JEE Journal of Ecological Engineering

Journal of Ecological Engineering 2023, 24(11), 321–329
https://doi.org/10.12911/22998993/171652
ISSN 2299–8993, License CC-BY 4.0

Received: 2023.08.12
Accepted: 2023.08.31
Published: 2023.09.15

Impact of Mountain Grassland Management on Groundwater Recharge in the Polish Carpathians

Agnieszka Kowalczyk[1*], Andrzej Jaguś[2], Beata Grabowska-Polanowska[1]

[1] Institute of Technology and Life Sciences – National Research Institute, Falenty, Hrabska Av. 3, 09-090 Raszyn, Poland

[2] Department of Environmental Protection and Engineering, University of Bielsko-Biala, Willowa 2, 43-309 Bielsko-Biała, Poland

* Corresponding author's e-mail: a.kowalczyk@itp.edu.pl

ABSTRACT

Which modern use of grassland is the most beneficial for the protection of water resources in the Polish Carpathians is scarcely known; thus, the deep outflows from organically, extensively, semi-intensively and intensively used and unused grasslands between 2019 and 2022 were measured. The studies showed that use impacted the process of deep infiltration, but the differences were clearest between the areas where management was reduced to a minimum (lowest outflow) and the areas which were mown most often (highest outflow). No effect of fertilisation was detected. To intensify groundwater recharge, it is evidently necessary to mow vegetation twice or three times per season; more frequent mowing changed the characteristics of the vegetation in an undesirable way. The fallowing of grasslands proved to be a practice unfavourable to groundwater resources.

Keywords: mountain areas, land use, water resources protection, deep infiltration

INTRODUCTION

The use of grasslands in Poland is one of the elements of the Common Agricultural Policy of the European Union. The ratio of the area of meadows and pastures to the total area of cultivated land has been set for Poland at 18.33% (Polish legal system, ID: M.P.2023.279). This value cannot be reduced by more than 5% of 18.33, so grasslands need to be cared for, especially in the mountains, where arable farming is too costly and can also pose a threat to natural resources [Jaguś, 2021].

Mountain grasslands perform the functions that are important for the environment and the human economy, such as protecting soils from erosion, enhancing biodiversity as well as providing cheap and natural feed for livestock [Krajčovič et al., 2001; Zhu and Zhu, 2012; Loucougaray et al., 2015; Gil et al., 2021; Liu et al., 2023]. A particularly important function in mountainous areas is the protection of water resources, primarily because grasslands reduce runoff processes in favour of soil retention and deep infiltration and also reduce the movement of chemicals from soils into the aquatic environment [Kostuch and Kopeć, 1980; Hagyo et al., 2006; Deng and Wang, 2010; Avetisyan, 2018; Wang et al., 2022]. This deep infiltration of precipitation water (including snowmelt) is beneficial; it determines groundwater recharge, which not only slows down the outflow from catchments, preventing flood phenomena, but also reduces the occurrence of water shortages in watercourses during periods without rain [Ryffel et al., 2014; Stoffel et al., 2016].

Environmental management conducive to deep infiltration is badly needed in the Polish Carpathians [Wyżga et al., 2018], which occupy 6% of Poland's area, and produce as much as 13% of the country's water resources [Starkel, 1990]. Currently, the retention capacity of this region is small, and flows in the rivers are highly variable [Wałęga and Młyński, 2017; Jaguś, 2019], which hinders the efficient use of water resources. Due to the deficit of dam reservoir capacity in the

Polish Carpathians [Dmitruk et al., 2012], various measures are postulated to reduce runoff and erosion [Jaguś, 2021; Grzybowska-Pietras and Derbin, 2021]. The unfavourable situation can be improved, among others, by proper use of grasslands. Grasslands in the Polish Carpathians, when used, are important for increasing soil retention and deep infiltration. Kostuch and Kopeć [1980] have shown that the root system of vegetation in meadows and pastures has a strong structuring effect on soils, contributing to the water holding capacity of soils reaching up to 500 mm in a profile 1 m deep. Furthermore, these ecosystems reduce the runoff phenomena. For example, the average annual runoff in meadows can account for up to 2.4% of the precipitation [Kopeć, 1990].

