REPORT ON THE RESTORATION OF WETLANDS, SPRINGS AND STREAMS IN A MOUNTAIN LANDSCAPE

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ABSTRACT

As the ongoing climate change increases water problems, society is starting to understand the importance of re-establishing a functioning water regime in the landscape and restoring wetlands, watercourses and springs. Restoration techniques and methods used in landscapes at low and middle altitudes are relatively well developed. But the same cannot be said for mountainous and hilly areas, which are a challenge hydrologically due to sloping terrain and soil erosion. Restoration technologies in such landscape are still being developed. Upland and hilly areas are, however, an important source of water for lower regions and well-functioning water regime is very important. This also applies to the Šumava region, which is an important spring area, declared as a Protected Area of Natural Water Storage. There have been significant changes in the hydrology in the Šumava Mts. in the past, mainly in drainage. The extent of drainage and its effect on wetlands, springs and watercourses, have been the reason for starting a comprehensive programme of hydrological restoration.

The aim of this paper is to show it is possible to restore hydrology in challenging mountain conditions. The micro-catchment approach and water table concept is emphasized. Particular attention is paid to some hidden and still neglected problems, such as drainage of springs and the need for their restoration. This paper summarizes the results and experiences gained during 25 years of restoration (1999–2024). During that time, a total of 296 km of drainage channels were blocked in the Šumava region, 36 km of small mountain streams and 28 spring areas were restored. The total area of hydrological restoration is 2718 ha. The cross-border LIFE for MIRES project (2018–2024), currently in its final year, played an important role in this achievement.

Keywords: drainage; hydrological restoration; mountains; springs; streams; wetlands

Introduction

Wetlands cover about 5–8% of the Earth's terrestrial surface and are the most endangered and rapidly degrading ecosystems on the planet (Mitch and Gosslink 2015). It is estimated that about half of the wetland areas disappeared during the 20th century (Russi et al. 2013). Europe lost 60–80% of its wetlands, with most of the loss attributed to agriculture (Revenga at al. 2000). Currently there is great interest in wetlands because of climate change and its effects, because of the important role they have in the landscape water regime and the cycling of carbon and nutrients. They are also important as an air-conditioning unit, absorbing heat from solar radiation and helping to mitigate overheating of the earth's surface (Pokorný et al. 2017). Their beauty and high species diversity is only now being appreciated with the loss of most wetlands.

One of the consequences of this is the growing effort to restore wetlands. The first restored wetland was reported in Western Europe as early as the middle of the last century. The industrially mined peat bog at Engbertsdijksvenen in the Netherlands, was restored early in the 1950s (Schouwenaars 1992). Until the 1980s, however, wetlands, especially peatlands, were rarely restored. A major escalation in restoration occurred in the 1990s (Kozulin et al. 2010; Cris et al. 2014; Similä and Aapala 2014; Mitch and Gosslink 2015; Joosten 2021; Pakalne et al. 2021), which was mainly because of the subsidy policy of the European Union that enabled the implementation of many restoration projects (Andersen et al. 2016).

In the Czech Republic, restoration began 15 years later than in Western Europe and Scandinavia. Surprisingly, the first wetland habitats restored in this country were peatlands and wetland pools. The first hydrological restoration of bogs occurred in the 1990s in the Šumava region and Krušné hory Mts; however, restoration in the Czech Republic did not fully begin until after 2000. Similarly, this was the case for the restoration of streams and rivers. The early projects involved minor modifications to the beds of rivers or the removal of obstacles for migrating organisms, especially fish. It was not until the turn of the millennium that a more comprehensive approach was adopted, which involved the restoration of diverse and dynamically evolving riverbeds, including their connection to the surrounding floodplain (Just et al. 2005).

Hundreds of projects aimed at rewetting wetlands, and returning natural watercourses are currently being implemented in the Czech Republic (Bufková et al. 2010; Paterova 2016; Just et al. 2021). The idea of a near natural restoration of the hydrology of a landscape is also increasingly coming to the fore. There are many examples of successful restorations of rivers, streams, pools and mires. Plans to remove piped drainage systems and streams are increasingly being addressed (Krejčová et al. 2021; Oppong et al. 2023). Detailed methods for ecological restoration of different wetlands and freshwaters have been prepared by the Nature Conservation Agency (Birklen et al. 2014; Vrána et al. 2014; Just et al. 2021).

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In any case, the percentage of restored wetlands and watercourses in the Czech Republic is still moderate compared to the extent of the damage done to the water regime in the past. Near natural restoration is mainly achieved in protected areas and on state-owned land. The main obstacle to hydrological restoration is currently the attitude of most landowners and users, who block many proposed projects for privately owned land.

Study area

The Šumava National Park (680 km^2) and adjacent Protected Landscape Area (996 km^2) are important wetland and mire regions in Central Europe and together include most of the SCI[1] Šumava involved within the Natura 2000 network. In this area there are wetlands at high altitudes (around 1300 m a.s.l.) and in the foothills (around 800 m a.s.l.). According to results of habitat mapping by the Nature Conservation Agency of the Czech Republic (NCA) in 2023 (NCA 2023), wetlands make up more than a fifth of the Šumava National Park (Fig. 1).

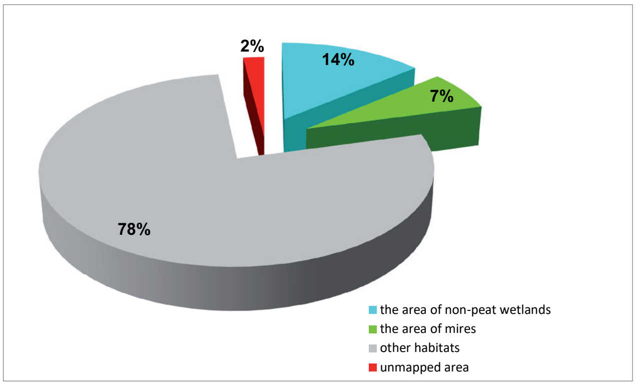

Fig. 1 Percentages of the area of the Šumava National Park that are made up of wetlands (unpublished data from habitat mapping NCA, 2023).

Mires are the iconic habitats in this mountain range and include both ombrotrophic bogs, which depend mainly on precipitation and minerotrophic mires dependent on either ground or rainwater occur here (Svobodová et al. 2002). The second includes mainly spruce mires and treeless fens. The total area of mires in SCI Šumava is 5457 ha (NCA 2023). However, other types of wetlands, such as, waterlogged spruce forests, moun-

Table 1 List of the different types of wetland in SCI Šumava and the Šumava National Park (unpublished data from habitat mapping NCA, 2023).

