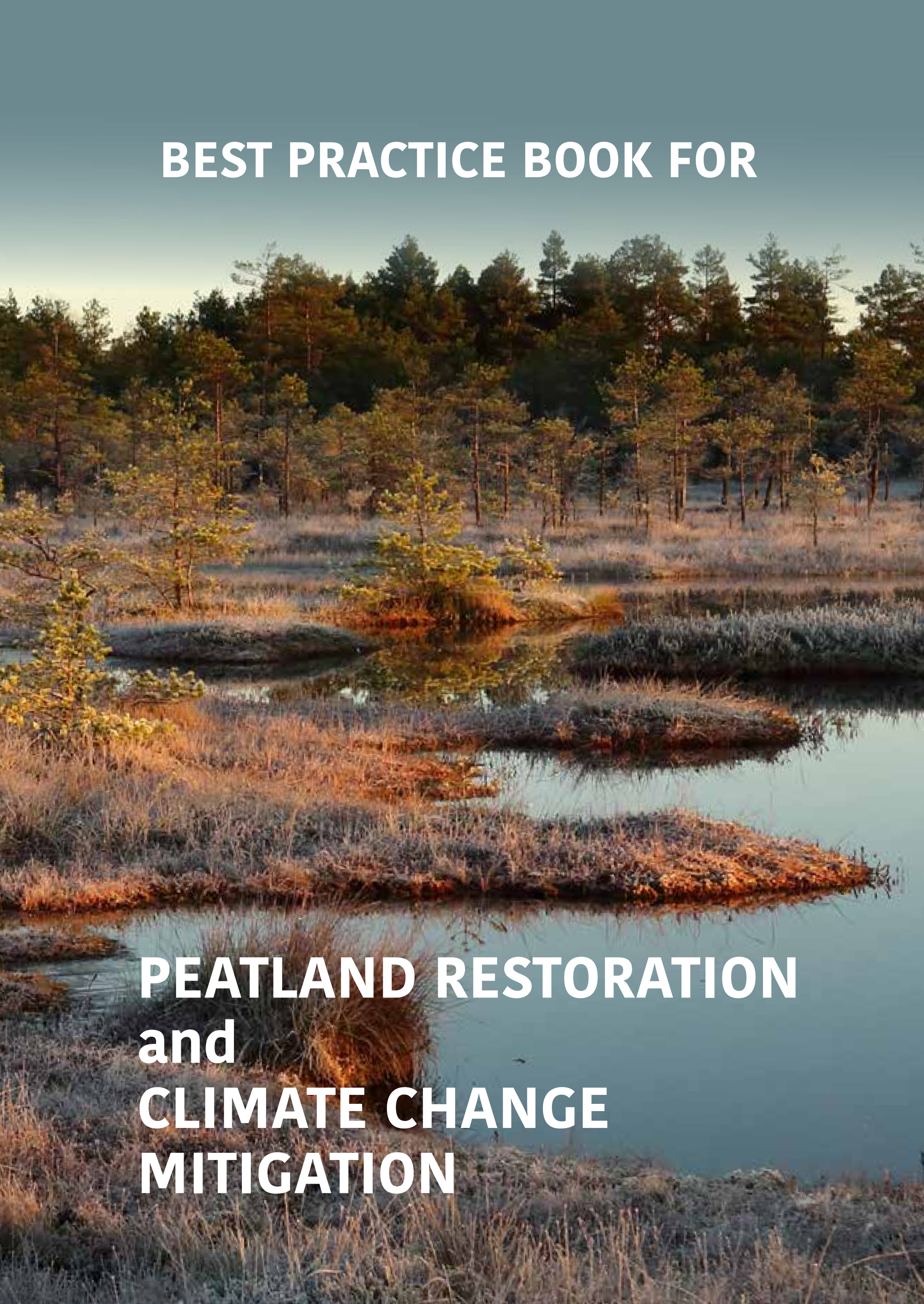


BEST PRACTICE BOOK FOR

PEATLAND RESTORATION and CLIMATE CHANGE MITIGATION

BEST PRACTICE BOOK FOR

PEATLAND RESTORATION and CLIMATE CHANGE MITIGATION

EXPERIENCES FROM LIFE PEAT RESTORE PROJECT

2021

Authors: Māra Pakalne[1]
Jonathan Etzold[2]
Mati Ilomets[3]
Leonas Jarašius[4]
Paweł Pawlaczyk[5]
Katarzyna Bociąg[5]
Izabela Chlost[5]
Roman Cieśliński[5]
Krzysztof Gos[5]
Krišjānis Libauers[1]
Raimo Pajula[3]
Anna-Helena Purre[3]
Jūratė Sendžikaitė[4]
Līga Strazdiņa[1]
Laimdota Truus[3]
Nerijus Zableckis
Leticia Jurema[2]
Tom Kirschey[2]