The aim of the present study was to identify for the first time the influence particularly of current management practices in mountain grasslands on the amount of groundwater recharge from precipitation. On the basis of authors' own observations and interviews with farmers in 2017, the grassy areas are managed organically, extensively and semi-intensively, rarely intensively or are left as fallow land (details below); these uses in the last 10–15 years have been completely different from the past. Until the 1990s, intensive use dominated [Twardy et al., 2001], and studies on the water cycle in grassland soils were conducted under yield-stimulating conditions (i.e. the use of high doses of fertilisers), using typical fodder grass species such as *Dactylis glomerata* L. which are uncommon in the Polish Carpathians, especially in higher locations [Misztal, 2001]. At the turn of the 21st century, there was a strong trend towards reducing or even abandoning the use of meadows and pastures [Kopacz and Twardy, 2013]. At that time, the experiments were carried out without the use of any fertilisers [Jaguś and Twardy, 2006].

MATERIAL AND METHODS

Study area

The studies were conducted using the experimental infrastructure of the Institute of Technology and Life Sciences – National Research Institute (ITP-PIB) in the area of a tourist resort called Jaworki (49°24' N, 20°34' E). Geographically, the study site is located at an altitude of about 600 m above sea level, on the border of the Pieniny and the Beskid Sądecki mountain ranges. Hydrographically, it is the catchment of the Biała Woda stream, which has an area of 10.91 km^2 (Figure 1), and grasslands occupy as much as 32% of it [Kopacz et al., 2021].

Study methods

A test stand with lysimeters was used. Each lysimeter was a tank with a capacity of 1 m^3 (a cube with 1 m sides) filled with soil. It had an additional canister underneath filled with drainage aggregate to allow water to drain freely from the soil. The structure with the lysimeters was made so that the surface of the soil filling the lysimeters was level with the ground surface. In the underground section, it was possible to collect the leachate from the lysimeters, which flowed into plastic canisters (Figure 2). The lysimeters were filled with local soil, preserving the natural layout of the soil profile. This soil is characterised by a grain size of sandy clay loam in the top layer and sandy loam in the deeper layers. The field water capacity of the soil, or

Figure 1. Research location – the Biała Woda catchment in the Polish Carpathians based on cartographic database BDOT10k (https://www.geoportal.gov.pl/)

Figure 2. Above-ground and underground part of the experimental structure with the lysimeters (photo by Jaguś & Kowalczyk)

more precisely of the soil profile 1 m deep, was 329.5 mm, while the amount of usable water was 160.4 mm [Misztal, 2000]. Lysimeters are not adapted to the studies conducted where there is a groundwater table and this was the case in the present location and is the case of the Polish Carpathians in general.

The soil filling the lysimeters was sodded with a mixture of grasses characteristic of the Carpathian areas in southern Poland, which were: *Festuca rubra* L. (10%), *Festuca pratensis* Huds. (10%), *Phleum pratense* L. (10%), *Lolium x boucheanum* Kunth L. (10%), *Lolium perenne* L. 'Grasslands' (10%), *Lolium perenne* L. 'Solen' (15%), *Lolium multiflorum* L. 'Mowestra' (10%), *Lolium multiflorum* L. 'Tuetetra' (25%). The mixture was sown in the spring of 2018, with additional reseeding in the spring of 2019.

A total of 24 lysimeters were sodded and used in eight ways (n=3 replicates per way) between 2019 and 2022 (measurements were taken from April to October); the eight surfaces are described in Table 1.

The amount of precipitation (mm) was measured at a meteorological station, owned by ITP-PIB, operating in the vicinity of the structure with lysimeters. Measurements were recorded each day by an ITP-PIB employee using a Hellmann rain gauge.

A standardised rainfall anomaly index (SRA) was calculated for each study season (April-October) using the formula by Agnew and Chappell [1999]:

$$SRA = \frac{Ps - Psav}{SD} \quad (1)$$

where: *Ps* – precipitation in the April-October season; *Psav* – average precipitation in the April-October season from the multi-year period; *SD* – standard deviation of precipitation in the April-October season from the multi-year period

To calculate *SRA*, the precipitation data from the meteorological station during 1993–2022 (30 years) were used. The different study seasons of 2019–2022 were classified in terms of precipitation conditions using the appropriate scale [Agnew and Chappell, 1999; Marelign, 2020]: extremely wet, very wet, moderately wet, near normal, moderate drought, severe drought, extreme drought.