Wetland type	Mapped habitat code	Area in the SCI Sumava (ha)	Area in the Sumava NP (ha)
Open raised bogs	R3.1	403	397
Raised bogs with *Pinus mugo*	R3.2	569	561
Bog hollows	R3.3	9	8
Degraded raised bogs	R3.4	255	223
Bog pine forest	L10.4	392	324
Bog spruce forest	L9.2A	1313	1233
Transitional mires	R2.3	999	815
Acidic moss-rich fens	R2.2	936	569
Total area of springs	R1.2; R1.4	48	20
Meadow springs without tufa formation	R1.2	4	2
Forest springs without tufa formation	R1.4	45	18
Montane grey alder woodland	L2.1	178	63
Ash-alder alluvial forest	L2.2	2527	251
Alder carrs	L1.1	22	2
Petasites fringes along montane brooks	M5	6	2
Waterlogged spruce forest	L9.2B	9859	7028
Willow carrs	K1	370	109
Willow scrub on loamy and sandy riverbanks	K2	18	0
Total herbaceous and grassy meadow wetlands	T1.4; T1.5; T1.6; T1.9	4531	1764
Total reed and tall-sedge beds	M1	446	267
Total herbaceous wetlands on bare soils	M2.1; M2.2	12	0,5
Unvegetated river gravel banks	M4.1	3	1
Total macrophyte vegetation in natural eutrophic and mesotrophic still water	V1C; V1F; V1.G; V2A; V2C	552	29
Macrophyte vegetation in oligotrophic lakes and pools	V3	8	8
Macrophyte vegetation in streams	V4A	143	122
SUM of wetlands		**23648**	**13817**

tain alders along streams, herbaceous wet meadows, reed and tall sedge beds, etc., are also abundant. Mosaics of intertwined different types of mires and wetlands form remarkable wetland complexes (Kučera 1995).

The total area of non-peaty wetlands in SCI Šumava is 18724 ha (NCA 2023). The actual area of wetlands in Šumava, however, is higher, as many wetlands were included in the category of habitats strongly influenced or created by man during the habitat mapping (NCA 2023), although these habitats have a relatively natural character (e.g. pre-forest successional stages of abandoned fens or wet meadows). In addition, some wetland sites are incorrectly classified or not even registered due to their small size (springs) or badly degraded (e.g. intensively grazed wet pastures).

The Šumava region is an important headwater area with a high number of springs, which are the sources of small mountain streams. Therefore, any interventions or changes in its functioning may affect the downstream parts of the catchment. Therefore, a great deal of attention is paid to protecting the water regime and restoring the hydrology.

Human effects on wetlands

As in the rest of Europe, wetlands and mires in the Šumava region were affected by various human activities in the past (Schreiber 1924; Bufková et al. 2010), with drainage the most serious. Traditionally, waterlogged sites were drained for agriculture, increasing timber production on water-affected forest soils and for peat mining. The extent of drainage was already considerable at the turn of the 19th and 20th centuries, even in relatively remote border areas (Schreiber 1924). At that time, surface ditches were dug manually, so they were not too deep (mostly up to one meter), but this occurred in the whole region and affected most of the wetlands. Some of them naturally disappeared due to succession, especially in flat areas. The second phase of drainage took place during the intensification of agriculture and forestry in the 1970s and 1980s. This time the drainage system was well built and extensive. Piped drainage was constructed on agricultural land, especially at low altitudes. So-called *compensatory reclamation* was often carried out as a substitute for high-quality soil lost in newly built-up areas inland. Unfortunately, drainage is not just an unwanted legacy of the past as local repairs or even the construction of new surface channels still occur, especially on private and municipally owned land at low altitudes in the Šumava foothills.

The inventory of mires compiled in the 1990s and updated in 2010, revealed that 87% of mires in SCI Šumava (Bufková, unpubl. report) were drained in the past. For non-peaty wetlands it is at least 65%, but this is only a very rough estimate as the inventory of non-peaty wetlands was not completed, and it does not include extinct wetlands. The only positive message is that drainage was not equally intensive everywhere. The range is from weakly affected sites capable of self-regeneration to strongly degraded sites close to extinction or already extinct. The total area of badly damaged mires, where restoration measures are needed, is estimated at about 2000 ha (Bufková et al. 2010). There is no similar analysis for non-peaty wetlands.

In the Šumava region, there are significant changes to springs caused by past drainage (Bufková et al., in press). At many sites, the underground water is upwelling only at the bottom of the drainage ditches, which can be up to 1–2 meters below the ground surface, which is where the last remnants of the original spring habitat, including specific vegetation and fauna survives.

In addition to drainage, ombrotrophic raised bogs were also negatively affected by peat extraction, especially in the vicinity of settlements and in easily accessible areas. In most of these bogs, peat was extracted manually from about the 18th century up to the first half of the 20th century. Only four bogs (Soumarský Most, Vlčí Jámy, Borková, Světlík) were industrially mined in the Šumava region. The first three of these have already been restored. Other anthropogenic effects that increase the negative effects of drainage include an inappropriate location or construction of road network, intensive agricultural use, eutrophication, or intensive forestry. An inconspicuous but significant damaging factor is the network of forest roads accompanied by deep drainage ditches. Within the Šumava National Park, wetlands of a total area of about 14,000 ha are crossed by roads of total length 117 km (Bufková et al., in press). In many places, roads act as barriers and via the ditches can redirect the small streams or surface runoffs into a completely different sub-catchment. Great attention, therefore, needs be paid to the correct design and construction of the road network during the preparation for a restoration project.

History of the restoration of the hydrology in the Šumava Mts.

Restoration began in Šumava at the end of the 1990s, with in 1998 the adoption of a long-term concept “Programme for the restoration of the Šumava mires and wetlands”, which, in addition to the main objectives and restoration measures, also included the spatial priorities and logistics of the restoration work, which was last updated in 2018.