1 – University of Latvia (LV), 2 – NABU (Nature and Biodiversity Conservation Union, DE), 3 – Tallinn University (EE), 4 – Lithuanian Fund for Nature (LT), 5 – Naturalists' Club (PL)

Editor: Agnese Priede
Design: Daiga Brinkmane
Cover photo: Māra Pakalne

Produced by Printing house "Jelgavas tipogrāfija"
Publisher: Latvijas Universitāte

Citation:
Pakalne M. et al. 2021. Best Practice Book for Peatland Restoration and Climate Change Mitigation. Experiences from LIFE Peat Restore Project. University of Latvia, Riga, 184 p.

The book was prepared and printed with the financial support of the European Commission's LIFE programme within the project "Reduction of CO_2 emissions by restoring degraded peatlands in Northern European Lowland" (LIFE15 CCM/DE/000138, LIFE Peat Restore).
The book reflects only the authors' views. The European Climate, Environment and Infrastructure Executive Agency (CINEA) is not responsible for any use that may be made of the information it contains.

ISBN 978-9934-556-73-9

CONTENTS

Glossary

Most definitions of terms are as provided by Joosten et al. (2017). For exceptions, references are provided.

Bog: Mire only fed by precipitation.
Bog peat: Peat formed by bog vegetation (*Sphagnum* mosses, cottongrass).
Calcareous: Rich in calcium carbonates.
Calcareous fen: (1) A fen with a very high mineral richness in peat and water characterised by basiophile (calciphile) species. Synonymous to extremely rich fen; (2) A fen with communities depositing tufa (travertine, terrestrial chalk).
Carbon dioxide (CO_2): A gas made of one atom of carbon and two atoms of oxygen which is produced whenever carbon-based fuels are burned (or oxidised more slowly in plants and animals).
Carbon dioxide equivalent (CO_2-eq): A carbon dioxide equivalent or CO_2 equivalent is a metric measure used to compare the emissions from various greenhouse gases on the basis of their global-warming potential, by converting amounts of other gases to the equivalent amount of carbon dioxide with the same global warming potential (EEA 2017).
Carpet: A subfeature in a mire with continuous vegetation cover consisting mainly of bryophytes and with the water table close to the surface (generally less than 5 cm above or below, which together with the sparse cover of vascular plants.
Clear-cutting: Felling and removal of all trees and bushes.
Ecosystem: A dynamic complex of plant, animal and micro-organism communities and their non-living environment interacting as a functional part.
EU importance habitat type: A habitat type listed in the Annex I of the Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora.
Evaporation: The process by which liquid water at or near the Earth's surface turns into vapor at temperatures lower than boiling.
Evapotranspiration: The loss of water by physical evaporation and biological transpiration.
Fen: (1) Peatland that receives water that has been in contact with mineral soil or bedrock; (2) Peatland where the peat is or has been formed under geotropic (see *Geotropic*) conditions.
Fen peat: Peat formed by fen vegetation (mainly sedges, cottongrasses, reed, brown mosses).
GEST approach: Using vegetation components as a proxy for a certain emission level of peatlands, an instrument developed as a rough assessment of greenhouse gas emissions before and after rewetting of drained peatlands to avoid costly direct greenhouse gas measurements (Couwenberg 2011).
Global warming potential (GWP): An index describing the radiative characteristics of well-mixed greenhouse gases that represents the combined effect of the differing times these gases remain in the atmosphere and their relative effectiveness in absorbing outgoing infrared radiation is known as global warming potential. This index approximates the time-integrated warming effect of a unit

mass of a given greenhouse gas in today's atmosphere, relative to that of carbon dioxide (Adhikari et al. 2011).