The amount of water leaching from the soils was measured irregularly, depending on the filling level of the canisters, with a mandatory measurement after the end of each month. The measurement consisted of pouring water from the canisters into a calibrated bucket. The quantity

Table 1. The use of experimental surfaces.

Type of grassland [livestock unit (LU) per hectare]	Mowing	Fertilizer per hectare
1. Organic meadow	first after 15 June second before 30 September	not fertilized
2. Extensive meadow	once in the first half of July	60 kg N (early spring) 40 kg P_2O_5 (autumn) 50 kg K_2O (autumn)
3. Extensive meadow	first after 15 June second before 30 September	60 kg N (early spring) 40 kg P_2O_5 (autumn) 50 kg K_2O (autumn)
4. Semi-intensive meadow	first before 15 June second before 15 August	60 kg N (early spring) 60 kg N (after first mowing) 50 kg P_2O_5 (autumn) 80 kg K_2O (autumn)
5. Intensive meadow	first before 31 May second before 31 July third before 20 September	80 kg N (early spring) 80 kg N (after first mowing) 60 kg P_2O_5 (autumn) 120 kg K_2O (autumn)
6. Simulated extensive pasture [LU=0.5]	first before 31 May second before 30 June third before 31 July fourth before 15 September	15 kg N (early spring) 30 kg N (after first mowing) 30 kg P_2O_5 (autumn) 40 kg K_2O (autumn)
7. Simulated semi-intensive pasture [LU=1.5]	first before 31 May second before 30 June third before 31 July fourth before 15 September	40 kg N (early spring) 40 kg N (after first mowing) 40 kg N (after second mowing) 40 kg P_2O_5 (autumn) 60 kg K_2O (autumn)
8. Sodded unused area	not mowed	not fertilized

in dm^3 was recorded, which corresponded to the quantity in mm for the lysimeters used. This is due to the surface area of each lysimeter, equal to 1 m^2 (1 $dm^3 \cdot m^{-2}$ = 1 mm). Therefore, in the remainder of this paper, outflow is given in mm (for each surface with n = 3).

A Pearson correlation analysis was first carried out between monthly precipitation and outflow values. Then, deep outflows were analysed. A linear model with interaction of the two variables was used to examine the variation of outflows over time (study seasons 2019, 2020, 2021, 2022) and between ways of use (1–8). The normality of the distribution within groups (among years and ways of use) was checked using the Shapiro-Wilk test. Pairwise comparisons between the ways of use were made with the Dunn-Šidák correction for multiple comparisons.

RESULTS

The precipitation varied between the months of the study seasons (Figure 3). The precipitation totals from April to October in the consecutive study seasons were as follows: 598.3 mm (2019), 848.1 mm (2020), 647.3 mm (2021), 461.7 mm (2022), while the total for the same months from the 1993–2022 multi-year period was 722.1 mm (SD = 177.3). The following SRA values were obtained for the consecutive study seasons: -0.70 (2019), 0.71 (2020), -0.42 (2021), -1.47 (2022). On this basis, the study seasons of 2019, 2020 and 2021 can be classified as ‘near normal’, while the last season can be classified as ‘severe drought’.

The monthly outflows from soil profiles varied in each successive study season and were as follows: 0.3–91.9 mm (2019), 3.4–152.6 mm (2020), 1.3–81.9 mm (2021), 0.1–32.5 mm (2022). In the two study seasons (2019–2020), a significant correlation was found between precipitation and outflows. A positive correlation ($r > 0.5$) also occurred in the third study season, but was not statistically significant. In the fourth drought season, the precipitation – outflow relationship was not found (Table 2).

