Natural Water Retention
(The East Carpathian Biosphere Reserve)

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Abstract

Effective management of ecosystem water retention requires a comprehensive understanding of landscape-scale hydrological processes and their spatial heterogeneity. This study investigates the hydric potential and runoff dynamics within selected mountain catchments of the East Carpathian Biosphere Reserve, focusing on the interplay between topography, geology, soil characteristics, and land cover. Using a combination of the Topographic Wetness Index (TWI) and the Landscape Hydric Potential (LHP) index, we assessed the spatial capacity of ecosystems to retain precipitation and mitigate surface runoff. The TWI was derived from a digital elevation model, incorporating flow accumulation and slope data while addressing slope-zero conditions to avoid computational errors. The LHP index was calculated based on a weighted integration of key environmental layers, including precipitation, evapotranspiration, geomorphology, soil infiltration capacity, bedrock hydrogeology, and land cover.

The results revealed a pronounced spatial variability in water retention potential. Areas with high TWI and excellent LHP values were predominantly associated with flat, alluvial valleys with fluvial sediments, thick soils, and forested land cover, while regions with shallow soils, steep slopes, and flysch-dominated geology exhibited low to considerably limited LHP values. These areas were also characterized by a high susceptibility to rapid runoff, and erosion processes.

Based on the LHP classification, we proposed tailored management recommendations for each category. In areas with excellent or high hydric potential, the emphasis is on conservation, biodiversity enhancement, and avoidance of land-use intensification. For average and limited categories, adaptive measures such as erosion control, slope stabilization, and afforestation with native species are recommended. Considerably limited areas, often prone to landslides and shallow infiltration capacity, require highly restrictive management including geotechnical assessments, careful planning of infrastructure, and the exclusion of agricultural intensification or water-retention interventions that could exacerbate slope instability.

Our findings highlight the importance of integrating hydrological modelling with spatially explicit environmental data to guide evidence-based landscape planning. The study underscores that while water retention is a critical ecosystem service, it must be context-sensitive, particularly in areas where increased soil moisture could lead to irreversible landscape degradation.

Figures and tables

Preface

Natural water retention is a key element for sustainable water resource management, especially in ecologically sensitive and hydrologically dynamic areas such as the East Carpathian Biosphere Reserve. This report aims to provide a comprehensive understanding of the mechanisms of natural water retention in this region, analyze the influence of geological, soil and vegetation factors, and identify challenges and opportunities for effective water management.

The East Carpathian Biosphere Reserve (ECBR - Fig.1) is a transboundary protected area spanning Poland, Slovakia, and Ukraine. It is renowned for its high biodiversity, unique landscape mosaics, and significant ecosystem services, including natural water retention. However, scientific research and environmental monitoring across this tri-national region face substantial challenges due to disparities in data availability and accessibility, especially concerning the Ukrainian segment of the reserve.

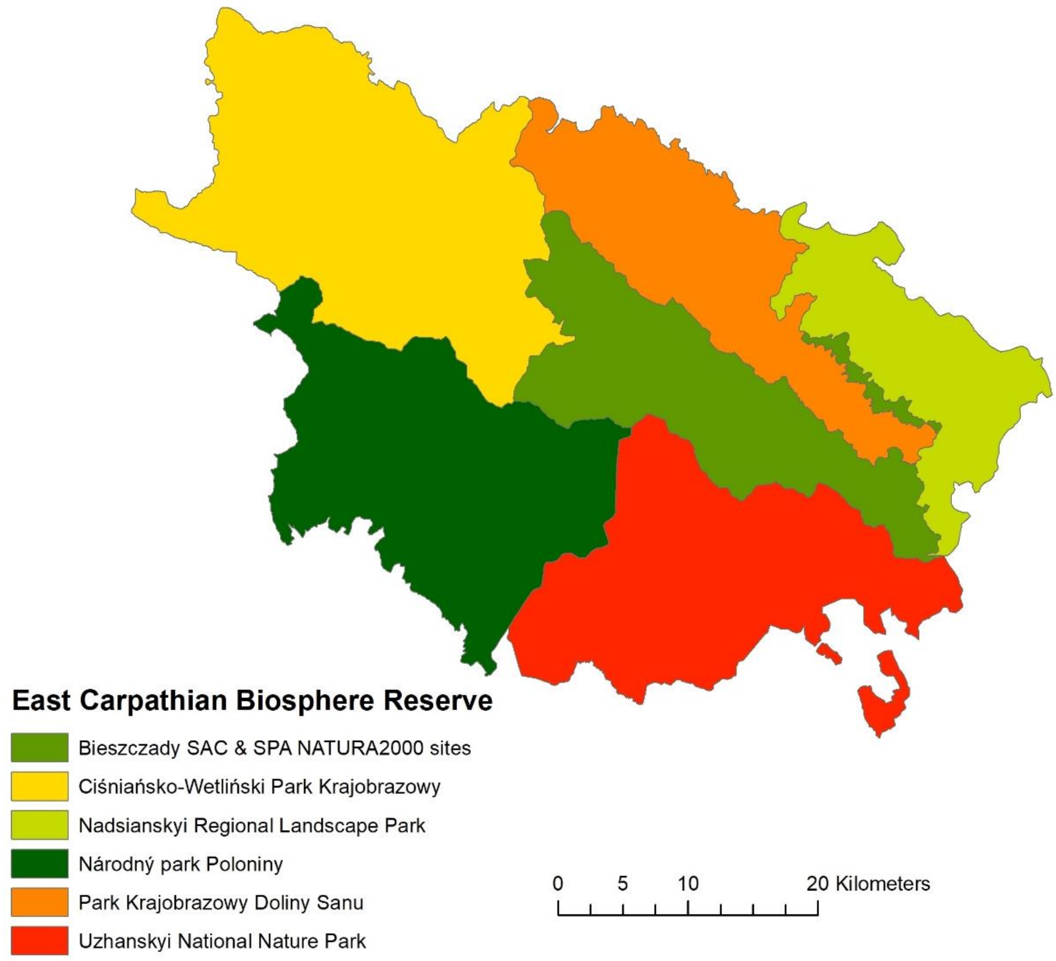

Fig. 1 East Carpathian Biosphere Reserve

A critical limitation in cross-border environmental research arises from the uneven distribution and accessibility of geospatial and ecological datasets. While Poland and Slovakia generally maintain relatively comprehensive and openly accessible environmental databases—ranging from high-resolution remote sensing imagery, detailed land use/land cover maps, to hydrological and soil datasets—the Ukrainian territory exhibits a pronounced scarcity of such open-source and standardized data. Several factors contribute to this deficiency, including historical constraints, institutional fragmentation, limited digitization efforts, and restrictions on data sharing policies with Ukraine.

The paucity of accessible, high-quality datasets for the Ukrainian part of the ECBR creates several scientific and practical implications:

1. **Reduced analytical recision:** The absence of detailed, consistent data limits the capacity to conduct fine-scale spatial analyses and to accurately model ecological processes natural water retention. Consequently, modelling outcomes for the Ukrainian area often rely on coarser, outdated, or indirect proxies, diminishing the reliability of cross-border comparative studies.

2. **Imbalanced cross-border comparisons:** Due to disparate data resolution and quality, research results often demonstrate an inherent bias favouring the Polish and Slovak territories. This leads to an uneven representation of ecological conditions and management needs, complicating efforts for integrated conservation planning and natural resource management across the entire reserve.

3. **Impediments to ecosystem service assessment:** Natural water retention—a key ecosystem service in the ECBR—is highly sensitive to spatial heterogeneity in soil properties, land cover, and topography. Limited Ukrainian data curtails comprehensive assessment of this service at the regional scale, hindering the formulation of effective transboundary water management policies in the context of climate change adaptation.

To mitigate these issues, concerted efforts are required to harmonize data collection methodologies and promote open data initiatives involving Ukrainian institutions. Advances in remote sensing technologies, including freely available satellite imagery and global digital elevation models, can partially compensate for ground data gaps. Furthermore, international cooperation frameworks and capacity-building programs are essential to improve data infrastructure, enhance digital literacy, and foster transparent data sharing agreements within Ukraine.