Geogenous: Originating from the lithosphere, the pedosphere or the sea (e.g. water feeding a mire).

Geotropic: Supplied with nutrients by the lithosphere and the pedosphere. See *Minerotrophic*.

Greenhouse effect: Warming that results when solar radiation is trapped by the atmosphere; caused by atmospheric gases that allow short wave radiation to pass through but absorb long wave heat that is radiated back from the warmest surface of the Earth.

Greenhouse gas: Any gas in the atmosphere that contributes to the greenhouse effect. These include primary carbon dioxide, methane, ozone, nitrous oxide, CFCs and water vapour. Most occur naturally as well as being created by human activity.

Greenhouse gas emissions site types: Mire vegetation form classified to indicate quality and quantity of greenhouse gas emissions.

Groundwater: (1) All water beneath the land surface; (2) All underground water beneath the water table.

Groundwater level: Level of water under land surface in which pore spaces are saturated.

Habitat: The ecological environment of an organism or community.

Hydrology: (1) The occurrence, circulation, distribution, and properties of the water's of the Earth and its atmosphere; (2) The study of the occurrence, circulation, distribution, and properties of the water of the Earth and its atmosphere.

Hummock: Mire feature raised 20–50 cm above the lawn or carpet and characterised by *Calluna vulgaris* and other dwarf shrubs and bryophyte and lichen species occurring in relatively dry environments.

Kettlehole mire: Self-sealing water rises mire in a kettle-shaped basin without contact with the regional groundwater that is fed by precipitation and interflow and grows by forming a progressively higher impervious layer in the previously permeable mineral subsoil of a basin.

Lagg: A fen strip between a bog and the surrounding mineral surface.

Lawn: Mire feature, situated generally 5–20 cm above the water table, with a dominance of graminoids whose roots and rhizomes make the lawn so firm that a footprint rapidly disappears.

Lithosphere: The solid portion of the Earth, as distinct from the atmosphere, hydrosphere, the pedosphere, the biosphere, and the noosphere.

Mineral soil: Any soil that is not organic.

Minerotrophic: Supplied with nutrients by the lithosphere and the pedosphere.

Mire: A peatland where peat is currently being formed and accumulating.

Mire complex: The entire extent of a mire area bounded by mineral soil. Formed by fusion or combination of various mire massifs; often comprise large areas.

Mire expanse: Mire site, mostly extensive open mire with deep peat, centrally situated in a mire massif.

Mire margin: Type of mire site at the margin of a mire massif, e.g. the rand of a raised bog or shrubs and trees on thin peat in case of fens.

Mire massif: The structural and functional element of the mesotope level of organisation in mires.

Mire site: The structural and functional element of the microtope level of organisation in mires, including mire expanse (see *Mire expanse*), lagg (see *Lagg*), mire margin (see *Mire margin*).

Mire type: A distinct entity in a mire classification system.
Mixed mire: Mire massif where minerotrophic and ombrotrophic patches are interspersed.
Oligotrophic: Fed by very few nutrients.
Ombrogenous: Originated under the influence of solely precipitation water.
Organic: Resulting from carbon chemical biosynthesis
Peat: Sedentary accumulated material consisting of at least 30% (dry weight) of dead organic material. Peat formation from dead plant particles in mires, where they do not decompose completely in water due to lack of oxygen.
Peat accumulation: (1) Accumulation of peat (process); (2) Peat deposit (result).
Peatland: An area with a naturally accumulated peat layer at the surface.
Percolation: Diffuse flow of groundwater through a porous medium without a definite channel, e.g. in a percolation mire.
Phreatic water level: The water table in an unconfined aquifer or the groundwater table.
Piezometer: A device which measures the pressure of groundwater at a specific point. They can be read by data loggers or portable readout units, allowing faster or more frequent reading (Dunnicliff 1993).
Piezometric station: A group of piezometers for groundwater pressure measurement in different depths of a sediment; here, in peat deposits.
Plant community: A collection of association of plant species that forms a relatively uniform patch and that is distinguishable from neighbouring patches of different communities.
Raised bog: Peatland with its surface and water level clearly raised above the surrounding, geogenous mire that receives water and nutrients only from the atmosphere.
Soil: The portion of the Earth's surface consisting of a mixture of minerals, organic matter, gases, liquids, and countless organisms.
Special purpose clearings: Forest clearings to create an open peatland landscape, preserve and restore typical mire habitats and biodiversity.
Terrestrialisation: The accumulation of sediments and peat in open water.
Terrestrialisation mire: Mire type in hydrogenetic mire classification: mire formed by peat formation in open water.
Thinning: Removal of excess trees above the natural tree density during the restoration of tree-colonized peatlands.
Transitional mire: (1) Mire with properties between a rich fen and a bog, i.e. a mire characterized by a dominance of *Sphagnum* species together with some mineral soil water indicators covering poor fen and intermediate fen; (2) Mire with medium nutrient availability; (3) Mire that in a drained state is covered by at least 20 cm of birch peat, pine peat or *Scheuchzeria*-brown moss peat; (4) Mire in a stage of succession from geogenous to ombrogenous peat growth.
Transpiration: The process by which plants (and animals) release water vapor to the atmosphere.
Vegetation: The plant cover at a given place taken as a whole.
Vegetation form: Vegetation type based on the joint classification of vegetation and environmental conditions.
Water level: Absolute elevation of a phreatic water surface in relation to datum (see *Water table*).
Water table: Elevation of a phreatic water surface relative to the soil surface (see *Water level*).