Although the main ideas and approaches remain the same, the hydrological restoration in Šumava developed over time. At present, there are three main stages in the restoration (Table 2), which can be characterized by a certain level of knowledge, experience and differences in technology and financial support. Initially, the focus was mainly on mires and biodiversity, with the preservation of valuable sites with rare and endangered species. This was followed by restoration aimed mainly at improving the hydrology in this disturbed landscape. Currently, the aim is not only to restore the previous water regime, but

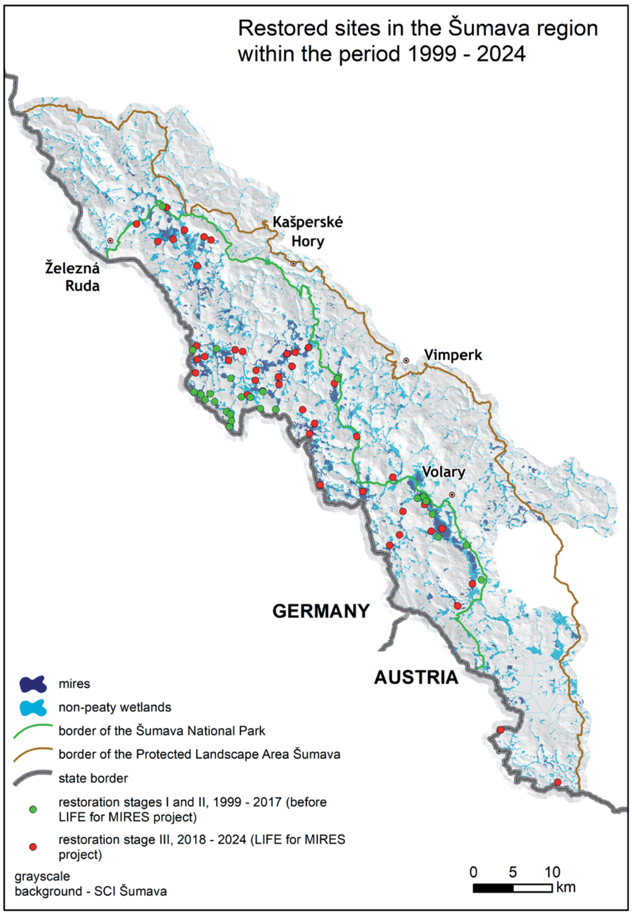

Fig. 2 Map showing the sites that were restored in the Šumava region between 1999–2024.

also to mitigate the negative effects of climate change, such as extreme conditions of drought and flooding.

First stage – biodiversity (1999–2012)

The first site at which the drainage channels were blocked was the Kamerální bog, with the first phase of restoration starting between 1999 and 2012 when the drained mires were restored. This was part of forestry management and implemented in cooperation with the forest administration of the Šumava National Park and financed from the national park budget for forestry management.

During the first stage, mainly raised bogs in bog forests were restored. Also, the first industrially mined peat bog, Soumarský Most, was restored funded by subsidies and subcontracted. This project was also the first occasion when there was close cooperation between the local inhabitants and local government (municipality of Volary). In total, around 490 hectares of mires and wetlands were re-wetted. This revealed among other things, the importance of backfilling of the dams situated on slopes and restoring the natural movement of water in the wetland. In 2005, a detailed monitoring of the effect of restoration on mire habitats was started and continues to the present. Moreover, volunteer events “Days for mires” were launched, so anyone could get involved in mire restoration and are still very popular.

Second stage – water regime (2012–2018)

This stage differs in several ways from the first as the scope was broader as it included already targeted large areas with different types of wetlands and regulated streams. The focus was on functional restoration, i.e. the restoration of natural or near natural hydrological conditions, processes and structures. The projects were financed by European funds, Operational Programme Environment (OPE), which is in the ERDF (European Regional Development Fund) Programme. As a result, the projects were implemented exclusively by subcontracting. During this period, the following: Hučina stream, Žlebský brook and Jedlový brook and their alluvial wetlands, were restored. In addition, two micro-catchments with extensive mire complexes (Černohorský peat bog and Mires along Zhůřský brook) were also restored. The Černohorský peat bog, including the slopes above the Vltava River and large eroded gullies, was one of the most technically demanding restorations ever carried out in the Šumava region. In this stage, 150 ha of wetlands and 4.5 km of streams were restored.

Third stage – LIFE for MIRES project (2018–2024)

This step involved the LIFE project, which is a large international project called “Transboundary restoration of mires for biodiversity and landscape hydrology in Šumava and Bavarian Forest”, abbreviated as LIFE for MIRES. Four institutions were involved in this project, the Šumava National Park as the coordinating beneficiary together with the National Park Bavarian Forest, BUND Naturschutz in Bavaria and the University of South Bohemia in České Budějovice. For the first time in this region restoration involved cross-border cooperation.

Within the LIFE project, the extent of restored areas increased many times. This project aimed to restore the water regime over an area of 2,059 hectares and, in addition, to mires and wetlands, it also included springs and small mountain streams, which also used to be part of the artificial drainage network. In total, 47 sites were planned to be restored on both sides of the border, 43 of them on the Czech side (Fig. 2). Compared to the originally planned elimination of 80 km of drainage channels and restoration of 13 km of streams, 196 km of drainage ditches were blocked, and 30 km of streams and 28 springs were restored (data as of 15/09/2024, i.e. not yet final). Another aim was to improve the state of important habitats for black grouse (*Tetrao tetrix*).

The restoration of hydrology is based on micro-catchments and aimed at restoring the main water macrostructures, i.e. wetlands, springs and watercourses. The emphasis is on the restoration of natural or near natural hydrological processes and ecological links. The advantage of the LIFE project is that it enables the linking of field measures with monitoring and with awareness-raising activities, which are often crucial for the promotion of restoration plans.

Table 2 List of sites restored by the Administration of the Sumava National Park in the Šumava region (as of 10 October 2024).

