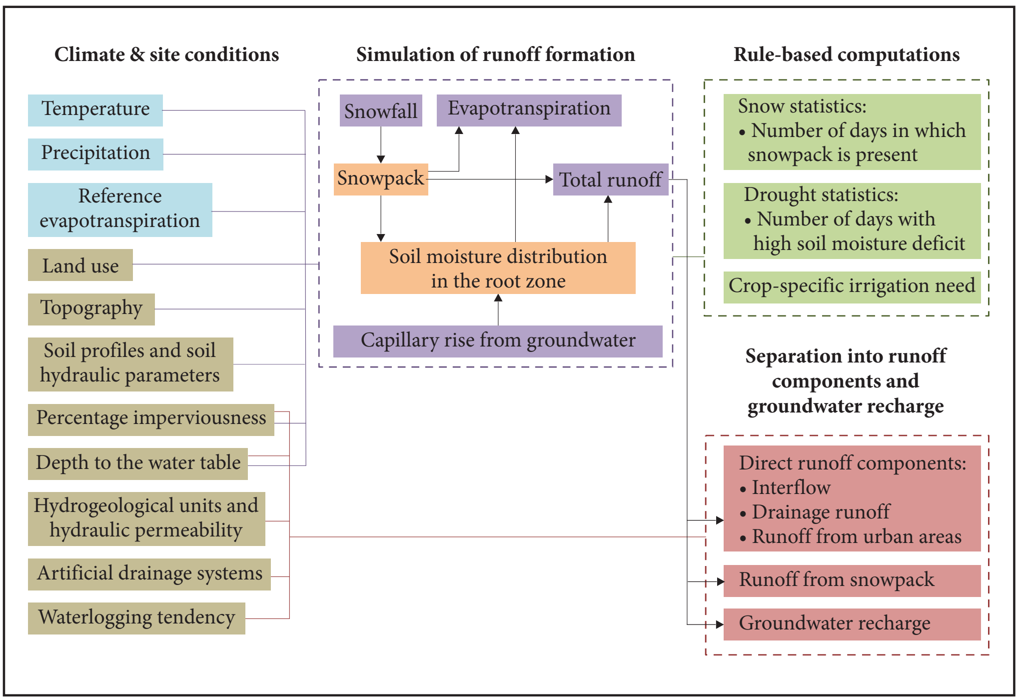


Figure 2: Model flowchart of the mGROWA water balance model.

2.2.4 The mGROWA water balance model

The mGROWA model (see Figure 2) is a deterministic raster water balance model. It is based on the German mGROWA model, which has been adapted and upgraded for Slovenia. The water balance elements in the model are calculated on the basis of static and dynamic input data and simplified hydrological processes for each 100 × 100 m model cell at a daily time step with outputs available at different time scales.

The model is based on geographical data derived from the landscape, the pedological and hydro-geological characteristics. The model analyses the water cycle in 100 m cells with the use of dynamic climate data on precipitation, potential evaporation and air temperature (Herrmann et al. 2013; Herrmann et al. 2015). The model calculates the soil-water and the snow-water separately. The output of the soil and snow modules is evaporation and total runoff. The total runoff is structured into various types of runoffs, the most significant of which is groundwater recharge. The latter can be equated to baseflow values (Frantar et al. 2023). We analysed groundwater recharge, which is calculated in the »Qrn« layer of the mGROWA model.

Groundwater recharge is approximately equivalent to the total recoverable groundwater volume. Due to the dynamics of recharge, data are aggregated on a monthly basis (Frantar et al. 2023). The mGROWA model is continuously upgraded in collaboration with the Slovenian Environment Agency (sl. *Agencija Republike Slovenije za okolje*, ARSO) and the Jülich Research Centre (ger. *Forschungszentrum Jülich*, FZJ). The groundwater recharge layers that were the subject of this analysis derived from the r158 model run at Slovenian Environment Agency in August 2024.