In conclusion, addressing the lack of accessible and standardized datasets in the Ukrainian part of the East Carpathian Biosphere Reserve is critical for improving the quality, consistency, and applicability of scientific research. This will enable more equitable cross-border environmental assessments, inform sustainable management of natural resources, and support the long-term conservation of this valuable transboundary ecosystem.

1. Introduction

Why is the infiltration and retention of atmospheric precipitation important? How does it contribute to improving runoff processes and the quality of water resources? The answers must be sought in the fundamental principles of the water regime of the geological environment—through which pathways precipitation enters the soil, the hydrogeological environment, how long water is retained within ecosystems, how much of it runs off on the surface, how much evaporates, and how much infiltrates into the soil and rock layers. In hydrology, retention is understood as the natural or artificial (typically short-term) holding of water in the landscape (ecosystem). This water may be temporarily stored in various components of the landscape—vegetation, surface humus, soil profile, streambed—or through technical measures and infrastructure such as reservoirs, polders, etc. The infiltration of precipitation and its subsequent retention are critical factors in slowing down runoff from the land and transforming peak and flood flows. By enabling infiltration and retention, we reduce immediate flood discharges while extending the duration of elevated flows, which results in longer and more regular water supply for consumers. This is undoubtedly true but represents only a partial answer to the question posed at the beginning of this section. It focuses solely on the quantity of water. We must also talk about the quality, as well as the availability and spatio-temporal distribution of water resources. Accelerated runoff due to reduced water retention in the landscape affects flow rates, the incidence of droughts (both hydrological and agricultural), and the groundwater table. Rapid runoff also intensifies soil erosion, alters sediment regimes, and ultimately degrades the quality of surface waters (streams, reservoirs) by increasing dissolved and suspended substances, as well as subsurface waters, which are contaminated by nutrients and xenobiotics leached from the soil profile. Since the mid-20th century, generations of water managers, farmers, and foresters have been trained, who could—and should—have approached land and natural resource management in a comprehensive way. In the context of water retention, this means caring for the retention and accumulation functions of the landscape. Yet the outcomes are visible today: solutions to key water-related problems (floods, drought, soil erosion, and water pollution) continue to be addressed in isolation.

Natural water retention in the landscape is a key process underpinning hydrological stability, ecological resilience, and water security. It reflects the capacity of ecosystems and landforms to intercept, infiltrate, and temporarily store precipitation before it contributes to runoff or groundwater recharge. This function is not uniform across regions—it is shaped by a complex interplay of natural landscape attributes and land use patterns. In the following section of this report, I will focus on the specific influence of selected landscape and ecosystem attributes on precipitation retention. The goal is to identify and describe the mechanisms through which various natural and anthropogenic factors contribute to, or undermine, the retention function of the landscape. This approach will provide a foundation for evaluating the water retention potential and implications for the water retention management.

2. Landscape and ecosystem determinants of natural water retention

2.1 Precipitation and evapotranspiration as key climatic drivers of water retention

Water retention in terrestrial ecosystems is fundamentally influenced by climatic conditions, with precipitation and evapotranspiration representing the two primary fluxes that control the input and output of water in the soil-vegetation-atmosphere system. Their magnitude, temporal distribution, and spatial variability determine the overall water balance, affect hydrological processes at multiple scales, and shape the ecosystem's capacity to retain and regulate water. Precipitation is the principal mechanism through which atmospheric moisture is transferred to the Earth's surface. It includes all forms of water, liquid or solid, that fall from the atmosphere—such as rain, snow, sleet, and hail. From a hydrological perspective, the amount, frequency, intensity, and seasonal distribution of precipitation are critical in determining the quantity and variability of water available for infiltration, surface runoff, groundwater recharge, and storage within soils and vegetation.

Precipitation regimes are highly influenced by regional climatic patterns (e.g. Atlantic, continental, or Mediterranean influences in Europe), orographic effects, and atmospheric circulation systems. In mountainous and forested areas such as the Carpathians, precipitation can vary markedly over short distances due to elevation gradients and microclimatic factors. Interannual and seasonal variability in precipitation plays a decisive role in the recharge of soil moisture and aquifers. Extended dry periods (meteorological droughts) reduce infiltration and retention potential, while high-intensity events often exceed the infiltration capacity of soils, leading to increased surface runoff, soil erosion, and flash floods. Evapotranspiration (ET) encompasses the sum of water vapor flux from two processes: evaporation, which refers to the physical loss of water from soil, water bodies, and wet surfaces; and transpiration, which involves the biological release of water vapor by plants through stomata during photosynthesis. Together, these processes represent the dominant form of water loss from the terrestrial system, especially during the vegetation period. Evapotranspiration is a complex function of multiple climatic variables, including solar radiation, air temperature, relative humidity, wind speed, and the vapor pressure gradient between the plant/soil surface and the atmosphere. The magnitude of ET also depends on land cover, vegetation type, leaf area index (LAI), root depth, and soil moisture availability. In temperate climates, potential evapotranspiration (PET) can exceed precipitation during the summer months, especially under conditions of prolonged high temperatures and low humidity. This creates a climatic water deficit, which reduces the amount of water retained in the soil and subsoil layers and can lead to agricultural and ecological droughts.

Furthermore, climate change is expected to intensify both precipitation extremes and evapotranspiration demand. Rising temperatures, shifting vegetation phenology, and increased frequency of heatwaves may enhance atmospheric water demand and alter the seasonal water balance—potentially reducing natural water retention capacities, particularly in ecosystems already vulnerable to water stress. The dynamic balance between precipitation and evapotranspiration defines the climatic water balance and exerts a direct control on the water available for retention in ecosystems. In regions where precipitation consistently exceeds evapotranspiration, surplus water contributes to infiltration, groundwater recharge, and streamflow. Conversely, when evapotranspiration exceeds precipitation, retention capacities decline, soils desiccate, and ecosystems become more susceptible to hydrological stress.

Understanding the spatial and temporal interactions between these two key climatic variables is thus essential for evaluating the water retention function of landscapes, assessing the resilience of ecosystems under climate variability, and guiding land and water management strategies aimed at sustaining hydrological services.

In this study to estimate the spatial diversity of the climatic characteristics we used monthly climate data (precipitation and potential evapotranspiration) from the WorldClim database (Fick and Hijmans, 2017). The temporal coverage of the dataset: 2018. Annual precipitation in the Carpathians varies significantly depending on altitude and/or orographic conditions. In some depression areas, total annual precipitation may reach less than 600 mm. However, in mountainous areas, precipitation increases significantly, with annual totals exceeding 1500 mm (Mostowik et al. 2019). When assessing the moisture balance in the ECBR, it is appropriate to also take into account the total evapotranspiration, the average annual totals of which rarely exceed 500 mm.r^{-1} (mostly in the range of 400-450 mm.r^{-1}).

The streams in the area – such as the Cirocha, Uzh, San and their tributaries – have a Carpathian regime with a spring maximum (melting snow) and a secondary summer maximum (precipitation). The area is sensitive to torrential rains, which cause a sudden increase in discharges – the so-called "flash floods". The short delay time of precipitation-runoff is related to the slope of the slopes, low soil retention capacity and flysch subsoil. The streams are predominantly 1st and 2nd order, with significant fluctuations in discharges. In the alluvial zones, occasional inundation occurs, especially in the San and Cirocha valleys, which creates favorable conditions for natural retention in the floodplains.

2.2 Geological and hydrogeological factors and water retention

The retention space in the soil and rock environment is difficult to detect with the naked eye, but it is crucial for water retention. Keeping water in the three-dimensional space of the landscape is a key need, especially in conditions of climate change. It follows that understanding the movement of water in the area from atmospheric precipitation, through hypodermic and underground runoff to water drainage into surface runoff in any of its forms must be perceived as one common set of events, even if this set consists of a different number or significance of individual events in different parts of the basin. The occurrence of subsurface water is one of the important elements of this set, and because subsurface runoff is, among other things, a function of the geological structure and hydrogeological characteristics of the area, we dedicate a separate article to it.