Analysing the effect of land use on deep outflow on a monthly basis is problematic due to

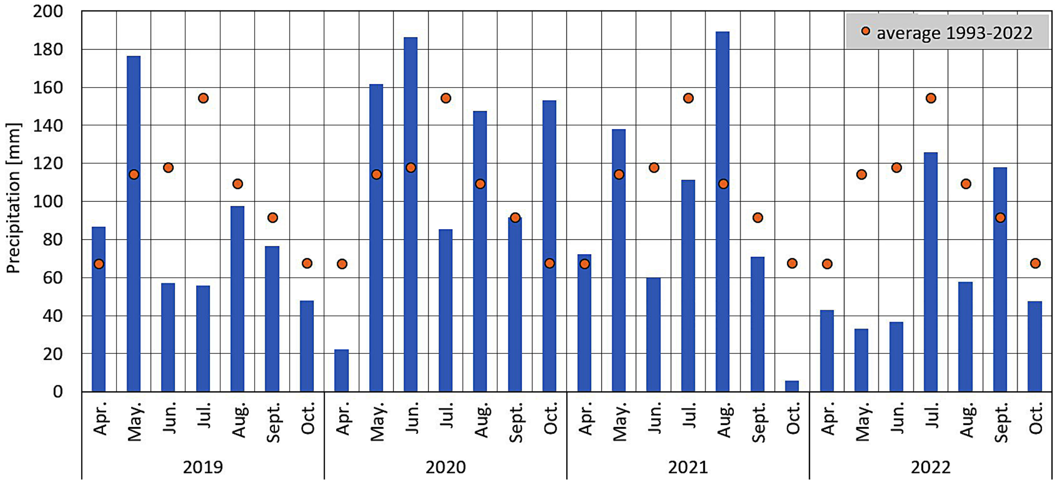

Figure 3. Precipitation in the area of the experiment site

Table 2. Pearson's r-correlation coefficients between monthly precipitation and outflow (statistically significant values for p = 0.05 and n - 2 = 5 are in bold)

Research season	Surface							
	1	2	3	4	5	6	7	8
Apr.-Oct. 2019	**0.83**	**0.88**	**0.84**	**0.79**	**0.86**	**0.87**	**0.87**	**0.87**
Apr.-Oct. 2020	**0.87**	**0.86**	**0.85**	**0.87**	**0.89**	**0.87**	**0.87**	**0.85**
Apr.-Oct. 2021	0.61	0.53	0.58	0.58	0.61	0.70	0.67	0.54
Apr.-Oct. 2022	-0.19	-0.33	-0.25	-0.22	-0.13	-0.01	-0.01	-0.19

the different timing of mowing and fertilisation of the surfaces. It is easy to observe that for the precipitation that occurred just before mowing, the infiltration capacity is different from that for the precipitation that occurred just after mowing. Therefore, the analysis of groundwater recharge according to use is more readable for the entire study seasons from April to October.

The seasonal outflows from soil profiles in the consecutive years were as follows: 152.2–195.2 mm (2019), 395.6–485.0 mm (2020), 211.9–268.4 mm (2021), 40.5–79.0 mm (2022) (Table 3). In 2019–2021 (normal precipitation conditions), it was found that the least water drained from surfaces 2 and 8, and the most water drained from surfaces 6 and 7. In the last year (drought), the least water drained from surface 2, about 40 mm, and the outflows from the other surfaces were about 60–80 mm. A varying proportion of precipitation, expressed by the outflow coefficient in the range of 0.000–1.000, was subject to deep infiltration (Table 3). In the first year of the studies, about 25–30% of precipitation was subject to outflow, in the second year about 50%, in the third year about 30–40%, and during the drought a dozen or so% with the exception of surface 2, from which precipitation outflow was less than 9%.

Table 3. Seasonal deep outflow (the average of three replicates) and outflow coefficient for individual ways of use (1–8)

Research season	1	2	3	4	5	6	7	8
	Deep outflow [mm] / Outflow coefficient							
Apr.-Oct. 2019	164.8 / 0.275	152.5 / 0.255	170.0 / 0.284	179.6 / 0.300	169.5 / 0.283	189.1 / 0.316	195.2 / 0.326	154.7 / 0.259
Apr.-Oct. 2020	422.8 / 0.499	396.6 / 0.468	415.5 / 0.490	440.3 / 0.519	423.3 / 0.499	448.1 / 0.528	485.0 / 0.572	395.6 / 0.466
Apr.-Oct. 2021	262.5 / 0.406	211.9 / 0.327	244.1 / 0.377	239.6 / 0.370	240.3 / 0.371	258.8 / 0.400	268.4 / 0.415	214.6 / 0.332
Apr.-Oct. 2022	62.2 / 0.135	40.5 / 0.088	58.9 / 0.128	79.0 / 0.171	77.0 / 0.167	76.1 / 0.165	78.0 / 0.169	68.4 / 0.148

The statistical analysis showed variation in outflows between study seasons (years) and ways of use. The problem of variation between ways of use is of particular interest (Figure 4). Pairwise comparisons showed differences found for the following pairs of surfaces: 2 – 4, 2 – 6, 2 – 7, 3 – 7, 6 – 8, 7 – 8. The differences concerned mainly surfaces 2 and 8 which were distinguished by the lowest outflow values, and surface 7, for which the outflow from the soil profile was the highest.