In the mGROWA model, baseflow is equated to groundwater recharge, which ensures flow stability during droughts and serves as a key parameter for determining ecologically acceptable flows (Herrmann et al. 2015; Frantar 2022), maintaining the natural water balance and enabling sustainable management of water resources (Herrmann et al. 2015; Andjelov et al. 2016).

2.3 The geospatial join of spatial and groundwater recharge data

The basis for groundwater data is constituted by the results of the mGROWA r158 model run – annual grids for the hydrological years from 1972 to 2023. The mGROWA grid layers were intersected with a joined raster of common lands and land cover CLC2006. This cross-section identified land use in each AC area. Based on that the »Zonal Statistics« were computed from all the groundwater recharge grids for the modelled data from year 1972 to 2023. The output was a table of recharge values for each individual AC unit that was joined with a table of area and other basic geospatial statistics.

Groundwater recharge data and basic entity parameters were merged into a new table for geostatistical analysis by a part of Primorska (the Alpine or Sub-Mediterranean group of common lands) and land cover type (CLC). The analysis considered annual values from hydrological years 1972–2023, with the 30-year period 1991–2020 as the climatological reference for climate comparisons (WMO 2017).

In addition, we linked water protection zones to the AC (intersected in GIS) to test eventual groundwater potential for ES provision.

3 Results and discussion

3.1 Groundwater as ES

Groundwater ES and evaluation of its benefits stem out of a complex mechanism of water recharge. Recent research findings on the groundwater recharge of two karst river catchments of the Primorska region have indicated that precipitation and land use changes are not the only factors influencing the availability of groundwater of ES, such as drinking water (Ravbar et al. 2023; Ravbar et al. 2024), but there are also several other factors. Forests play a pivotal role, and as such, their management is worth being analysed and, therefore, acknowledged in following sections.

3.2 The amount and dynamic of groundwater recharge on dominant land uses

According to mGROWA model both, the Alpine and Sub-Mediterranean group of common lands in Primorska are dominated by CLC Class »forests and semi-natural areas«, with the Alpine group exhibiting a forest cover of 168.5 km² (97%) and the Sub-Mediterranean group of common lands displaying a forest cover of 133.3 km² (87%). Consistently forest (CLC classes 311, 312, 313) in both groups of common lands cover almost identical share of area (67%). Forests infiltrate less water than grassland (CLC classes 231, 321) as seen in Table 2 respectively. It is evident that the Sub-Mediterranean group has significantly lower groundwater recharge than the Alpine group of common lands.

The average groundwater recharge for all land uses in the Alpine group of common lands for the 1991–2020 period is 845 mm, annually ranging from 504.7 mm in 1989 to 1,461.6 mm in 2001 (Table 1, Figure 3). As expected, the CLC class 300 (»forests and semi-natural areas«) have almost identical recharge (845 mm) as this CLC main class is dominant of this land category. On forested land, the recharge averages 779 mm, ranging from 444 mm in 1989 to 1379 mm in 2001. On grassland the recharge averages 972 mm, ranging from 548 mm in 2003 to 1686 mm in 2001.

In the Sub-Mediterranean group of common lands, the average groundwater recharge for the 1991–2020 period is 289 mm. On forested land, recharge averages 274 mm, ranging from 106 mm in 2012 to 466 mm in 2001. On grassland the recharge averages 313 mm, ranging from 126 mm in 2012 to 521 mm in 2010 (Table 2).