Abbreviations

a.s.l. – above sea level
CO_2-eq – carbon dioxide equivalent
EU – European Union
GHG – greenhouse gas
GEST – Greenhouse Gas Emissions Site Types
GWP – Global Warming Potential
LAI – Leaf Area Index, defined as the one-sided green leaf area per unit ground surface
NDVI – Normalized Difference Vegetation Index
SPN – Słowiński National Park
UAV – Unmanned Aerial Vehicle (drone)


Photo: M. Pakalne

Introduction

Although peatlands cover only 3% of the global terrestrial surface, they have a diverse and significant impact on both nature and human needs. Healthy peatlands are critical for preserving biodiversity, provide safe drinking water, food, medicinal plants, fodder and fibre, minimise flood risk and contribute to climate change mitigation (IUCN 2021). Peatland ecosystems belong to wetlands and play an important role in nature as they regulate climate through sequestering carbon from the atmosphere and storing it in peat sediments. They provide habitats for many plant and animal species that are unable to live in other environments. Peatlands are part of a hydrological network that links streams, rivers, lakes, water flows, water level and water quality; they improve groundwater supply and support water resource management (IUCN 2021). Peatlands worldwide contain around 650 gigatonnes or 30% of planets' soil carbon, twice as much as all forests on the Earth (FAO 2020).

However, these ecosystems are affected by human activity, mainly drainage, thus converting them into important sources of greenhouse gas (GHG) emissions. Degraded peatlands annually release almost 6% of global anthropogenic carbon dioxide (CO_2) emissions. In terms of biodiversity conservation, nowadays peatlands are among the most threatened habitat types in Europe. According to the European Union's 2010 Biodiversity Baseline adopted in 2015 (EEA 2010), 87.3% of European wetlands are in unfavourable conservation status.

The year 2021 marks the first year of the United Nations Decade on Ecosystem Restoration highlighting the tremendous need to keep ecosystems functional and turn back their degradation as a task for humankind of utmost importance. Countries are encouraged to include peatland restoration in their commitments to global international agreements, including the Paris Agreement on climate change. Peatland restoration has been proven to be cost-effective as a nature based solution compared to other available carbon reducing technologies. It also has the added bonus of re-establishing the multiple benefits arising from peat-forming ecosystems (IUCN 2021).

The LIFE Peat Restore project "Reduction of CO_2 Emissions by Restoring Degraded Peatlands in Northern European Lowland" (LIFE15 CCM/DE/000138, 2016–2021) was financed by the European Commission, LIFE subprogramme "Climate change mitigation and adaptation". The project contributed to the mitigation of climate change in different climatic regions (from 52° NL to 59° NL) in the lowlands around the Baltic Sea in five European countries: Germany, Poland, Lithuania, Latvia, and Estonia. The project highlighted the need to pay attention to degraded peatlands and demonstrated restoration as a tool to reduce CO_2 emissions and mitigate climate change, covering 5300 hectares.