Site name	Area (ha)	Number of dams	Length of blocked drainage channels (km)	Length of restored streams	Implementation
Kamerální slať	3		0,7	0	1999
Novohuťské močály	57	346	3.4	0	2003–2004
Vrchové slatě a Malá slať	27	286	3.9	0	2003–2004
Cikánské slatě	122	1336	14.5	0	2003–2006
Malý luh	38	211	1.4	0	2004
Chalupská slať – Šindlov	26		1.8	0	2004
Blatenské slatě I a II	41	264	2.9	0	2005–2006
Luzenské svahy I–II Luzenská slať – Březnické slatě	15		4.5	0	2004–2006
Hučina I	17	221	2.8	0	2005
Biskupská slať	1		0.3	0	2005
Ptačí nádrž	8			0	2006–2007
Černohorský močál I	23	148	1.6	0	2006–2011
Na Ztraceném	17	223	1.9	0	2009
Schachtenfilz	5	203	1.2	0	2008
Nad Rybárnou	5	135	1.2	0	2008
Pod Prameny Vltavy	16	300		0	2006
Soumarský Most	55	500	9	0	2003–2004
Hučina II	12	20	1.2	1.7	2013
Černohorský močál II	67	596	2.1		2013–2014
Rašeliniště na Zhůřském potoce I	31	1285	7.4	0.5	2014–2015
Revitalizace Žlebského potoka a přilehlých mokřadů v nivě Vltavy	13	96	2.6	1.825	2014–2015
Jedlový potok – revitalizace			1.6	1.6	2014–2015
Luzenská cesta I a II	14		1.5		2009
Pěkenský potok	18	45	1.16	1.1	
Starý potok	9	18	0.538	0.18	
Gerlova Huť	24	372	3.8	1	2020–2021
Nová Hůrka	112	299	7.9	2.8	2020–2021
Malý Bor	28	102	2.5	1.6	2020
Slučí Tah	21	59	2.1	0.2	2020
Pod Skelnou	36	310	4.1	2.4	2020–2022
Kameničná	67	474	9.1	0.5	2020–2022
Gayerrück	18	146	1.7	0.4	2020
Smrkový vrch	32	340	3.7	0.1	2020
Střelecký průsmyk	4	97	0.6	0.1	2020
Rybárny I	35	547	5.7	2.1	2021
Střelnice	13	108	1.2	0.1	2020
Devítka	21	223	4.2	0.4	2020
Stožecká	44	716	8.5	1	2020–2021
Nové Údolí	62	593	9	1.6	2020
Černý Kříž	32	82	3.4	0	2020
Vchynice Tetov	21	167	2.3	1.1	2021–2022
Ovesná	62	236	8.6	0.2	2021–2022
Ptačí slať	12	111	1.2	0.4	2021
Dobrovodské louky	75	208	8.5	1.4	2021–2022
Rybárny II	43	404	8.2	1.5	2021–2022
Rovina	45	964	12.6	2.8	2022

Site name	Area (ha)	Number of dams	Length of blocked drainage channels (km)	Length of restored streams	Implementation
Nová slať	23	317	4.1	0.9	2021
Vlčí jámy	41	256	9.6	0	2021–2022
Vlčí jámy			0	0	2023
U Tremlů	11	171	2	0.7	2021
Rokytecké slatě	104	312	5.2	0.3	2021–2022
Jezerní slať	101	87	1.1	0.1	2022
Hamerská slať	16	138	2.2	0.1	2022
Silniční slať	55	511	5.4	0.3	2022–2023
Mezilesní slať	70	204	3.1	0.4	2022
Pod Lovčí	35	368	5.3	0.2	2022–2023
Zhůří III	93	514	11.4	0.3	2022–2024
Novosvětské slatě	58	298	7.2	0.9	2022
Ježová	3	32	0.5	0	2023–2024
Bučina	36	350	3	0.4	2023–2024
Horní Světlé Hory	29	170	3.7	0.3	2023
Stráženská slať	135	152	6.5	1.1	2023–2024
Multerberg	13	173	2.5	0.3	2023
Knížecí Pláně	7	67	1.2	0	2023
Černohorský močál III	20	106	1.1	0.1	2023
Raškov	15	104	2.6	0.7	2023
Březová Lada	27	125	4.2	0.3	2023
Pramenská	27	121	1.9	0	2023
Mrtvý luh	315	65	3.2	0	2023
Mlynářská slať			0	0	2024
SUMA	2583	17432	265	36	

Specific features of mountain environments and sloping terrains

Restoring the natural water regime in hilly and especially montane areas is very different that in flat lowland areas. In particular, the slope of the terrain has a crucial role as the speed and erosive power of runoff water creates different conditions for its infiltration into the soil and runoff from the area. Rainfall in mountains tends to be much higher, which also significantly affects runoff conditions.

As a result of these and many other factors, restoration of hydrology is much more difficult in sloping than flat landscapes. The risk of erosion and the water draining via ditches or regulated stream channels is very high and may result in failure. These risks must be considered when selecting procedures and methods for blocking the drainage channels.

Mountainous and hilly landscapes are important headwaters of many streams. The smallest outlets are from springs, which are often re-directed into the surface channel network, which is subject to restoration. Mountain streams are generally characterised by certain geomorphological features and flow conditions, which results in their restoration being different from that for large streams in lowlands. Due to the risk of strong vertical erosion, it is important to rapidly re-establish an appropriate substrate in a restored streambed.

Another feature of mountains and hills is their poor accessibility. The rugged and heavily sloping terrain, poor road network and high forest cover, greatly limit the use of machinery for restoration and the transport of materials. The isolated nature of the area also limits the availability of certain materials, which must be imported and increases the cost. Some measures that are easy to apply on the plains, such as stabilising eroded stream beds with stone backfill, are often very difficult on forested slopes in remote mountain areas.

Mountain and foothill areas are also characterised by a lower population density and overall lower land use. As a result, there is usually a higher number of naturally valuable areas, many of which are protected nature reserves. This also limits for the implementation of restoration measures.

Finally, a general feature in valuable areas is the lack of soil, which can only be obtained from certain places. This severely limits the infilling of drainage ditches as using only local material is preferable. Transport over longer distances is often impossible. There is also the risk of interactions with foreign material or introduction of invasive species, both of which should be minimised. Various alternative procedures are therefore used when blocking channels, but this must not be at the expense of their functionality.

Main approaches and goals of restoration

The term restoration usually means the changing of a habitat and ecosystem functioning to as close as possible to the original state before it was damaged (Charman 2002). In the case of wetlands and especially mires, which are dependent on a surplus of water, the basis of restoration is in almost all cases the re-establishment of the previous hydrological conditions. Many projects declare that restoration is aimed at returning the degraded ecosystem to its original natural state, but a return to the pre-damaged stage is virtually impossible under current conditions. In reality, restoration is more about re-establishing new natural or "near natural" conditions (Vasander et al. 2003). For this, the comprehensive restoration approach is very important.

Early restorations of hydrology in the Sumava region focused on the re-establishment of particular biota in wetlands (see restoration stage I). All efforts focused on saving the peatlands, which are the iconic Šumava wetlands and are unique and relic ecosystems. The aim of the restoration was to increase biodiversity by protecting rare species and communities.

Soon, however, it became clear that the mere restoration of habitats or localities where there were rare species was insufficient. The concept of restoration has therefore, changed considerably in terms of the remediation of landscape hydrology. At the same time, the reduction of the negative effects of drainage were addressed as a priority. The measures were aimed at the restoration of wetlands, springs and watercourses that were damaged by human activity and the restoration of their ecological links and functions. The restoration of natural flow of water in particular areas or micro-watersheds also became an important objective.