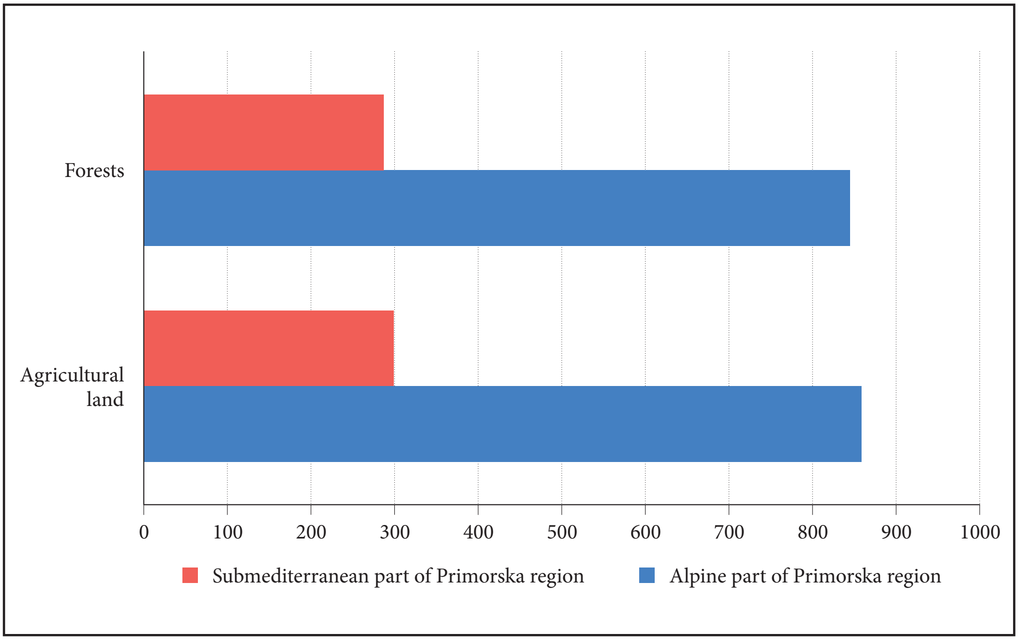


Figure 3: Average annual groundwater recharge (in mm) on dominant land uses in the Alpine and Sub-Mediterranean group of common lands.

Table 1: Annual groundwater recharge of CLC class »forest and semi natural area« for the period 1991–2020 (in mm) and indication of extreme year.

Groundwater recharge (mm) in CLC class 300 (forest and seminatural areas)	Alpine group	Sub-Mediterranean group
Average	845	287
Minimum (extreme year)	504.5 (1989)	113.2 (2012)
Maximum (extreme year)	1461.6 (2001)	483.1 (1977)

Table 2: Annual groundwater recharge of forest and grassland in the Alpine group of common lands for the period 1991–2020 (in mm).

Groundwater recharge (mm)	Forest			Grassland		
	average	min	max	average	min	max
Alpine	779	444	1379	972	548	1686
Sub-Mediterranean	274	106	466	313	126	521

These data provide evidence of a more significant impact of dry periods in the Sub-Mediterranean group of common lands, affecting vegetation, especially the dominant forest.

The amount of infiltration depends not solely on precipitation amount and distribution, but also on hydro-pedological characteristics and land cover water requirements. Forests, for instance, require greater quantities of water than meadows (Madani et al. 2018). This can be seen also from model mGROWA through land use specific evapotranspiration factors, i.e., for CLC class 321 »natural grassland« the factors in spring and summer months are from 1.00–1.06; for CLC class 312 »coniferous forest« factors are from 1.18–1.27. This indicates higher water demand of forests (Herrmann et al. 2015; Frantar 2022). Therefore, the groundwater recharge is also smaller in forest as compared to grassland. Given the same soil moisture levels, forests experience less infiltration compared to grasslands with easier percolation of water. Consequently, drought conditions may develop earlier in forests than in grasslands, leading to differences in infiltration data between these vegetation types.

Overview of relative annual variations (Figure 4) shows that the inter-annual variations can be from –60% to +70%. It also shows that after 2000 an increasing number of drier years with lower recharge is observed. The driest years for groundwater recharge were 1989, 2002, 2003, 2012 and 2022, with the largest relative negative variations in the Sub-Mediterranean group of common lands.