The geological structure of the East Carpathian Biosphere Reserve has a fundamental impact on hydrological processes, including infiltration, groundwater accumulation, and runoff dynamics. From the point of view of geological (tectonic) conditions, the ECBR extends almost exclusively on the flyschoid rocks of the Magura nappe, the Dukla tectonic unit, the Predukla tectonic unit, the Silesian tectonic unit and the Podsilesia tectonic unit (Haczewski et al. 2007; Jankowski & Margielwski 2021).

Lithologically, medium to thick-bedded sandstones predominate, often alternating with less permeable claystones. The area also contains softer marls, conglomerates and carbonate intrusions, which are less significant. The flysch complex has a tectonically complex structure – in the form of thrust nappes, with frequent zones of subsidence and fractures. This structure significantly affects the movement of water and its accumulation – especially in fractures and between permeable sandstone horizons. These rocks are characterized by high mechanical disintegration, which causes slope instability, landslides and erosion processes, which significantly affects water retention in the soil and in the wider landscape.

The above-mentioned tectonic units are almost entirely formed by flysch, sequences of sandstone and shale layers. Flysch aquifers are generally fed by periodic springs with low flow rates. These rocks are characterized by low storage capacity (typically less than 6% porosity) and low hydraulic conductivity (1.4×10^{-6} to 2.4×10^{-7} $m\cdot s^{-1}$). Water flow in these aquifers occurs primarily through fracture or fracture-pore systems. The combination of steep slopes and low retention capacity of the subsoil, together with a dense drainage network, limits groundwater accumulation and promotes rapid surface runoff.

Attributes of hydrogeological characteristics were chosen according to the level of aquifer productivity. Aquifer productivity describes the potential of an aquifer (a bedrock or superficial deposit unit that contains significant amounts of groundwater) to sustain various levels of groundwater flow (O Dochartaigh, et al., 2011). Aquifer productivity is the ability of a bedrock to release (produce) under certain mutually comparable conditions, gravitational groundwater due to the effect of a hydraulic gradient. A direct indicator (quantitative characteristic) of this ability is the transmissivity coefficient. In this study, the International Hydrogeological Map of Europe 1:1,500,00 – IHME1500 (BGR, 2015) was used as a base to calculate aquifer productivity. The temporal coverage of the IHME1500 dataset: 2019. Locally aquiferous rocks, porous or fissured is the dominating hydrogeological aquifer class, in the floodplains of more significant streams are situated low and moderately productive porous aquifers – Fig. 2 (BGR, 2015).

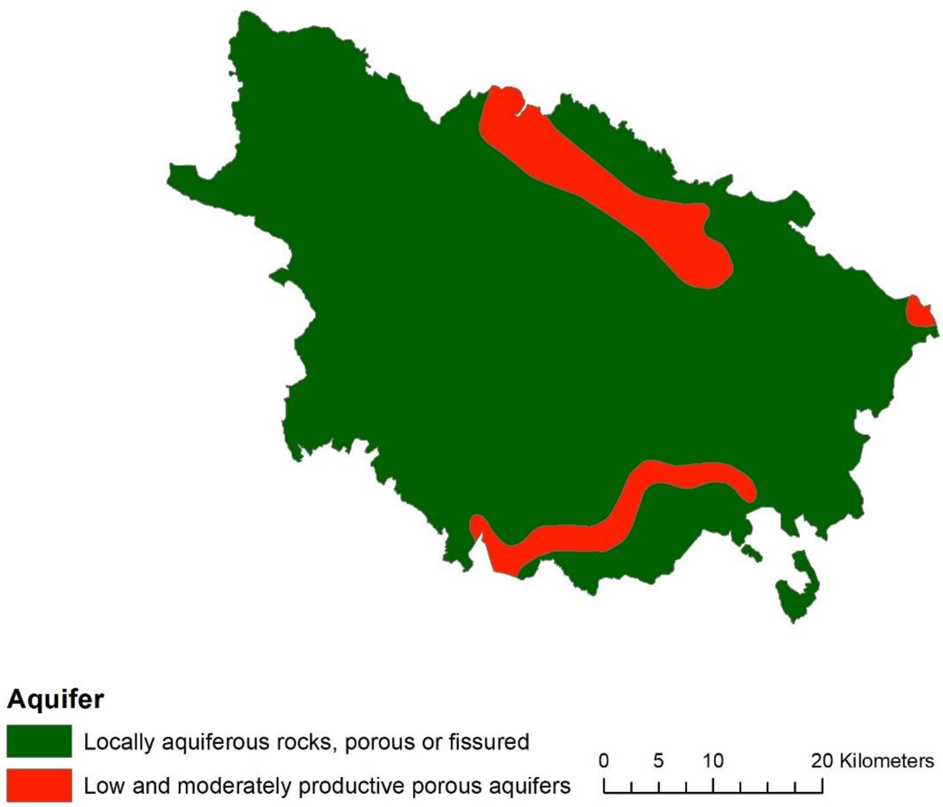

Fig. 2 Aquifer types of the ECBR

2.3 Soil and hydropedological characteristics

The amount of water in the soil-weathering layer and its spatiotemporal distribution depend on the ability of the soil to absorb precipitation, retain it in its space and on the movement of soil water. Infiltrated precipitation water is the most important source of subsurface water. Knowledge and understanding of the infiltration-influx and retention capacity of the soil is a key prerequisite for rational use of the landscape and proposals for revitalization measures. Each soil in its space is exposed to a certain load - most often perceived as the effect of negative processes such as soil disturbance and erosion, its redeposition, accelerated humus mineralization, compaction, loss of nutrients, etc. Once a certain limit is exceeded, some soil properties such as thickness, porosity, bulk density, grain size, biological properties may change (deteriorate). In extreme cases, soil loss occurs, or. the formation of the so-called abandoned soils, when the soil abruptly returns to the initial stages of development. Anthropogenic pressure on the soil environment is growing and leads to intensive changes, in order of importance, erosion, pedocompaction, contamination, acidification and debasification.

Good condition of the soil layer is a guarantee of lower costs for overcoming the consequences of weather - heavy rainfall, drought episodes with a projection into a more favorable hydric effect of soils. It is favorably manifested in the preservation of the quantity, quality, availability and temporal and spatial distribution of water resources. The development of weather in recent years has become increasingly extreme and the role of soils will be increasingly important in dampening flood waves, surface runoff, but also in dampening the manifestations of meteorological drought in forest ecosystems, agroecosystems as well as the entire country.

Light skeletal soils (sandy, gravelly, stony) with a low content of humus and organic matter dry out faster and to a greater extent, and conversely, they become wet slower and to a lesser extent. This is mainly related to the capillary rise of water from the groundwater level to a smaller extent of reduction processes in compact larger grains of primary minerals, to a greater loss of water through evaporation, etc. The infiltration of precipitation atmospheric water into the soil is unproblematic due to the high permeability of the soil mass. Reduction-oxidation zones do not form in the soil. Heavy soils with a higher content of organic matter and humus dry out slower and become wet faster. More extensive reduction processes of chemical compounds in the colloidal state occur more easily, and the large volumetric capacity of organic matter (peat, humolite) for water is also significant. Due to their high binding capacity and lower macroporosity, clay soils have lower evaporation rates, which is also the cause of their greater waterlogging.

The precipitation retention possibility of soils depends particularly on soil type and on the amount of humus contained in it (Charman and Murphy, 1998). A direct indicator of soil water retention depending on the soil type is saturated water content. To estimate the saturated water content, we used the Soil Hydraulic Properties map of the European Soil Data Center - *ESDAC SHP* (ESDAC SHP, 2016; Tóth and Weynants, 2016). The temporal coverage of the *ESDAC SHP* dataset: 2016. Due to the saturated water content according to Tóth and Weynants (2016), soil types were categorized into three groups: low (< 0.40 cm^3/cm^3), moderate (0.40 – 0.50 cm^3/cm^3), and high (> 0.50 cm^3/cm^3). Within the ECBR were developed soil types with high saturated water content.