In addition, hydrological restoration can buffer the adverse effects of climatic extremes. Enhancing the adaptation of the landscape to climate change, therefore, became another objective of restoration. Particularly important in this respect is the restoration of the connection of natural watercourses to adjacent floodplains and alluvial wetlands, which can moderate the velocity and power of flood water (Dixon et al. 2016; Goyette et al. 2023). In addition, restored wetlands enhance long-term accumulation of water in soils and can also mitigate overheating of the land surface during hot and dry periods (Pokorný et al. 2010; Pokorný et al. 2017).

In line with the change in the objectives of restoration, the spatial priorities have gradually changed as well as the framework schedule of measures in the distinct stages, all of which are described in detail in the long-term restoration concept (upgraded in 2018). The stated main goals define the basic framework, which is followed by many sub-objectives that already apply to specific habitat conditions and solved problems.

Three basic concepts have been formulated for the implementation of restoration projects in Šumava that consider the sloping terrain and other specific conditions of mountainous and hilly regions.

Micro-catchment concept

Hydrological restoration of the headwater area with a complex mosaic of interconnected wetlands and streams requires a comprehensive approach. Therefore, a principle of complex restoration of the water regime within coherent hydrological units, such as micro-catchments was quickly developed (Bufková et al. 2010). These micro-catchments typically included springs, mires, various non-peaty wetlands and streams, all of which were included in the restoration of the hydrology (Fig. 3). The area of the restored micro-catchments did not have to be large and was usually only tens or low hundreds of hectares. In all the micro-catchments, drainage channels were blocked, springs were restored, and streams were returned back to their original courses. Emphasis was also placed on restoring near-natural water movement in wetlands. As part of the restoration, the effect of the road network on the surrounding wetlands was mitigated.

Functional one-off restorations

Restoration of damaged wetlands and watercourses were perceived as one-off or highly time-limited activities. Restoration of a micro-watershed was usually completed within 1–2 years, with if necessary minor changes in the following two years. The main purpose of these restorations was to start a spontaneous regeneration. Primary ecosystems were left to regenerate spontaneously, and treeless fens and wet meadows were managed, which was not part of the hydrological restoration.

Although the restoration of secondary wetlands aimed at the re-establishment of abiotic conditions, in some cases it also included active support of the surviving components of the ecosystem. A typical example are the peat-forming species, which are important for the regeneration of industrially mined peat bogs, which are bog mosses (*Sphagnum* species) and some species of *Cyperaceae*. If bog mosses become extinct at a particular site, recolonization is likely to be very slow as these mosses have low powers of dispersal. Thus, it is recommended that the peat-forming vegetation be returned to such sites. In rare cases, extremely rare or rapidly disappearing species, such as black grouse (*Tetrao tetrix*) and coral necklace (*Illecebrum verticillatum*) should also be included as part of the hydrological restoration.

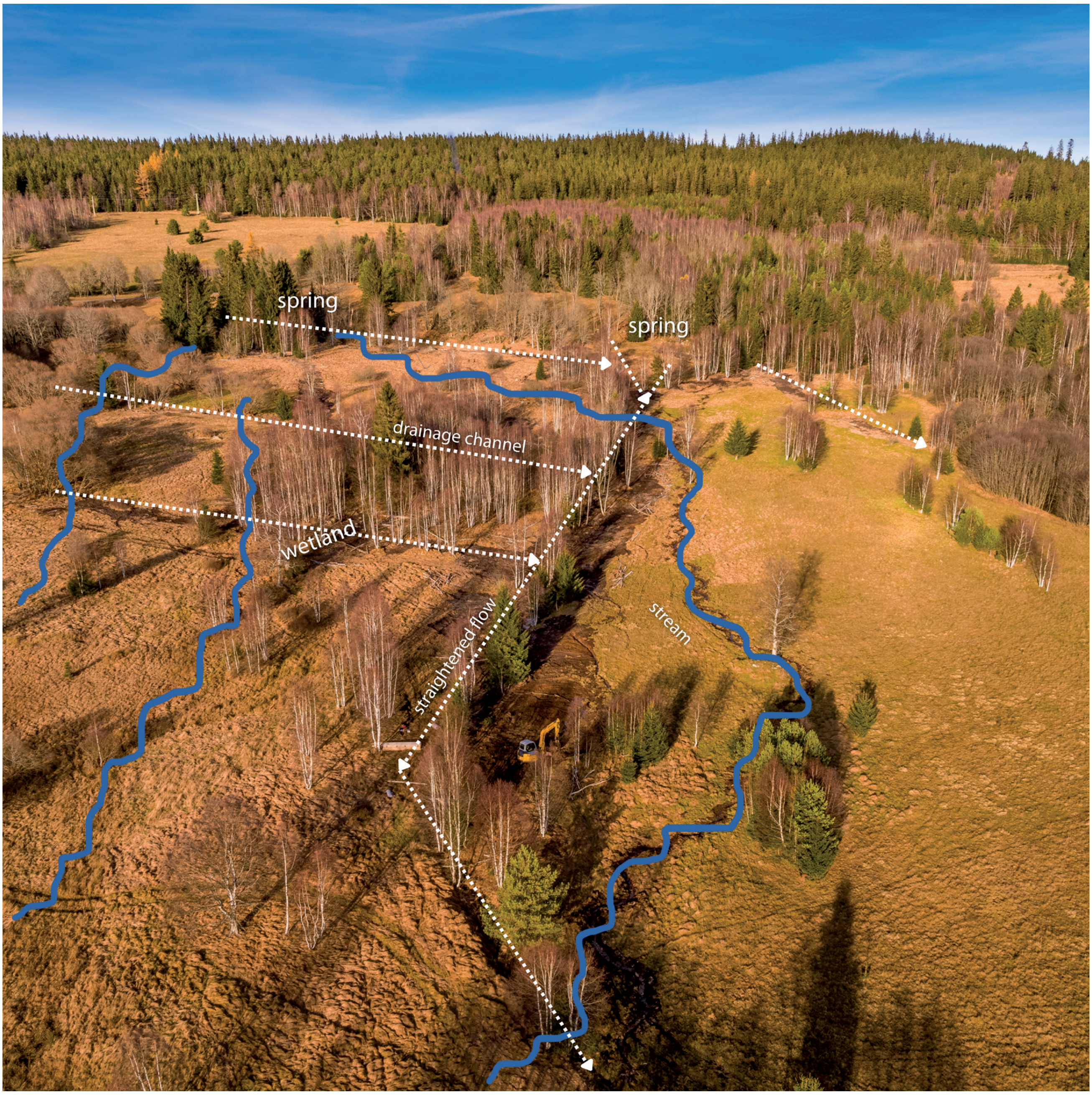

Fig. 3 An annotated photograph of an example of the hydrological restoration of a micro-catchment on the slopes of the Křemelná basin (in blue), which previously included drained springs, wetlands and straight water courses, location Pod Skelnou, 2022 (photographer R. Plíhal).