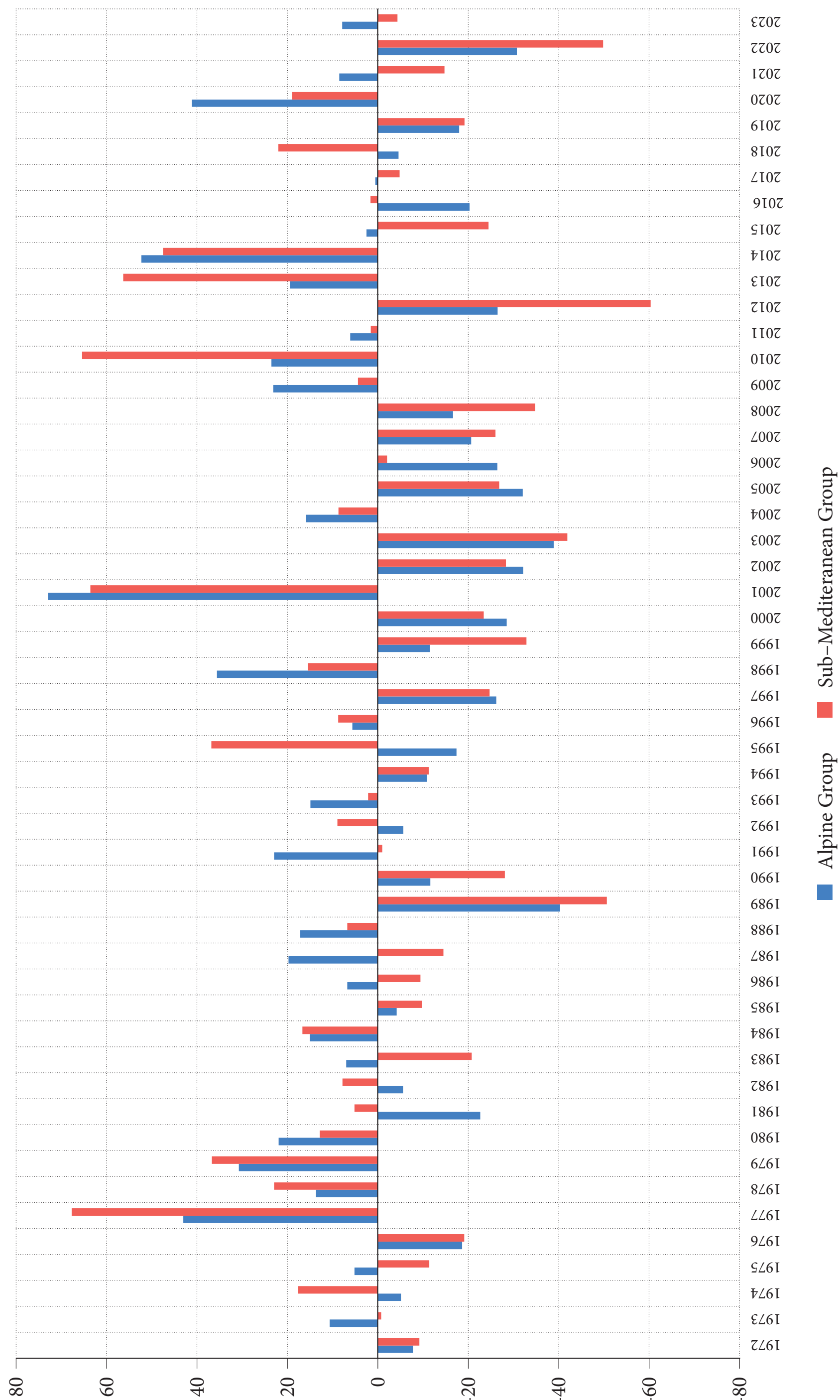
A comparison of the two subregional groups reveals greater recharge variability in the Sub-Mediterranean, with 28 of 52 years showing negative deviations and 24 positive deviations. In contrast, the Alpine group of common lands exhibits the opposite, with 25 negative and 27 positive years.