The intensity of precipitation infiltration into the soil depends particularly on soil texture (Zachar, 1982; Leeper, Uren, 1993). To estimate the attribute of soil texture we used the European Soil Database v2.0 – *ESDB* (ESDB, 2004; Panagos, 2006). The temporal coverage of the *ESDB* dataset: 2022. The soil texture values were estimated taking into account hydrological soil groups (Hong and Adler, 2008; Ross et al., 2018), soil texture, and soil infiltration rate triangles (Berhanu et al., 2013, United States Department of Agriculture, 2017). In the ECBD dominate loams and sandy clay-loams. The slope covers are mainly silty-clayey, which determined the dominant geomorphic processes such as mass movements, gully erosion, soil piping, and tree uprooting (Rączkowska et al. 2012).

2.4 Geomorphological conditions and runoff processes

The study area is characterized by structural relief (Haczewski et al. 2007; Gorczyca et al. 2016). The main ridges are relatively narrow and elongated, running from NW towards SE (Fig. 3). They have developed in the relatively resistant sandstones, whereas valleys are cut into less resistant rocks, predominantly shales and mudstones (Henkiel 1982; Haczewski et al. 2007). The height of the ridges increases towards the SE up to 1300 m asl, with the highest peak of Mt. Tarnica (1346 m asl). Also, the altitude of valley bottoms rises in the same direction. Relative altitudes are up to 700 m, resulting from considerable incision by rivers, facilitated by the intensive uplift of the ECBR territory. Slope inclination is one of the most important geomorphological factors influencing infiltration intensity and detention of precipitation. An increase in the slope inclination leads to an increase in surface runoff, diminishing the capacity to retain water in the environment and reducing the intensity of its infiltration. Categories of slope inclinations were determined based on the curve of dependence between surface run-off intensity and slope inclination (Midriak, 1988; Lepeška, 2010). To estimate the spatial diversity of the geomorphological conditions attribute we used the Copernicus Digital Elevation Model for Europe – *Copernicus EU-DEM* (Neteler et al., 2022). The temporal coverage of the *Copernicus EU-DEM* dataset: 2022. Within the model territory of ECBR dominate slopes with 0-7° inclination and 7.1-18° inclination. Steeper parts of slopes are also common and are concentrated mainly in areas with large vertical relief dissection. These slopes are concentrated in the deeper incised valleys of the headwaters of watercourses (Fig.3).

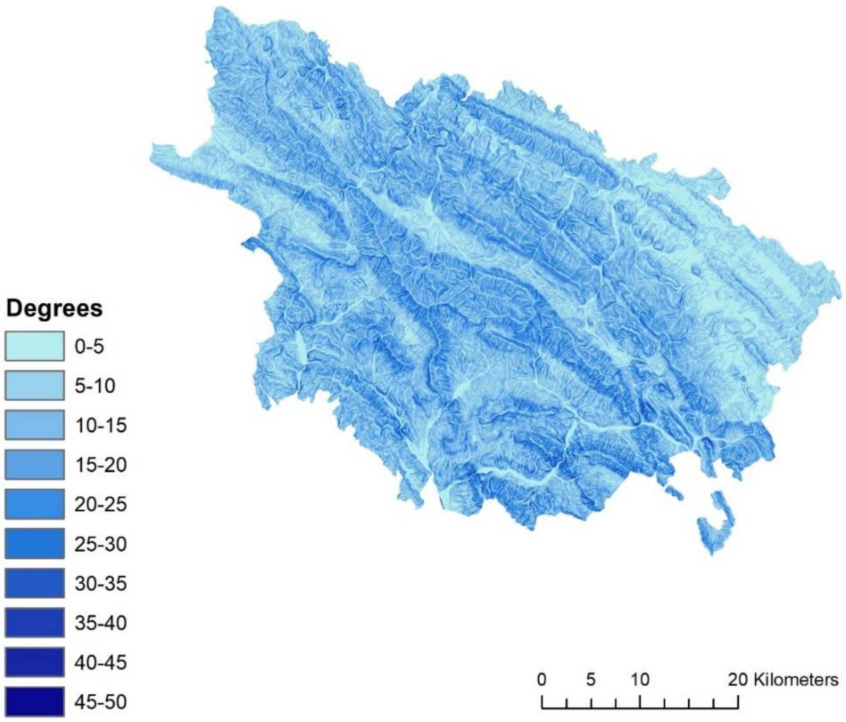

Fig.3 Geomorphological conditions of the ECBR

The flysch formations of the Eastern Carpathians, composed of rhythmic alternations of permeable sandstones and impermeable or semi-permeable claystones and shales, represent one of the most erosion- and landslide-prone geological settings in Central and Eastern Europe. The combination of steep topography, high precipitation totals, and lithological contrasts contributes to the frequent occurrence of both surface erosion and deep-seated slope deformations.

Surface erosion is particularly intense in deforested or poorly vegetated areas, such as pastures and logged forest clearings, where direct raindrop impact and overland flow mobilize fine soil particles. Rill and gully erosion often develop along compacted paths or forest roads lacking drainage infrastructure, leading to rapid degradation of the topsoil and increased sediment transport downstream.

More critically, the flysch structure is predisposed to slope instability due to the presence of impermeable claystone layers that act as slip planes once saturated. Water accumulation above these layers increases pore water pressure and reduces shear strength, ultimately triggering translational or rotational landslides. These mass movements vary in scale from shallow soil slips to complex, multi-phase landslides that may involve significant volumes of bedrock and regolith.

Landslides in flysch terrains are frequently reactivated by prolonged rainfall, snowmelt, or anthropogenic interventions such as forest road construction and drainage alteration. Numerous examples across the region—including the Poloniny Mountains, Uzhanskyi National Nature Park, and the Solinka and/or the San River Valley—demonstrate the geomorphic and hydrological importance of landslides as both hazards and hydrological features.

2.5 Land cover and land use

The ability of individual types of landscape to infiltrate and retain rainwater depends, in addition to the above-mentioned components or properties of the natural environment, also on the method and intensity of its use by humans. Activities related to individual types of landscape use affect, for example, the composition of the vegetation cover, the character of the landscape surface, the density of soils (agricultural mechanisms, tourism, grazing of livestock) and thus the ability to infiltration and retention of atmospheric precipitation. We decided to divide the landscape of ECBR according to the prevailing basic classes of landscape cover into urban landscape (residential landscape, infrastructure, etc.), agricultural landscape (arable land, meadows and pastures, orchards, vineyards, etc.) and forest areas.

A significant part of the urban landscape is built up with buildings, roads, parking lots, squares, etc. Compared to natural (natural) catchments, they are characterized by a high area of areas with impermeable surfaces, which largely affect ecohydrological processes in the settlement landscape. As a result of soil sealing with impermeable surfaces, infiltration and disruption of natural ecological links are reduced or completely suppressed. The infiltration of precipitation (especially intense) into the soil can significantly extend the time that elapses before this water reaches rivers, thereby reducing the size of the maximum flow and reducing the risk of floods. However, this means that the greater the proportion of impermeable surfaces in the catchment, the greater the proportion of rainwater that reaches the recipient as direct runoff. This leads to an acceleration of the runoff process, an increase in maximum flow rates and increased sediment transport. The settlement landscape in the ECBR territory does not constitute a large proportion of land cover. It is mostly distributed chaotically, clustering mainly around the Uz, Yablunka and Rika rivers, or their tributaries.

Non-forest landscape ecosystems have mostly human-influenced hydrological efficiency. The reduced ability of individual types of non-forest landscape to infiltrate rainwater compared to forest stands also depends on the smaller proportion of humus in the soil. Increasing thickness of overlying humus, the intensity of precipitation infiltration increases and surface runoff decreases. A layer of overlying humus about 6 cm thick is sufficient to completely eliminate surface runoff (Midriak 1988).