Target water table

The main aim of restoration is to re-establish water regimes similar to those in natural or pre-drainage conditions. Different types of wetlands and mires, with different genesis and hydrology, however, are usually addressed together, but they also differ in the level and dynamics of the water table. A classic example is that rewetting should reflect the differences between ombrotrophic raised bogs, wet spruce forests, fens and springs.

A basic assumption is that blocking the drainage ditches will result in raising the water table in drained wetlands. A suitable method on slopes is to block the ditches using a cascade of solid dams followed by backfilling (Stoneman and Brooks 1997; Calvar et al. 2021). In the Šumava region, the blocking of drainage ditches did not result in flooding but returned the water table to a level close to the natural or pre-drainage state. This level is referred to as the target water table (TWT) (Bufková et al. 2010). Given the ecology and diversity of wetlands and mires, it is clear that the target water table would be different for various types of wetland habitats. In mires it could be related to the thickness of the aerobic soil layer just below the surface, in which the water table may fluctuate. This layer remains aerated for at least a certain time and oxidation can occur. In any case, restoration should not result in flooding where it is not natural. The TWT values for the restored wetlands and peatlands in the Šumava region based on field measurements (Bufková et al. 2021) or analysis of published data (Neuhäusl 1972; Rybníček 1974; Neuhäusl 1975; Rybníček et al. 1984; Dierssen and Dierssen 2001) are listed in Table 3.

Table 3 Values of the target water table for the main types of mires and springs in the Šumava region.

Type of habitat (Chytrý et al. 2010)	**Target water table** (cm below surface)
Active raised bog	5
Lagg of raised bog	0–5
Spruce mire (sedge type)	5
Spruce mire (dwarf shrub type)	10–15
Waterlogged spruce forest	20–35
Springs (all types)	0
Transitional mires	0–2
Acidic moss-rich fens	10–20

The TWT is an important parameter in the blocking of drainage ditches, especially on sloping terrains. It determines, along with the surface gradient, the number of dams required and their distribution on a given section of a drainage ditch, so that the water table can be increased to near natural levels along the entire length of the drainage ditch. For the purpose of restoration, the target water table can be expressed as the maximum allowable water level below the downstream wall of the dam. This concept is illustrated schematically in Fig. 4. The TWT can be specified for a given section of the ditch according to the wetland or vegetation crossed by the ditch. Knowing the surface gradient, the correct distribution of dams and their number in a particular section of a ditch can be calculated.

It is pointless to use this method in flat areas, where all that is necessary are wooden barriers or compacted soil dams in positions suitable for specific surfaces or rewetting needs. Other cases where it is not necessary or even impossible include non-peaty habitats in wet meadows and forests. For these habitats, the dams should be located so that the level of the water is at least 2/3 or 1/2 the height of the above-ground side of the next upstream dam. Water should be retained along the entire length of the ditch, and the dams should not be conspicuous and only retain a limited volume of water in the upstream direction. Important role of ditch damming and infilling is, in addition to raising the water table is to block the preferential water runoff through man-made drainage network.

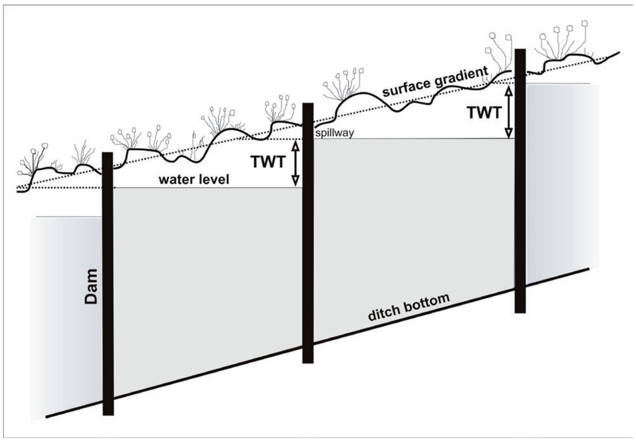

Fig. 4 Cascading method of damming drainage ditches based on the concept of targeted water table (Bufková et al. 2010).

Restoration methods

Restoration involves removing artificial water losses and restoring the water supply to wetland at the level they were before they were drained (Laine et al. 2006; Gatis et al. 2023). The most appropriate measures depend on the type of wetland, habitat conditions, type and extent of damage and degree of habitat degradation (Joosten 2021).

In the Šumava region (Bufková et al. 2010) this mainly involves blocking the drainage ditches, which can be done in several ways, but only some of them are suitable for mountainous and sloping terrain. For example, drainage channels cannot be filled in with soil as in flat areas. As a result of water erosion, backfilled material is easily washed away near the bottom and the drainage channel is then underground with no sign of its presence on the surface. On sloping terrain, therefore, the transverse blocking of the channel must be always done before infilling in order to stop water flow through an underground channel the result of water erosion (Stoneman and Brooks 1997; Armstrong et al. 2009; Similä 2014; Calvar et al. 2021).

Cross-blocking of channels on slopes raises the water table and re-wets the soil profile (Joosten et al. 2021). This must be implemented in the form of a cascade as one-off blocking drainage channels on a sloping surface have no effect. The blocked ditches must be infilled in any case; neither of the two steps work on slopes if done separately. In the Šumava region, the cross-blocking of channels with wooden dams surrounded by a backfill of compacted soil and subsequent infilling of the channels has proved successful (Bufková et al. 2010). These practices are especially suitable for oligotrophic areas with a predominance of nutrient-poor bedrock. In limestone or more fertile areas it is necessary to determine and monitor in much greater detail the water sources re-wetting a site.

Drainage ditch or stream?

In the upper parts of catchments, this is a frequently asked question. The reason is that the sources of small streams flow from springs directly into a network of surface drainage channels. The flow rates of these small streams tend to be very low and can, especially when water levels are high, be easily confused with the flow in classic drainage ditches simply due to seepage from a saturated soil profile or by the overflow of surface runoff.