Given the lower recharge in the Sub-Mediterranean group, the management and protection of common lands are disproportionately more critical and require greater attention than in the Alpine group. The total average recharge rate in AC in the Alpine group is 4.65 m^3/s but only 1.41 m^3/s in the Sub-Mediterranean group. In the latter, annual declines of up to 50% can reduce recharge to just 700 l/s in dry years (Figure 4), with even more pronounced seasonal fluctuations. The importance of groundwater as ES is, therefore, substantially higher on the Sub-Mediterranean common lands (the lower recharge means greater sensitivity of ES to its variation) than on the Alpine common lands, exposed to eventual floods due to the increased variability in annual recharge in recent decades. In the Alpine group, there was an increase in annual recharge from 17% (1972–2000) to 24% (2001–2023), while in the Sub-Mediterranean region the absolute variation rose from 18% (1972–2000) to 27% (2001–2023). This trend reflects growing hydrological extremes, with some years experiencing greater aridity and reduced recharge that impact ES.

3.3 The correspondence between groundwater and common lands

Spatial correspondence of groundwater recharge and forest management on common lands, analysed by Kozorog and Leban (2023), inform future assessments of groundwater ES at least for Primorska where common lands cover twelve percent of land, which is predominantly forested, and exhibit lower levels of management intensity compared to other private forest properties within the same region. For instance, between the years 2013 and 2022, in the Alpine area, more than half of AC (53.8%) cut less than other private forest owners. This proportion is even higher (71.7%) in the Sub-Mediterranean region. Generally

Figure 4: Relative deviation of annual groundwater recharge from the reference period 1991–2020 in %. ➤ p. 47


Alpine Group
Sub-Mediterranean Group
80
60
40
20
0
−20
−40
−60
−80
1972
1973
1974
1975
1976
1977
1978
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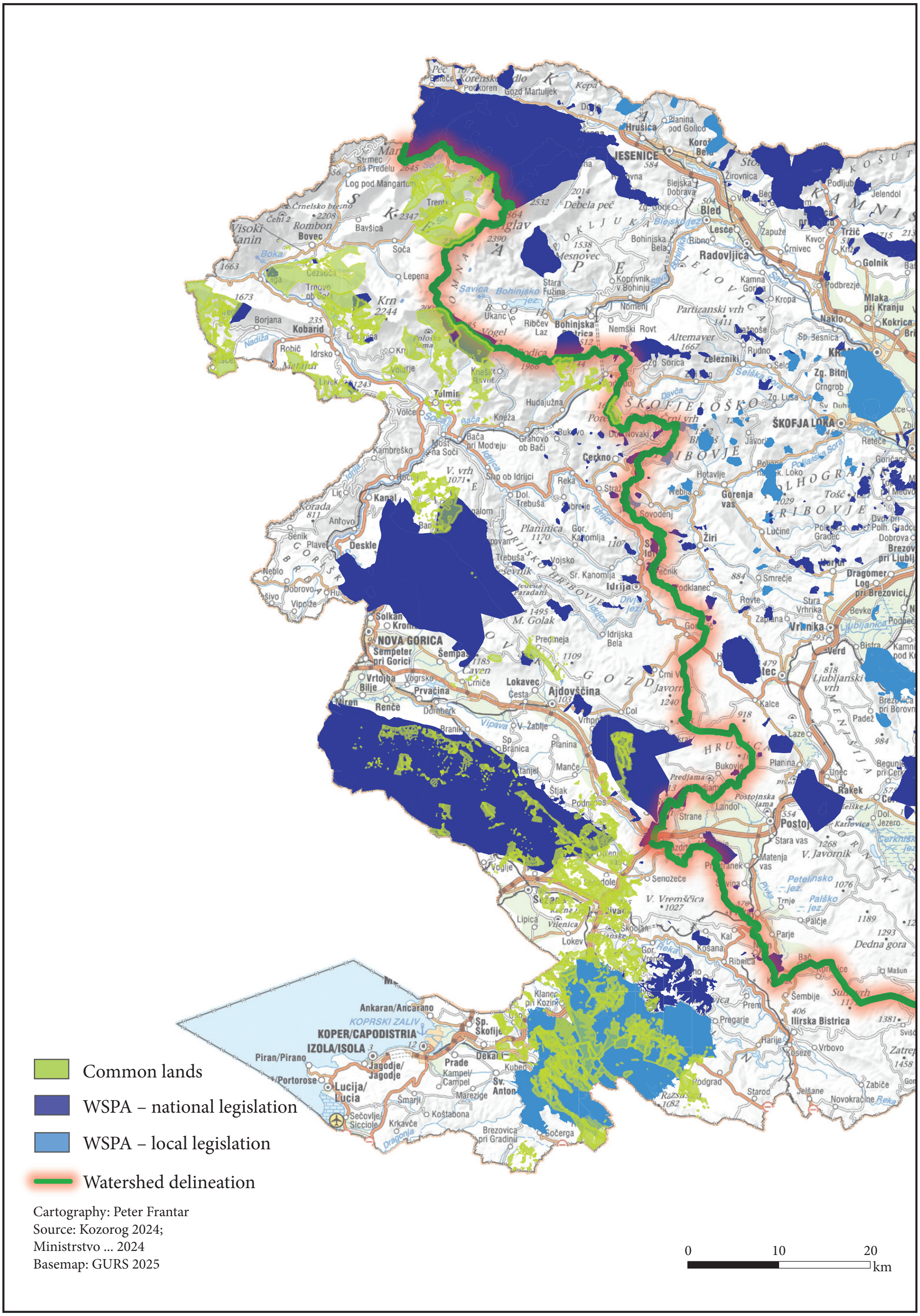