Many authors have addressed the issue of the influence of non-forest vegetation on the infiltration and retention of atmospheric precipitation in the soil environment. Their research has mostly related to the anti-erosion effect of individual agricultural crops. All research shows that cultivated, annual plants protect the soil less perfectly than plants in natural, permanent communities. This is mainly due to poorer infiltration and retention of fallen atmospheric precipitation and less developed above-ground and underground biomass. Therefore, in accordance with the works of the above-mentioned authors, we can say that in terms of individual types of vegetation cover and their relationship to the hydrological efficiency of the active surface, the descending order of efficiency applies: forest → transitional forest scrub → permanent grassland → forage crops → cereals → root crops → bare field. In the ECBR area, non-forest landscape ecosystems consist mainly of unirrigated fields, transitional forest scrub, and mowed, but especially grazed meadows.

The absolutely dominant component of the ECBR landscape is forest ecosystem. In addition to production forests, forests also consist of remnants of the largest European complexes beech and fir-beech virgin forest (Kricsfalusy et al. 2010) as well as mountain meadows supporting a rich biodiversity including rare and endangered species. Precipitation first falls on the surface of the trees, gradually falling on the surface of the vegetation of the lower layers and on the soil surface, where it also flows down the tree trunks. Part of the precipitation captured on the surface of the plants evaporates (interception), the rest reaches the soil surface together with water flowing down the trunks or falling through gaps in the crown canopy. On the soil surface, in small depressions, the water is partially retained, as a result of which surface accumulation occurs, later it seeps into the soil or flows down the soil surface. The water that gradually seeps into the forest soil creates soil water reserves there. Forest ecosystems have a demonstrable impact on a) protection of water recipients from transport and deposition of sediments, b) accumulation and retention of precipitation, c) local effect on the extent and occurrence of flood situations, d) impact on water quality (reduces the proportion of solids in water, affects chemistry and improves bacterial purity of water, e) regulation of runoff from the basin and water content of watercourses (transformation of surface runoff into underground; damping of flood waves, retardation), f) impact of the forest on the formation of horizontal precipitation (growths from 800 m above sea level enrich the amount of precipitation by 250-300 mm per year with horizontal precipitation – non-deciduous conifer stands capture the most horizontal precipitation) and, g) impact of the forest on water evaporation (desuction function).

3. Methods

The methodology employed in this study focuses on a geospatial analysis of hydrological processes, integrating two key indices: the Topographic Wetness Index (TWI) and the Landscape Hydric Potential (LHP) index. These methods were selected for their ability to provide complementary insights into the distribution and dynamics of water across the landscape, crucial for understanding and modelling hydric conditions within the study area.

These two methods, when used in conjunction, allow for a robust analysis of the spatial variability in water availability and saturation, which is critical for the understanding the role of ecosystem attributes in hydrology dynamics and for the adequate management measures. The subsequent sections will detail the specific data sources, processing steps, and analytical techniques employed for the calculation and interpretation of TWI and LHP within the context of this research.

3.1 Topographic Wetness Index

The Topographic Wetness Index, also known as the Compound Topographic Index (CTI), is a steady-state wetness index that quantifies the tendency of a given terrain to accumulate water. It is derived from topography and is calculated as:

$$TWI = \ln(\alpha/\tan\beta), \qquad (1)$$

where:

α - the specific upslope contributing area per unit contour length, and $\tan\beta$ - the local topographic slope.

High TWI values indicate areas prone to water accumulation, such as valleys and depressions, while low values suggest drier, more elevated areas. TWI has been widely applied in hydrological modelling, soil moisture mapping, and ecological studies due to its effectiveness in representing hydrological connectivity and the spatial distribution of soil moisture patterns at various scales (e.g., Beven & Kirkby, 1979; Sørensen et al., 2006). Its strength lies in its physically-based derivation, making it a robust indicator of hydrological processes influenced by topography.

3.2 Landscape Hydric Potential index

The LHP index is a concept of the practical application of GIS tools for the water management. The word “hydric” refers to the combined influence of the environmental attributes of the landscape on retention, infiltration, accumulation, retardation, flow regulation, water quality, and snow accumulation. The method allows to describe the ability of the environment to slow down the runoff, by increasing precipitation retention and the capability of the water to infiltrate into the ground. It presents the cumulative impact of all significant environmental attributes on the amount, quality, accessibility as well as spatial and temporal distribution of water. The methodology for LHP index calculation has been described in detail by Lepeška (2010), Lepeška et al. (2017), Wojkowski et al. (2019), Wałęga et al. (2020), Wojkowski et al. (2022), and Wojkowski et al. (2023). The value of the LHP index can be determined from the following equation:

$$LHP = 1.5\,H + 2.5\,St + 3.0\,Ss + 4.0\,CWB + 3.0\,Si + 3.5\,F + 2.0\,N \qquad (2)$$

where:

H – the attributes of hydrogeological conditions,
St – the attributes of soil types,
Ss – the attributes of soil textures,
CWB – the attributes of climatic conditions, Si – the attributes of geomorphological conditions,
F – the attributes of the hydric effect of forest stands, and N – the attributes of the non-forest landscape.

Landscape Hydric Potential provides a more holistic assessment of hydric conditions by incorporating multiple environmental factors beyond just topography. The LHP aims to capture the overall capacity of a landscape to retain and supply water, reflecting the interplay of climatic, edaphic, and biological factors that influence the water balance. This multi-criteria approach allows for a nuanced understanding of hydric potential, accounting for both supply and demand side of water availability within the ecosystem. The combination of TWI, which highlights topographic control on water accumulation, and LHP, which provides a broader ecological and climatic context, offers a comprehensive framework for characterizing the hydric regime of the study area and for investigating the spatial patterns of water availability.

4. Results

4.1 Topographic Wetness Index

To facilitate the spatial interpretation of surface wetness potential and water retention capacity in the East Carpathian Biosphere Reserve, the Topographic Wetness Index was calculated and subsequently reclassified into five equal-interval categories. The continuous TWI raster, originally ranging from 0 to 26.25, was divided into five classes using equal interval thresholds of approximately 5.25 units. This approach enables a consistent comparison of landscape positions based on their relative hydrological behaviour and potential for water accumulation. The resulting TWI classification is as follows:

Tab.1 TWI classification of the ECBR

Class	TWI Range	Description	Hydrological Interpretation
1	0.00 – 5.25	Very low wetness	Convex landforms, ridges, steep upper slopes
2	5.25 – 10.50	Low wetness	Well-drained slopes with limited accumulation
3	10.50 – 15.75	Moderate wetness	Middle slopes, transitional zones
4	15.75 – 21.00	High wetness	Lower slopes, footslopes, shallow depressions
5	21.00 – 26.25	Very high wetness	Valley bottoms, depressions, potential wetland zones

This classification highlights zones with increased potential for water retention, surface saturation, and subsurface flow convergence. Higher TWI values (classes 4 and 5) are typically associated with areas of lower slope gradient and higher upslope contributing area, thus indicating zones suitable for hydrological conservation measures, wetland restoration, and retention-based land use planning. Conversely, lower TWI values (classes 1 and 2) represent areas with steep slopes and minimal upslope input, which are typically well-drained and less prone to water accumulation. These zones may be more susceptible to surface runoff and erosion, especially on flysch bedrock common in the region. The TWI classification serves as a crucial input for identifying spatial hydrological patterns and guiding land use and ecosystem-based management strategies in both forested and non-forested subregions of the East Carpathian Biosphere Reserve.