The distinction between these drainage ditches and a straightened channel replacing a watercourse is crucial, as each is treated differently. Surface drainage ditches are blocked, whereas streams re-directed into a ditch must not be blocked. The water flow must first be returned to its original natural route. Only then can the former channel be blocked. The specific situation, when the drainage channel is in the line of the former natural course of the stream, is solved by specific procedures.

Blocking drainage ditches

Cross-blocking of drainage ditches combined with infilling is a relatively efficient way of stopping surface drainage. Typically, the aim of these measures is:

(i) raising and stabilising the water table,
(ii) stopping runoff via ditches and reducing water loss,
(iii) re-distributing runoff through the most natural routes possible,
(iv) encouraging infiltration of water into wetlands or mires.

In flat areas, backfilling with clay or compacted soil with a high percentage of impermeable components is often sufficient to block channels. On flat mires, compacted peat dams are commonly used in this way. On a sloping terrain in mountainous and hilly areas, however, this procedure cannot be used because of the erosive power of water and the risk of runoff flowing back into the ditch line. In practice, it is common for water to erode undammed channels and then flow along the junction between the channel bottom and the soil backfill. The result is a visually infilled and therefore "eliminated" drainage ditch, at the bottom of which, however, water flows through a hidden outflow similar to the streams in caves.

The best solution on a sloping terrain is therefore to block the channels with a cascade of fixed transverse barriers or dams, which stop the linear runoff. In any case, the dams must be designed to prevent water erosion and the return of the runoff to the channel. They must be well embedded in the banks and in the bottom, sufficiently covered by soil and supplemented by subsequent filling of the channels.

In addition to wood, various man-made materials such as hardened inert plastic, steel plates and rods are used in dams all over the world (Stoneman and Brooks 1997; Calvar at al. 2021). In the Šumava region, where most hydrological restorations are carried out on sloping terrains, wooden dams surrounded by compacted soil are used. This method is reliable and easy, especially in terms of transport of material and cost effectiveness.

Different types of wooden dams are used to block the channels. The most common are layers of wooden boards with inserted geotextile between them. On peat bogs, with a sufficient depth of peat in the bottom of a ditch, vertical planks are hammered into position. Specific massive dams are also used when streams cross drainage channels. Non-natural materials (such as plastic or steel) were not used in order to protect the flora and fauna in protected areas. Moreover, some materials interaction with the environment (plastic dams), especially in mires. The use of steel sheets was limited because they are difficult transport (heavy or assembled off-site) or the installation was difficult because of unsuitable soil or peat with a high content of logs of wood or stony soil.

The installation of only dams, however, is not sufficient, because they are likely to be damaged by water erosion and the limited lifespan of wooden dams. Each wooden barrier must be surrounded by compacted earth or peat backfilling of usually 1–2 m on both upstream and downstream sides. This backfilling stabilizes the dam, reduce its susceptibility to erosion and extends its life. And finally, backfilled dams should be combined with subsequent infilling of the spaces between them, which results in rapid overgrowth with wetland vegetation and final elimination of the channel (Fig. 5).

Suitable sources of material for both dam backfilling and infilling canals are soil deposits left on banks when

Fig. 5 Deep erosion gully along the former "Iron Curtain" at Černohorský močál above the Vltava River before restoration in October 2014 (a) and after channel damming and backfilling in July 2024 (b). The streams are now stabilised by mire and wetland vegetation (photographer I. Bufková).

Fig. 6 Spring in a large meadow at Pod Skelnou one year before restoration (a) and two years later (b), April 2019 (photographer I. Bufková) and May 2022 (photographer L. Linhart).

channels were built, trunks of felled trees, sods of vegetation, bundles of branches tied together, etc. If soil is unobtainable, it can be obtained by excavating shallow depressions in the vicinity of blocked canals. Subsequent support of the wetland or mire vegetation will significantly accelerate succession and elimination of the channel. Runoff along the drainage line should not persist after blocking the ditch but be dispersed as far as possible into the wetland or mire area.

Pipes used for drainage were also removed or blocked at several locations, by removing sections of approx. 3–5 meters in length. The remnants of the pipes left in the ground were always closed at both ends with overlapping wooden boards and the space filled with compacted soil. The piped streams were returned to the surface and restored to their natural state.

Restoration of springs

In the Šumava region, wetland type springs predominate, most of which were drained in the past. Their restoration consisted mainly in blocking drainage ditches with wooden dams after which the TWT value for all springs was zero, i.e. the water table was at ground level.

All the drainage ditches were filled with soil after damming (Fig. 6), as material other than soil is not recommended. Before starting the restoration, the original extent of the spring was determined. In the case of piped springs, all pipes including any lateral drainage system were removed. When restoring the outflow from helocrene springs, several (at least 2–3) small outlets were created, which take the form of an opposite delta usually only a few meters below the spring.

Fig. 7 Photograph showing the result of restoring a small stream that was previously drained using the pipes at, Dobrovodské louky, November 2021 (photographer I. Bufková).

Stream restoration

Many wetlands and watercourses interact with one another hydrologically and restoration of one can significantly affect the ecological status of the other. In upland areas where there are many wetlands and springs, this interdependence is clearly evident. Therefore, hydrological restorations should consider that water features are hydrologically interlinked in micro-catchments.

Stream restoration is based on published rules and methods (Just et al. 2021, some of which, however, are adapted for mountain conditions. Great attention is paid to the identification and re-establishment of the "original" or near natural stream beds. The main objective is to restore the natural character of a stable channel with both the erosion and accumulation processes close to nature. Another important objective is the re-establishment of the link between a stream and its floodplain.

In principle, four techniques have been used to restore the natural stream beds of watercourses in the Šumava region:

1) Returning a watercourse to its historical stream bed
2) Creating a new stream bed in the natural outflow route
3) Initiation of spontaneous stream bed formation by release of water into the natural outflow route
4) Restoring the natural stream bed in a modified watercourse

The choice of the most appropriate approach is always determined by the conditions at a site. Among the important factors are the degree of preservation of the historical stream bed, slope of the terrain, types of soil, its shape and hydrological parameters of the artificial and original stream, etc. A single approach is rarely used to restore the route of a particular watercourse, and it is quite common to alternate between different procedures depending on how much of the historic stream bed is preserved or the extent to which the stream was modified or directed into a drainage network.

Returning a watercourse to its natural stream bed is the easiest technically. The preserved beds of small streams are rarely modified (e.g. removing trees growing in abandoned beds, widening the channel). In total, sections of streams totalling almost 3 km long have been restored in this way.