Figure 5: Water source protection areas (WSPA) in Slovenia and on common lands in Primorska.

low management intensity of forests has positive implications for quantity and quality of groundwater and ES derived from it. Furthermore, common lands, being relatively large in size, are likely to make a substantial contribution to groundwater stability when compared to fragmented individual private forest properties. Therefore, high correspondence of legally protected groundwater areas is not a surprise. In the Alpine group, 18% (2553 ha) of the common lands fall within water protection zones, whereas in the Sub-Mediterranean group, this figure reaches 78% (9749 ha in total) (Figure 5).

The Alpine group includes 35.7% of AC (namely 15 out of 42) with at least some land in a water protection zone. Among them, 5 AC have less than 5% of their area protected, while one (2.3%) is entirely within the water protection area.

In the Sub-Mediterranean group, 58% (54 AC out of 93) have land within water protection zones, with only one having less than 5% protected. Remarkably, 34 AC (36.5%) are entirely in water protection areas.

3.4 Groundwater and land management

Groundwater ES, although classified by CICES (Haines-Young and Potshin 2018) and Iliopoulos and Damigos (2024), are largely understudied. We focused on the supply side of groundwater ES as a basis for future assessments and evaluations. Despite data scarcity, we were able to identify a region that possessed numerical data on the spatial and temporal dynamics of groundwater recharge on common lands already analysed from the perspective of forest management (Kozorog and Leban 2023). Data availability and spatial correspondence of data sources are the key added values of this analysis. However, the Primorska region was selected also due to the prevalence of common lands at the national level and regular reports of the SFS on model management practices of AC in this region which corresponds with literature on the local culture of self-limiting resource use (Crnko et al. 2015) and the accent on care for water (Bogataj and Rupnik Vec 2024). CORINE data and the water balance mGROWA model provides precise numerical information and incorporates a certain degree of complexity regarding land uses.