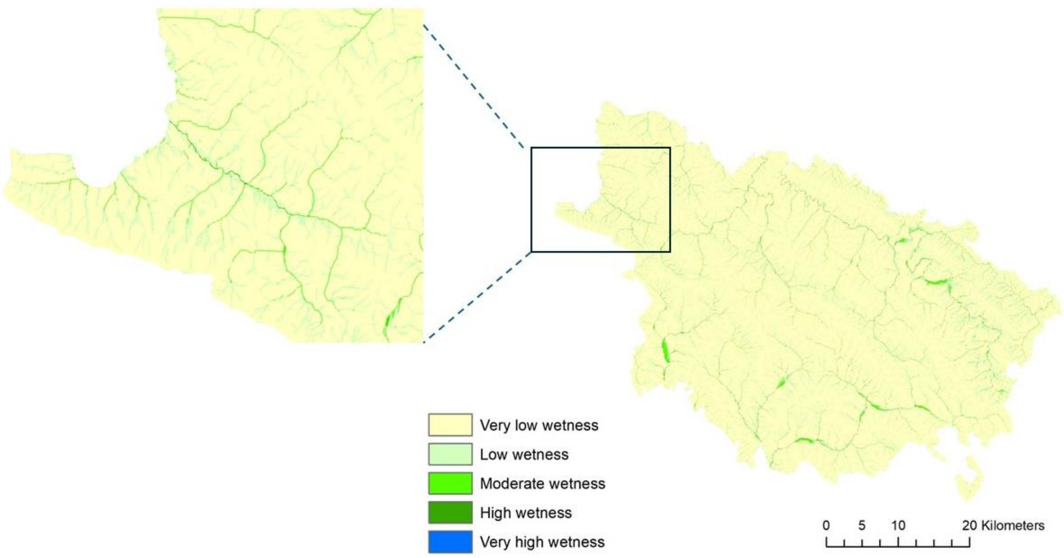

Fig. 4 TWI categories across the ECBR

The reclassified Topographic Wetness Index revealed a strong predominance of dry to moderately dry terrain in the study area. Category 1 (very low TWI), which represents steep slopes and convex terrain with minimal accumulation potential, covers approximately 1,850.88 km^2, accounting for 88.6% of the total area. Category 2, interpreted as moderately drained slopes, constitutes 9.9% of the area. Categories 3 and 4, which correspond to increasingly convergent terrain with moderate to high wetness potential, together account for only 1.55%. The highest wetness class (Category 5), often associated with valley bottoms or depressions, occupies a negligible proportion of the landscape (0.03 km^2, or 0.002%), likely reflecting the geomorphological and geological structure of the Carpathian flysch landscape, where broad saturated zones are scarce.

4.2 Landscape Hydric Potential index

The spatial diversity of the LHP index in Europe is presented in Fig. 5. Due to uneven distribution of open-source and standardized data we present spatial distribution of LHP index only from part of the ECBR.

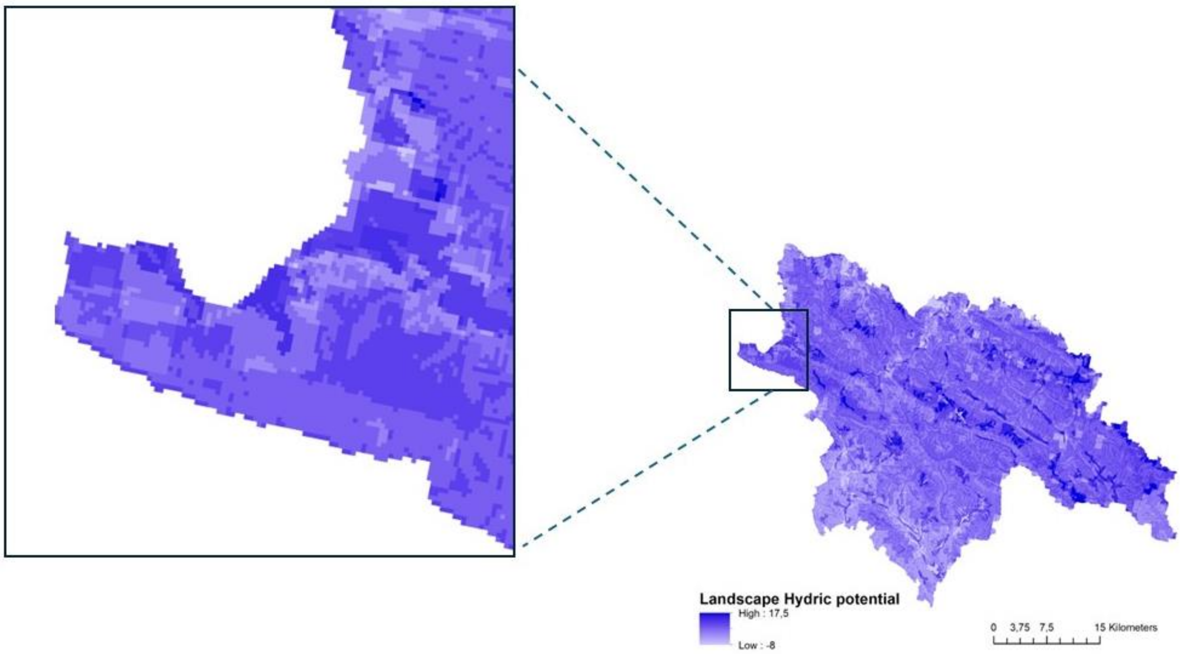

Fig. 5 Spatial distribution of Landscape Hydric Potential index in Polish and Slovak part of the ECBR

The LHP index provides a comprehensive spatial assessment of the capacity of terrestrial ecosystems to retain, store, and slowly release precipitation. It serves as a compound indicator reflecting the interaction between topography, land cover, soil characteristics, and slope-driven runoff processes. Within the East Carpathian Biosphere Reserve—a region characterized by its dynamic orography, flysch-dominated geology, and mosaics of forested and agricultural landscapes—LHP offers valuable insights into spatial heterogeneity of water retention and runoff dynamics.

Category 1 represents areas with *excellent hydric potential* (LHP ≥ 20.0). These are usually located in topographic depressions, valley bottoms, flat areas or colluvial zones where water naturally accumulates due to convergent flow conditions and minimal slope gradients. Such terrain units often possess hydromorphic soils or organic-rich layers with high porosity and water-holding capacity. The dominant hydrological process here is accumulation, leading to reduced surface runoff and increased infiltration. These sites frequently support wetlands, riparian zones, or hygrophilous meadows, and they play a critical ecological role in regulating local microclimates, buffering flood events, and providing habitat continuity. From a management perspective, these zones should be prioritized for conservation and ecological restoration. Anthropogenic modifications such as drainage or land conversion can significantly compromise their hydrological and ecological integrity. Areas within this category of LHP are rather scarce, stochastically distributed and have only a negligible proportion of the total area of the ECBR. Their significance is mainly local.

Category 2, classified as having *high hydric potential* (LHP between 10.0 and 19.9), comprises terrain with favourable water retention characteristics, albeit to a lesser extent than Category 1. These areas are often situated in concave lower hillslopes, shallow basins, or forested plateaus. They are typically associated with well-structured, relatively permeable soils and vegetation that facilitates both interception and infiltration. Although less prone to saturation/water retention than Category 1, they still exhibit reduced overland flow and can function as buffer zones within the hydrological network. Their role in supporting baseflow maintenance, and soil moisture regulation is significant. In terms of land use planning, they are well-suited for low-intensity forestry, traditional agroforestry systems, or managed grasslands with soil structure conservation practices. Within the Polish and Slovak part of the ECBR this category occupies 245.64 km^2.

Category 3, corresponding to *average hydric potential* (LHP between 0.1 and 9.9), denotes areas where the hydrological behaviour is relatively balanced, with neither dominant retention nor excessive runoff. These zones often lie on moderate slopes with variable soil depths and mixed land cover. They exhibit a transitional behaviour where hydrological functioning is sensitive to land management and seasonal changes. Under natural vegetation cover, such areas may support intermittent infiltration and delayed runoff. However, under altered land use or degraded cover, they may shift toward more erosive responses. Therefore, sustainable land management in these zones—such as conservation tillage, vegetated buffer strips, or rotational grazing—is essential to maintain their hydric function and prevent degradation. Areas with average hydric potential cover 1, 206.08 km^2 within the Polish and Slovak part of the ECBR.