The creation of a new stream bed in the original runoff route is the most common method used for restoring watercourses in the Šumava region (Fig. 7). The bed was re-shaped with the help of an excavator in sections where the water flowed in the past, but no historical stream bed has been preserved. When creating a "new" bed for very small streams, the geomorphological pattern of preserved natural streams occurring in comparable conditions in the vicinity was used. Shaping has always been directed towards restoring a broad but shallow bed. The depth of the newly formed small streams (with an average flow of a few litres per second) did not exceed 25 cm. In streams with channel widths of up to 0.8 m, typical features of bed morphology (riffles, pools, point bars) were only rarely replaced; their formation was assumed to occur during the subsequent development of the stream. In contrast, for large streams, measures to restore bed morphology (according to Just et al. 2021) are implemented or at least initiated.

Great emphasis is placed on the use of natural sediments and the insertion of dead wood into the restored beds of both small and large streams. In mountainous and hilly areas, restoration projects often lack suitable (especially coarser) natural sediments for restoring streambeds, even in the Šumava. The old stream beds with preserved sediments were only partially detectable here, and the bottom of the newly created sections usually consisted of soil or clay. Sandy and coarse sediments were rare. In the case of restored small streams below and close to a spring, the spontaneous occurrence of coarse bottom sediments was rare and access to these streams was very difficult. In such cases, suitable sediments were obtained from the immediate vicinity, most often with the help of volunteers. In large streams situated downstream and for which sections of the original course of the stream are preserved, suitable but finer sediments were replenished spontaneously over time.

Free flow release initiation of spontaneous stream bed formation is relatively common. It is only used for small streams with a flow of up to 5 l/s on gentle slopes with a gradient of up to 3%. In total, sections of streams 11 km in length were restored in this way.

The most technically demanding was to create a natural stream bed directly in the line of the regulated, often well buried and eroded stream. A method was developed to raise the bed of the eroded stream and re-meander and stabilize it with appropriately placed substrate (Fig. 8). This is very dependent, however, on the availability of sufficient soil to backfill the former erosion gully to the new stream bed level. Approximately a 7 km length of streams in Šumava have been restored in this way.

Areas of different habitats in which restoration has been implemented in the Šumava National Park

An overview of all the sites restored hydrologically by the Šumava National Park Administration up to the 10th October 2024 is presented in Table 2. Locations of the restored sites in the SCI Šumava and Šumava NP are depicted in Fig. 2. A total of 65 locations were restored be-

Fig. 8 Deeply incised and straight stream at Rovina just before restoration in October 2022 (a) and one year after its return to a natural state (June 2023) (b) (photographer L. Linhart).

tween 1999–2024. During this period, 265 km of drainage ditches were blocked, 36 km of mountain streams and 28 springs were restored. The total area restored was 2718 ha.

Most of the work was carried out within the LIFE for MIRES project (2018–2024). On the Czech side of the Šumava Mts., 43 localities with a total area of 2078 ha were re-wetted, 196 km of canals were blocked and 30 km of streams and 28 springs were restored. The areas of different types of wetland habitats (according to the Chytrý et al. 2010) restored at the sites is summarized in Table 4.

Table 4 The areas of different types of wetland restored between 2018–2024 (unpublished data from habitat mapping NCA, 2023).

Wetland habitat	Restored area (ha)
High raised bogs	608
Bog pine forest	89
Spruce mires	133
Fens	164
Wet meadows	185
Waterlogged spruce forest	406
Other forest wetland	112
Springs	1
Other treeless wetlands	18
Total number of Mires	**1094**
Total number of Non peaty wetlands	**630**

The largest areas restored was for waterlogged spruce stands (406 ha) and high raised bogs (608 ha). Significant areas of wet meadows (168 ha), treeless fens (163 ha) and spruce mires (133 ha) were also restored. The total area of the 28 restored spring areas did not exceed 1 ha, the majority of which were forest springs without tufa formation (0.7 ha).

About 92% of the restoration work was carried out with light machinery and the rest manually, mostly with the help of volunteers.

Discussion

Currently a great deal of effort and money is being spent on wetland and watercourse restoration. There are a large number of restoration projects not only in Europe and North America, but worldwide (Palmer et al. 2014; Joosten 2021). In their work, Palmer et al. (2014) emphasize the shift in stream restoration from structural to functional restoration of ecosystems and processes and the importance of an holistic approach and addressing the problems in the context of a catchment, where measures implemented elsewhere can also have a major effect on the success of restoration. It is one of the few studies which highlights the importance of wetland rehabilitation for successful stream restoration and vice versa. Hydrological restoration in the Bohemian Forest is based on the same concept, where the restoration of watercourses and wetlands is carried out together and in coordination within a given micro-catchment.

The importance of a holistic landscape or watershed approach to wetland restoration is also advocated by Verhoeven et al. (2008) and Joosten (2021). Verhoeven et al. (2008) even propose carrying out wetland restoration within a so-called operational landscape unit (OLU), which is an area connected by hydrological and biotic linkages. The goal of OLU is to conserve and, where appropriate, restore those landscape elements that key species and ecosystem functions need to function successfully. A holistic approach to hydrological restoration within watersheds is also proposed by a number of other authors (Grootjans et al. 2012). Cochand et al. (2020) highlight the negative effects and need to address an inappropriately managed road network on the water regime of fens. Yet, the proportion of projects addressing sub-sites without considering the wider environment is significant (if not predominant in some areas).

Hydrological restoration studies are reported, particularly for drained and mined peatlands in Europe and North America (Stoneman and Brooks 1997; Lode 1999; Price and Whitehead 2001; Poschlod et al. 2007; Armstrong et al. 2009; Buckmaster et al. 2011; Joosten 2021). Among them, guidelines and case studies dealing with flat or only slightly undulating areas at low altitudes prevail (Similä et al. 2014; Andersen et al. 2016; Pakalne et al. 2021). Peatland restoration in mountain and foothill areas is uncommon as is the restoration of other types of upland wetlands. Early projects were undertaken in upland areas in both Great Britain and Ireland (Stoneman and Brook 1997; Farell et al. 2024). Other notable ventures include the functional restoration of peatlands in the Jura Mountains in France (Calvar et al. 2021) and Switzerland (Cochand et al. 2020), in the Black Forest, the Bavarian Forest and the German side of the Alps (Poschlod et al. 2007) and in mountainous areas in Scandinavia (Kyrkjeeide et al. 2024). More extensive hydrological restoration has been carried out on both sides of the Šumava (Bufková et al. 2010) and Ore Mountains (Haupt 2007).

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