DISCUSSION

Experiments with the use of lysimeters are dominated by qualitative analyses of leachates [Soltysiak and Rakoczy, 2019]. The authors approached the issue of outflow quantitatively in an effort to help understanding of soil water balance and water circulation.

The research by Misztal [1988] shows that within the grasslands in the Polish Carpathians, water infiltrating through the soil to a depth of more than 1 m participates practically entirely (at least 95%) in the groundwater recharge. It is therefore justified to conduct research on deep infiltration using lysimeters with a depth of 1 m. In addition, the results of lysimetric studies can be referred to larger areas, as shown by measurements of drainage fields outflow and mathematical modelling [Kopeć and Misztal, 1981; Misztal, 2001]. However, it is worth noting that the infiltration process depends on many geographical factors, e.g. precipitation parameters, grain size and soil structure [e.g. Wegehenkel and Gerke, 2015; Zupanc et al., 2020]; therefore, the values of outflow coefficients calculated on the basis of experimental studies should be related to the geographical region where the research was conducted.

The present research has demonstrated that the amount of deep outflow was primarily shaped by the amount of precipitation – abundant precipitation caused a continuous process of deep infiltration. In the dry year, there was no correlation found between precipitation and outflow – the soil was often over-dried, so it happened that precipitation, if it did occur, was entirely retained in the soil profile and no water was found in the canisters under the lysimeters.

When undertaking the experimental works, it was expected that the fertiliser doses would have an effect on the deep outflow, or more specifically, with a higher fertiliser dose, the outflow would be lower due to the fertiliser stimulating plant growth and therefore higher water consumption. Such a hypothesis was adopted on the basis of the studies conducted by Misztal [1999, 2001], who recorded the decreasing values of outflow coefficients while increasing the dose of nitrogen fertiliser (from 120 to 360 kg N per hectare). The works have not confirmed this hypothesis. An example is the comparison of outflows from the organic meadow mowed twice (unfertilised) and the extensive meadow mowed twice (60 kg N). These outflows were mostly very similar. The second example is the comparison of outflows from the extensive meadow mowed twice (60 kg N) and the semi-intensive meadow mowed twice (120 kg N). The outflows from the semi-intensive meadow were most often similar or slightly higher. A similar situation was found in the extensive pasture mowed 4 times (45 kg

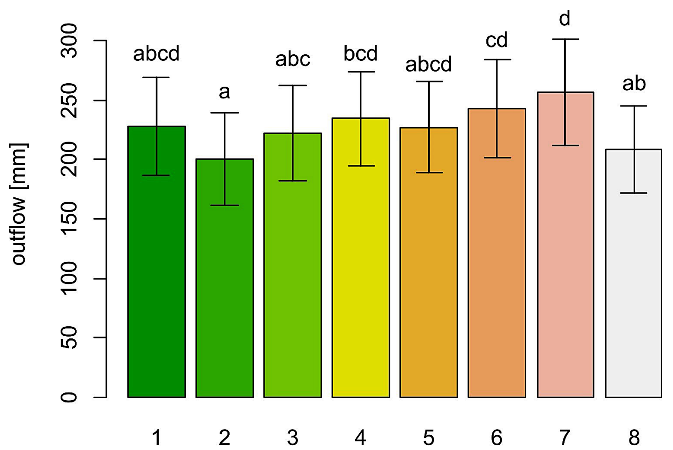

Figure 4. The comparison of outflows (average ±SD) between surfaces (1-8); bars with the same letter (a, b, c, d) do not differ statistically

N) and the semi-intensive pasture mowed 4 times (120 kg N). The unconfirmed effect of fertilisation on deep infiltration (research novelty) may result from the use of moderate doses of fertilisers in the experiment, corresponding to modern agricultural practice. Such doses probably do not affect the water consumption of mountain grassland vegetation.