The overall objective of the LIFE Peat Restore project was to reduce CO_2 emissions that cause climate change by restoring degraded peatlands. The project aimed to mitigate the situation by supporting CO_2 uptake by raising and stabilising the water table, thus re-creating conditions for the establishment of peat-forming vegetation, accumulation of organic matter and inducing a significant reduction of GHG emissions. In order to achieve these goals, the LIFE Peat Restore project initiated restoration in different types of degraded peatlands: post-harvested peat fields (bogs), slightly to heavily drained raised bogs, fens, transitional mires, and fen and bog woodlands using different techniques.

The results and experience of the project are summarised in this Best Practice Book for Peatland Restoration and Climate Change Mitigation providing guidelines and experiences for decision makers and experts. The Best Practice Book aimed to provide scenarios for the peatland restoration and to demonstrate the process, as different peatland types and variable disturbance levels require specific decisions and techniques in restoration that may vary from site to site.

The preliminary results in 2021 reveal that the peatland management actions support CO_2 uptake or reduction of CO_2 emissions through raising the water table that creates suitable conditions for peat-forming vegetation and eventually accumulation of organic matter. As a result, peat-forming mire vegetation has started to re-establish which is the first step towards the recovery of functional peatland ecosystems. It is estimated that the project has an impact of reducing around 9890 t of CO_2 eq/yr emissions (derived from estimates of indirect GEST approach).

Photo: M. Pakalne

1.

OVERVIEW OF THE PROJECT SITES

Photo: M. Pakalne

The LIFE Peat Restore project sites (Figure 1) represent different peatland types of the region around the Baltic Sea: raised bogs, transitional mires and fens, forested peatlands and lakes. The sites have been affected by peat extraction and drainage. Although all peatlands included in the LIFE Peat Restore project have a protection status (Table 1), they were degraded, and therefore restoration was needed.

Figure 1. *Location of the LIFE Peat Restore project sites in Estonia, Latvia, Lithuania, Poland and Germany.*

Table 1. *General information about the LIFE Peat Restore project sites*

No.	Project sites (mostly within Natura 2000 sites)	Project area (ha)	Management area (ha)
1.	Suursoo-Leidissoo peatland (EST)	3 343	3 343
2.	Augstroze peatland (LV)	1 880	95
3.	Engure Lake peatland (LV)	106	106
4.	Baltezers peatland (LV)	228	41.6
5.	Sachara peatland (LT)	82	82
6.	Pūsčia peatland (LT)	81	81
7.	Aukštumala peatland (LT)	10	10.0
8.	Amalva peatland (LT)	215	215.0
9.	Słowiński National Park: Kluki, Ciemińskie Błota, Wielkie Bagno peatlands (PL)	1310	808.0
10.	Biesenthaler Becken (DE), three peatlands	15.5	15.5

2.

PEATLAND RESTORATION

Photo: M. Pakalne

The peatland restoration within the LIFE Peat Restore project covered a rather wide range of actions and methods including innovative restoration approaches. The experiences are presented in this Best Practice Book, thus being available for decision makers, conservationists and others involved in peatland restoration.

Peatland restoration is a term used to describe management measures that aim to restore the original form and function of peatland ecosystems. The principal activity involved in restoration is a management for improving the site hydrology which, in turn, reduces greenhouse gas (GHG) emissions, such as carbon dioxide. Depending on the degree of degradation, peatlands may need rewetting and other actions to improve the peatland condition using a variety of techniques, such as peat dams, plastic piling and bunding, tree removal, transfer of *Sphagnum* or introduction of other peat-forming vegetation, or introduction of grazing, controlled burning, improvement of water quantity.

2.1. Pre-restoration requirements

Before starting peatland restoration, management or restoration plans and documentation such as technical designs must be prepared. The type and contents of the documents may differ in various countries. The first steps toward a restored peatland include planning and obtaining various permissions, as required by the national legislation.