The results indicate significant variability with regard to both geographical location and by land cover type. Natural grasslands exhibit higher infiltration rates in comparison to forested areas as found by other authors (Owour et al. 2016). An average annual groundwater recharge in Slovenia for the reference period 1991–2020 is estimated at 313 mm, while Alpine group of common land units with 845 mm is high above this average. Sub-Mediterranean group with 287 mm is slightly below this average. Deviation of annual groundwater recharge from the long-term reference period was found: an increase in the number of dry years after 2000 and more pronounced fluctuations. The 52-year record reveals substantial variability and a higher frequency of negative deviations. In the Sub-Mediterranean region at least, groundwater ES are exposed not only to eventual shortages, but also to significant risk of large-scale forest cover changes (Kozorog and Leban 2023; Ravbar et al. 2023; Ravbar et al. 2024). Moreover, in areas where forests are predominant, as is Primorska region, low management intensity reported for common land may be of critical importance for groundwater ES, irrespective of the underlying reason, such as marginal productivity on poor soils, inaccessibility of slopes, or inactive AC. Additionally, relatively large properties of common lands and their extensive use contribute to groundwater recharge comparatively more than fragmented individual properties. This suggests a significant positive potential impact on the provisioning of groundwater ecosystem services, with implications in both the short and long term. Moreover, it is important to note that local balancing of interests (Doneo and Conrad 2024) is a fundamental characteristic of AC which may be the key in provision of quantity and quality of groundwater ES (Juriševič and Medeot 2024) in the face of climate changes both regionally and beyond (Soliev and Thesfeld 2017; Bogataj and Krč 2023; Pagot et al. 2025). Finally, the SFS's recognition of AC's practice of sustainable forest management indicates important implications for groundwater ecosystem services, as evidenced by the considerable overlap between common lands and officially designated water protection zones. A full correspondence was found for 34 of the Sub-Mediterranean cases and one AC in the Alpine group of common lands. Substantial correspondence (50–99%) was noted for additional eight Sub-Mediterranean and two Alpine cases respectively. Together the substantial and full correspondence accounts for 10% of cases (14% of AC area) in the Alpine and 65% of cases (72% of AC area) in the Sub-Mediterranean group. This emphasizes the importance of land management within AC areas to protect drinking water resources and sustaining groundwater ecosystem services.

4 Conclusion

The aim of our work was not to conduct a monetary evaluation of groundwater ES, but rather to emphasise their variation and significance across different units along interdisciplinary understanding of a fragile karst socio-ecological system of Primorska, increasingly characterised with shortages of water. Rather than estimating the groundwater ES itself, our analysis provides an insight into their supply side and the complex interplay of the climate change and land-use factors (Leins et al. 2025). The mGROWA model regards both factors, consequently the present study revealed key spatial and temporal patterns for the period of five decades.

In order to quantify groundwater ES, the following should be taken into consideration: firstly, comparable circumstances to our own case should be sought; secondly, the presence of karst bedrock and land cover dynamic should be taken into account as well as the productivity of forests; and finally, management intensity and fragmentation of properties along gradual or sudden changes in land cover should be taken into account.

The common lands within the observation area largely overlap with water protection zones. Therefore, this relationship warrants further investigation to assess whether the preservation of groundwater quality is influenced by the specific land-use regulations or by adherence to conservation criteria in the management of these areas. AC manage resources (e.g., water, forest) with regard to uncertainty of their provision (Ahn et al. 2024; Rendla 2024), so a risk of losing AC, as experienced in periods of suppressive administrations is not justified. Moreover, AC should be included into the decision-making process on groundwater ES as both, theory (Ostrom 2012; Ahn et al. 2024; Meinzen-Dick and Bruns 2024) and domestic knowledge on large-scale natural disturbances, reinforce the role of local inhabitants and their organization into AC (Bogataj and Krč 2023; Ravbar et al. 2023).

It is on this basis that we argue that not only groundwater ES, but also the common lands management approach deserves recognition, protection and support, aligned with international nature conservation accents (Secretariat of the … 2011; Bassi 2022; Manzoni 2024). It is imperative to prioritise the AC land management in both, in the Alpine group with higher potential of flash floods, and in the Sub-Mediterranean group due to the expected increase of droughts (Sušnik et al. 2025) and the overlapping of 78% common lands with designated water protection zones.

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