Mowing can be considered as a differentiating factor for deep outflow. The lowest groundwater recharge was recorded in the extensive meadow that was mown once and in the unused (unmown) surface. The reasons for this situation could be as follows: 1) part of the precipitation was subject to interception on the lush and tall vegetation without reaching the soil; 2) the large total plant surface generated high transpiration; 3) water uptake by the root system was not disturbed by mowing which is a stress factor for plants. Studies have shown that intensification of groundwater supply requires mowing at least twice a season, which primarily facilitates the access of rainwater to the soil surface.

The highest deep outflows occurred within the simulated pastures mowed 4 times, but under conditions of such frequent mowing, a reduction in the density of plant growth was additionally observed, with more and more dicotyledonous plants displacing grass species. In the final phase of the research, the areas mowed 4 times were found to be dominated by: *Plantago lanceolata* L., *Sonchus arvensis* L., *Alchemilla pastoralis* Bus., *Geranium pratense* L., *Achillea millefolium* L., *Lithospermum arvense* L., *Filipendula ulmaria* (L.) Maxim., *Linaria vulgaris* Mill., *Rumex acetosella* L., *Cardamine pratensis* L. and *Agropyron repens* L. According to Klapp [1962], too frequent mowing reduces the fodder value of the meadow – it eliminates most tall grasses and plants that slowly accumulate reserve substances on the one hand, while on the other, stimulating the development of weeds that quickly accumulate reserve substances and plants which evade mowing by keeping their rosettes at the soil surface. The performed observations confirmed this and may be of interest to architects of turf areas, because in modern research on the ecology of grasslands, it is primarily the effect of extensive agriculture with one or two mowings per season that is analysed [e.g. Humbert et al., 2012; Szepligeti et al., 2018].

The worst environmental effects in the conducted studies were noted in the case of total abandonment of land use (fallowing). The deep infiltration process was severely limited and the vegetation was degraded. The sown grass species quickly disappeared, being replaced by *Conium maculatum* L. (a poisonous plant) and *Agropyron repens* L. The lack of mowing also resulted in the continuous accumulation of dead biomass. Literature reports [e.g. Gąsiorek and Kostuch, 2002] and practice indicate that fallow lands are characterised by fast self-forestation. In the Polish Carpathians, it is easy to observe the encroachment of pioneer herbs and shrubs (e.g. *Hypericum maculatum* Crantz, *Vaccinium myrtillus* L.), followed by expansive shrubby and woody species (e.g. *Rubus idaeus* L, *Juniperus communis* L., *Alnus incana* (L.) Moench, *Coryllus avellana* L., *Betula pendula* L.). As a result, forest biocoenoses with low biodiversity and tree stands unfavourable in terms of their species develop.

The conducted research indicates that sustainable use of grasslands contributes to the protection of water resources. It also enables maintaining the fodder function, biodiversity and landscape values of the Polish Carpathians. The use of grasslands in the Polish Carpathians is favoured by national agricultural support programmes. Farmers are encouraged to ensure a minimum stocking density on grasslands (extensive farming; livestock unit LU = 0.5) by breeding cattle, especially the Polish Red breed (traditional in this region), as well as by reinstating sheep and goat farming. The promotion of cultural sheep grazing is aimed at maintaining the biodiversity of mountain pastures and, at the same time, stopping the uncontrolled forest succession.

CONCLUSIONS

The amount of groundwater recharge depended primarily on hydrometeorological conditions. Between approximately 30% and just over 50% of precipitation was subject to deep infiltration under normal conditions. In the dry season, the outflow coefficients were below 0.2.

The manner of grassland use tended to have an impact on the deep infiltration process, but the differences in outflow were often not statistically significant. Significant variation occurred between sites where grass forage extraction was minimised and maximised. A differentiating factor for the deep infiltration was the frequency of vegetation mowing. No effect of fertilisation was found.

Reducing the use of grasslands decreased the process of deep infiltration. In order to intensify the groundwater recharge, it is necessary to mow the vegetation at least twice per season, but when mowing four times, undesirable changes in the vegetation growth structure were observed.

The fallowing of grasslands constitutes a loss of productive and forage acreage; here it also proved unfavourable to groundwater recharge.

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