In the case of the LIFE Peat Restore, most of the project areas did belong to the Natura 2000 network for which site management plans should be developed. Site management plans are planning documents that contain assessment and description of the ecological conditions of the protected area or part thereof, problems and opportunities for landscape protection and management, protected threatened species, and natural and semi-natural habitats. The plans define the objectives of management and protection measures (e.g. restoration of mire habitats), foresees the necessary funding and assigns the responsibilities for the implementing parties. Desktop studies are made by analysing the land cadastre, peatland drainage of the study site, soil, various databases, ownership of the site and the surrounding areas, identifying the stakeholders including the local communities, which are introduced with the proposed measures and their justification during the process. Depending on the legislative framework in a particular country and the funding available, the management plans can be developed by either the nature conservation authorities themselves or other parties, such as non-governmental organisations, contracted environmental consultants or land managers. Commonly, management plans are valid for 10–15 years, and then they should be updated, or a new plan must be developed. The plans are approved by the responsible authorities; mostly it is the competence of national ministries responsible for the environment.

Among the project countries, in Latvia and Lithuania, such management plans had to be developed to ease the procedure for approving the planned peatland restoration. In Germany, the examination of an existing Natura 2000 management plan had to prove that the planned peatland restoration measures do not violate conservation objectives or do not deteriorate the condition of the target habitats or species, i.e. habitats listed in Annex I of the Council Directive 92/43/EEC (1992/05/21) or species listed in Annex II are preserved in favourable conservation status, or, specifically, the ecological continuity of existing natural streams is maintained. In Estonia, specialists in mire ecology and restoration are often not involved in the development of Natura 2000 site management plans. Therefore, these management plans are sometimes too general, i.e. they only define the need for restoration and indicate the approximate management area. In this case, the restoration objectives, restoration areas and the specific restoration actions must be planned either within a special restoration plan (a separate document) or during the preparation of the technical design. In Lithuania, in most cases, especially in protected forests, timber removal if necessary for peatland restoration must be included in the forest management plan.

Before restoring the hydrological regime, it is very important to carry out a comprehensive inventory and planning that may include modelling. Since such details are often not available in the site management plans, they must be specified in the following detailed planning work stage.

Hydrological modelling helps to determine the potential impacts of restoration, the potential restoration effect and the most appropriate locations of dams or other constructions (several alternatives may be included in the model). Hydrological modelling, apart from investigating the conditions of the water cycle in the peatland by determining the zones of water supply, flow and drainage, is also used in predicting the effects of the planned restoration measures. Its purpose is therefore to evaluate these actions by quantifying and spatially determining the retention of the site. The simulation covers the retention state that can occur under extreme (anomalously high or low) conditions and under average precipitation.

For example, in Poland, the groundwater model for the area of Słowiński National Park was developed using the MODFLOW 2005 calculation algorithm (Harbaugh 2005), based on the partial differential equation of groundwater flow. The model considers the geological structure of the peat deposit and the mineral substrate. On this basis, the filtration coefficients of aquifers were determined, which amounted to 0.232 m/d (for peat) and 5.15 m/d (for sands), respectively. The model simulation was supplemented with data on fluctuations in groundwater level, the course of the drainage network as well as data on precipitation and evaporation. Model calculations were carried out with the use of a calibrated model in the zero variant (modern hydrological conditions of the study area) and in the variant taking into account blocking of the ditches. The modelling results were presented in the cartographic materials as the ordinates of the water table, also in the variant for different weather conditions.

In Latvia, the hydrogeological model LAMO (Spalviņš et al. 2012) was used to understand the interaction between the groundwater and surface water, as well as the lower horizons, as it may be important for restoring the water level in fens. The model allowed calculating various elements of the water cycle both in various flow directions and at different depths and to present the results on the map providing at least two alternatives for raising the water level.

For modelling the expected changes, developing or using digital terrain models is recommended. In areas where such digital terrain models are not available, data obtained by LiDaR laser scanners can be used before rewetting to create the model, especially in large areas. In smaller areas, also land-based levelling tools can be utilised.

The location of dams on the drainage ditches should be chosen not only considering the slope inclination or water flow direction in peatlands and other site conditions but also pragmatically assessing the accessibility options and possibilities to transport materials for dam construction. Dam width, height and stability should be planned in a manner to prevent damage to the dams by the water flowing along the ditch or around it. Based on these studies and plans, the technical designs are developed providing all the necessary information about the location and type of dams or other constructions.