Category 4, representing *limited hydric potential* (LHP between -10.0 and 0.0), includes terrain units where water retention is significantly constrained by topographic steepness, soil shallowness and compaction, reduced vegetative cover and/or impervious (artificial) surfaces. Hydrologically, they function predominantly as runoff-generating areas, especially during intense precipitation events. The limited infiltration and high runoff rates increase the risk of surface erosion, rill formation, and downslope sediment transport. From a geomorphological perspective, these zones contribute disproportionately to catchment sediment yield. Land use in such areas should therefore be managed with caution, favouring erosion mitigation strategies, controlled grazing, and vegetation reinforcement. Within the researched territory localities with limited hydric potential are situated particularly in urbanised environments and are part of forest road network. Although their area within the ECBR is 30.82 km^2 they can be responsible for adverse effects of runoff process at local to regional scale due their effect on soil infiltration capacity reduction, leading to increased surface runoff and altered flow paths. Forest roads often function as artificial drainage corridors, rapidly collecting and redirecting precipitation and hillslope water, thereby disrupting natural hydrological connectivity.

Category 5, denoting *considerably limited hydric potential* (LHP ≤ -10.1), encompasses the most hydrologically unfavourable environments within the landscape. These include steep, convex slopes, degraded lands, and areas with compacted soils or impervious (artificial) surfaces, where infiltration is minimal and overland flow dominates. The geomorphological setting of these zones predisposes them to accelerated erosion processes, including sheet erosion, gullying, and in some cases, shallow landsliding. Their contribution to downstream flood peaks and sediment loads is significant. These areas often coincide with disturbed or intensively used lands and require targeted interventions such as afforestation, terracing, slope stabilization, or exclusion from intensive land use. Long-term strategies for these zones should aim to reduce surface runoff and enhance soil-water interactions through nature-based solutions. Areas within this category of LHP are rather scarce, stochastically distributed and have only a negligible proportion of the total area of the ECBR.

5. From data to decisions: Toward improved landscape management

The spatial distribution of the Landscape Hydric Potential (LHP) reflects the complex interplay of environmental attributes, including precipitation, evapotranspiration, geomorphological conditions, soil properties, hydrogeological features of the bedrock, and land cover. These factors critically determine the hydric functioning of ecosystems. Varying levels of LHP influence the type and intensity of landscape management measures that should be applied. This variability is context-dependent and shaped by both constant factors (e.g., bedrock composition) and dynamic variables (e.g., seasonal or spatial fluctuations in soil saturation) within specific river catchments. The heterogeneity in the spatial distribution and quality of LHP highlights the significant influence of land cover and land use—particularly in terms of type and intensity—on the hydrological functioning of ecosystems within the East Carpathian Biosphere Reserve. Among all ecosystem attributes, land use represents the most direct human intervention, and thus, has a decisive impact on LHP. Numerous studies have shown that changes in land use and land cover can considerably reduce flood peaks in catchments (Viola et al., 2014), especially in areas where surface runoff is generated rapidly (Naef et al., 2002). Therefore, water and river basin managers, as well as decision-makers, should focus on improving the ability of ecosystems to retain and infiltrate precipitation. Key priorities should include optimizing land-use structure, sustainable natural resource management, regulating existing and planned human activities, and promoting landscape and river corridor restoration and renaturalization.

In forested landscapes, forest management regimes should be reclassified from production-focused groups to categories with primary water regulation or soil protection functions (Lepeška, 2013). In areas where timber harvesting is prescribed, a sensitive approach should be adopted—especially in harvesting, transportation, and storage of timber (Midriak et al. 1988). Stand regeneration should favour site-adapted native species. Natural disturbances create heterogeneity in otherwise continuous forest stands, contributing to age, species, and structural diversity, which ultimately enhances ecological stability (Holling, 1992; Spies, 1997) and therefore anthropogenic interventions in such areas should be at the level of minimal to zero management. It is crucial to avoid the development of dense forest road networks, which increase surface runoff and fragmentation (Wemple & Jones, 2003). Biodiversity conservation is key to supporting ecosystem functionality, especially regulatory services (Balvanera et al., 2006). In this context, it is recommended to retain a higher amount of coarse woody debris (CWD), which increases surface roughness, slows surface runoff (Bilby & Bisson, 1998), and extends infiltration time. CWD enhances the hydrological efficiency of forest ecosystems, buffers microclimatic extremes, serves as an important water reservoir during dry periods (Harmon et al., 1986), and protects the soil's productive functions (Brown et al., 2007). However, research shows that European forests still have insufficient levels of woody debris (Christensen et al., 2005).

A significant portion of the non-forested area in the ECBR consists of arable land, often arranged in a fine-grained patchwork of fields. Evidence from various agricultural catchments confirms that improved crop cultivation and tillage practices increase baseflow (Price, 2011). The use of cover crops during the off-season and conservation tillage significantly reduce surface runoff (Evrard et al., 2010). Grass buffer strips established along field margins enhance reinfiltration and reduce net soil loss (Ali & Reineking, 2016). In combination, improved cultivation practices and conservation techniques can significantly reduce peak flows and sediment loads (Evrard et al., 2010). It is therefore recommended to reevaluate crop rotations and include species that enrich soil organic matter (e.g., red clover, alfalfa; Charman & Murphy, 1998), and implement soil conservation techniques (Montgomery, 2007). These measures contribute to long-term soil health, increase landscape retention potential, and support sustainable water management at the catchment scale.

Management recommendations based on the LHP classification in the East Carpathian Biosphere Reserve

The classification of the landscape into categories based on the LHP provides a powerful framework for designing spatially explicit management strategies. In the context of the East Carpathian Biosphere Reserve—an ecologically sensitive and hydrologically dynamic region—tailored recommendations for each LHP category can support water retention, prevent land degradation, and enhance climate resilience. The following section outlines detailed management approaches for each LHP class, addressing both forested and non-forested land.

Category 1 – Excellent Hydric Potential (LHP ≥ 20.0)

Areas with excellent hydric potential are strategic zones of hydrological accumulation and ecosystem service provisioning. These often include wetlands, riparian meadows, peatlands, and alluvial valleys with saturated soils, high organic matter content, and frequent groundwater interactions. Management in these zones should emphasize strict protection and ecological conservation protection of existing wetlands and riparian zones, and ecological restoration where disturbance has occurred. Minimize any anthropogenic interventions.

Category 2 – High Hydric Potential (LHP 10.0–19.9)

Terrains in this class represent crucial buffer zones that mediate water retention and slow runoff from upslope areas. Characterized by moderate slopes and high infiltration capacity, they support soil moisture stability. Management should focus on enhancing natural processes of infiltration and retention. In forested areas, sustainable silviculture practices such as selective thinning, deadwood retention, and minimal-soil-impact logging are recommended. Maintaining continuous forest cover with high canopy interception contributes to long-term hydrological stability. Generally, the main ideas in forest ecosystems should be the preservation of old forests, especially virgin forests and natural beech forests, forest restoration by natural succession or planting of mixed stands, prohibition/restriction of logging on slopes with high TWI and/or low LHP index. Current steps should be the revision of forest roads and bridges, support of close-to-nature management (FSC). In non-forested or cultural landscapes, traditional agroforestry systems (if present), rotational pasture use, and permanent grasslands with deep-rooted vegetation are optimal. Soil compaction should be avoided through grazing control and regulated access. Restoration measures may include the re-establishment of vegetative buffer zones and contour-based agroecological practices. These zones can in future also serve as targets for payments for ecosystem services schemes focused on watershed management.

Category 3 – Average Hydric Potential (LHP 0.1–9.9)

Areas classified as having average hydric potential represent transitional landscape zones that possess moderately balanced infiltration and runoff characteristics. These areas are commonly located on gently undulating terrain or mid-slope positions, where soil depth, texture, and structure offer partial water retention capacity but remain sensitive to anthropogenic disturbance. While these zones are not always highly prone to rapid runoff or erosion, their hydrological balance can shift significantly in response to extreme precipitation, inappropriate land use, compaction, or vegetation loss. In forested areas, management should emphasize the maintenance of forest structure and canopy integrity. Selective thinning, rather than clear-cutting, is recommended to maintain soil protection while allowing for forest productivity. The retention of coarse woody debris is encouraged due to its positive influence on surface roughness, infiltration time, and soil microclimate regulation. Forest regeneration should prioritize native, site-adapted species, and mechanical operations should avoid periods of high soil moisture to prevent compaction. In agricultural and grassland areas, it is advisable to implement conservation tillage, cover cropping, and rotational grazing systems to reduce runoff and enhance soil water retention. Buffer strips, grassed waterways, and vegetative field margins play a crucial role in intercepting overland flow and promoting infiltration. Deep-rooted crops and leguminous species that improve soil organic matter should be favoured, alongside practices that minimize bare soil exposure, especially during high rainfall periods. At the landscape scale, introducing heterogeneous land use mosaics, such as agroforestry elements, can bolster ecological resilience. Implementation of contour farming, vegetated swales, and small-scale retention structures (e.g., infiltration trenches or check dams) can further mitigate flow accumulation and reduce peak discharge.

Category 4 – Limited Hydric Potential (LHP -10.0 to 0.0)

Zones with limited hydric potential are characterized by constrained water retention capacity, commonly resulting from a combination of steep slopes, shallow and skeletal soils, and impermeable surfaces or bedrock (flysch formations). These areas exhibit rapid hydrological response to precipitation events, with high surface runoff generation, minimal infiltration, and elevated susceptibility to soil erosion and mass movement. Their role in contributing to catchment-scale peak flows and sediment transport makes them critical targets for erosion control and slope stabilization measures.

In forested terrain, management must be focused on the preservation of continuous vegetative cover to ensure root cohesion and slope stability. Forest management operations should be highly limited and, where unavoidable, conducted only during winter months using low-impact harvesting techniques. Natural regeneration should be supported, but in degraded or unstable sites, assisted afforestation with site-specific, stress-tolerant species may be necessary. Forest interventions must also aim to minimize disturbance to the forest floor, particularly in shallow soils prone to slippage. In non-forested or degraded zones, the implementation of strict land use regulation is essential. Intensive agricultural cultivation is generally discouraged due to the high erosion risk, while extensive grazing may be conditionally permitted only in conjunction with anti-erosion agricultural techniques. Restoration of these areas should involve reforestation, hydroseeding with deep-rooted grasses, and, where necessary, the use of geotextile stabilization to prevent surface detachment and gullying. Moreover, infrastructure development and intensive recreational activities should be strictly avoided in these zones due to their slope instability and limited retention capacity. Land managers and planners should prioritize natural rehabilitation, erosion-proofing, and protection of existing vegetation in such zones to reduce downstream impacts and maintain catchment-scale hydrological functionality.

Category 5 – Considerably Limited Hydric Potential (LHP ≤ -10.1)

This class includes the most hydrologically unfavourable and geomorphologically hazardous zones. Very steep slopes, poor soil structure, and minimal infiltration lead to high surface runoff and erosion risks, often manifesting as sheet erosion, gully formation, or shallow landslides. Such conditions are common on convex ridgelines, deforested slopes, or anthropogenically disturbed zones. These areas require urgent remedial measures and strict exclusion from intensive use. In forested landscapes, ecological restoration should include afforestation with deep-rooting, soil-stabilizing species, application of biological erosion control, and engineering stabilization (e.g., fascines, crib walls) where necessary. In cases of active slope failure, geotechnical assessment is required before any intervention.

In open landscapes, slope recontouring, revegetation, and controlled exclusion of livestock are fundamental. Cultivation and construction must be strictly prohibited. These zones are best integrated into catchment-wide conservation plans and considered as "no-intervention". Effective management of landscapes characterized by low or limited hydric potential—particularly those in Category 4 and Category 5—requires a nuanced, interdisciplinary approach that integrates geological, ecological, and socio-economic factors. Several overarching principles should guide all interventions in these sensitive areas.

First and foremost, any significant land-use change or engineering intervention in these zones should be preceded by a comprehensive geotechnical assessment. The widespread presence of flysch bedrock, with its characteristic layering and variable permeability, necessitates a detailed understanding of substrate stability, hydrological conductivity, and landslide susceptibility. Such assessments form the foundation for informed decisions related to slope stabilization, construction, and vegetation planning.

Cross-cutting considerations for sustainable landscape management in low retention zones

Equally important is the protection of water quality. The steep slopes and erosion-prone soils in flysch-dominated terrains contribute to increased sediment transport and pollutant loading in downstream aquatic systems. Therefore, all management interventions—whether reforestation, erosion control, or land-use regulation—must be designed with the explicit objective of improving or maintaining water quality through enhanced infiltration and minimized surface runoff. The use of native, locally adapted plant species is critical in all revegetation and afforestation activities. These species are inherently better suited to local soil, hydrological, and climatic conditions, exhibit greater resistance to drought and pests, and contribute to the conservation of regional biodiversity. Their inclusion strengthens ecological resilience and improves long-term restoration outcomes. An often overlooked but essential component of sustainable management is community engagement. Involving local stakeholders in the planning, design, and implementation of landscape interventions fosters a sense of ownership, ensures alignment with local knowledge and needs, and enhances long-term effectiveness and maintenance. Participatory approaches can bridge the gap between scientific recommendations and practical, culturally appropriate implementation.

Furthermore, climate change resilience must be a central criterion in the design of all strategies. Anticipated shifts in precipitation regimes—including more frequent intense rainfall events and prolonged dry periods—pose significant risks to hydrologically sensitive landscapes. Interventions should therefore aim to enhance soil moisture retention, reduce runoff peaks, and increase vegetation buffer capacity, thereby building adaptive capacity at both local and catchment scales. Finally, it is essential to adopt a holistic, integrated approach to landscape management. The boundaries between LHP categories are not absolute, and hydrological processes function across spatial scales. Management actions in one zone inevitably influence adjacent or downstream areas. As such, interventions should be conceived and implemented within a landscape-scale framework, balancing ecological function, water regulation, and land use demands in a coordinated manner.

While enhancing water retention in ecosystems is widely recognized as a key strategy for mitigating hydrological extremes and improving landscape resilience, it is crucial to acknowledge the limitations of such interventions in geomorphologically sensitive areas. In particular, zones prone to landslides, slope instability, and shallow soil profiles - often associated with flysch formations or other structurally weak bedrock - present significant risks when subjected to prolonged or excessive soil moisture. Intentional retention or infiltration-enhancing measures in these regions may inadvertently raise the groundwater table or increase soil saturation, thereby reducing shear strength and amplifying the potential for mass movement events, including debris flows, earth slides, and rotational failures. In such contexts, the abiotic components of the ecosystem, especially substrate stability, pore water pressure dynamics, and slope hydrology, become critical limiting factors. Chronic or acute increases in moisture availability can lead to irreversible geomorphic changes, including the disintegration of soil structure, vegetation dieback due to root anoxia, and the permanent loss of productive or protective land functions. Therefore, landscape-scale water retention strategies must be carefully tailored to local geotechnical and hydrological conditions, and in high-risk zones, a precautionary principle should guide any intervention.

Conclusions

The assessment of Landscape Hydric Potential index, supported by the Topographic Wetness Index, reveals distinct spatial patterns of water retention capacity across the East Carpathian Biosphere Reserve. These patterns are shaped by an interplay of abiotic and biotic factors—most notably terrain morphology, soil depth and texture, land cover types, and bedrock permeability. The integration of TWI and LHP enables not only the identification of retention hotspots but also the delineation of areas where hydrological function is limited or severely constrained.

The study confirms that ecosystem-based water retention is most effective in areas with moderate to high LHP, where topography, soil infiltration capacity, and vegetation structure support gradual runoff, soil water storage, and baseflow maintenance. In such areas, nature-based solutions like reforestation, wetland restoration, contour farming, and green infrastructure can significantly enhance water retention and mitigate flood risks.

Key recommendations include:

- Land-use zoning based on LHP: Guiding forestry, agriculture, and infrastructure planning in line with retention capacity.
- Forest management adapted to hydrological function: Maintaining canopy cover, reducing road density, and preserving coarse woody debris in high-gradient forests.
- Sustainable agricultural practices: Promoting cover crops, conservation tillage, and buffer strips in areas with moderate LHP to increase infiltration and soil organic matter.
- Integrated catchment-scale planning: Recognizing that interventions in high-LHP zones can reduce downstream peak flows and sediment transport.
- Climate resilience: Ensuring that management actions consider projected changes in precipitation regimes and extreme events.

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