The technical designs for the restoration of the peatlands' hydrological regimes are prepared by experts with the relevant licence or certificate or specialised companies who hire the relevant specialists. In collaboration with ecologists and biodiversity experts, they define the target water level and concrete actions and technical solutions to achieve the target. It may consist of technical parts (elevation models, water flow directions, technical parameters of drainage ditches, drawings of dams, etc.) and cost estimations. Technical designs are agreed upon by the responsible authorities, such as administrations of the district, the administrations of the protected areas and eventually other involved stakeholders, e.g. the road authorities or owners of the surrounding lands (country- and site-specific). Restoration of the hydrological regime must avoid any damage to the functioning drainage systems outside the project site or to modify the hydrological conditions in the surrounding areas and in other properties.

In order to get more information about the hydrology of the site, it is recommended to establish a system of hydrological monitoring which provides valuable data on the water level before restoration and its dynamics after rewetting (see *Chapter 3.4*).

2.2. Peatland restoration techniques

Peatland restoration should always primarily focus on rewetting, i.e. restoring the water table that allows re-establishment of a functional peatland ecosystem that accumulates peat and carbon. There may be some additional measures, such as reintroduction of peat-forming vegetation or removal of excessive tree cover, however, these actions are supplementary to gain better results, while rewetting is the most important measure in restoring peatlands.

The choice of restoration options in drained or post-harvested peatlands depends on several factors such as hydrogeological and topographical conditions, surrounding landscape and the intensity of land use, attitude of the landowners or managers. According to the current situation in the particular area, the most appropriate peatland restoration techniques are chosen, for example, blocking or filling the ditches, removal of trees or reintroduction of the target vegetation.

In post-harvested peatlands, if there is a residual peat layer and presence of peatland species either on the restoration site or in the surrounding area, and the area is not entirely overgrown with forest or converted into another land use type, restoration of peatland-specific conditions, processes, and vegetation may be still possible. If due to low water level the peat surface has been dry for a long time, the upper layer of peat decomposes, and its water storage capacity significantly decreases. Thus, post-harvested peatlands have to be rewetted as soon as possible after peat extraction, as long as the properties of the uppermost layer of the remnant peat have not changed. In heavily overgrown areas, first, trees and shrubs should be removed so that they do not interfere with the movement of machinery, do not increase the evapotranspiration from the peatland surface and do not hinder the vegetation recovery after rewetting (Rochefort, Lode 2006).

2.2.1 General principles in peatland rewetting

Peatland rewetting is necessary if the peatland and the growth of peat-forming mire plants are unfavourably influenced by drainage. It means that the hydrological and trophic conditions are not any longer suitable for the peat-forming vegetation and, consequently, the peat formation and carbon sequestration process is disrupted. Therefore, in order to restore the conditions favourable for the particular mire type, it is essential to restore the original hydrological regime or at least to improve the conditions as far as possible. This can be done by interrupting the drainage system installed in the past, i.e. by filling or blocking the ditches or building other types of constructions to raise and stabilise the water level.

Peatland rewetting by filling the ditches or installing the dams on drainage ditches is a well-approbated and widely applied method in many countries (Figure 2, 3). Different types of dams and other types of constructions may be used: peat, mineral soil, plastic, wooden or composite dams. The ditches may be filled with peat or mineral soil, thus eliminating their effect on peatland. In exceptional cases when the dams or filling of ditches cannot ensure the desired water level, other constructions can be installed, e.g. dikes, sluices, barriers in sloping (inclining) mires or other depending on the site conditions and possibility of the machinery to reach the restoration area.

Deciding on how to restore a peatland depends on understanding the peatland type, its functionality, relation to the surrounding landscape and the past management (McBride et al. 2011). Generally, planning and implementing bog restoration is usually less complicated than the restoration of fens. Fens are often complex areas with more complicated hydrological conditions and feeding regimes than bogs. Before taking decisions on fen restoration and the solutions, much more thorough monitoring should be done than in bog restoration. There are common techniques in fen and bog restoration, though there are differences in locating the dams or other constructions to achieve successful results.

Figure 2. *Building a peat dam by an excavator. Photo: M. Pakalne.*

Figure 3. *A ditch filled up with peat. Photo: A. Priede.*

The surface of raised bogs is dome-shaped with slopes, thus the number of dams in raised bogs must be larger than that in fens occurring in flat areas. In raised bogs, the location and number of dams on the ditches depends on the dome slope inclination. The bigger the inclination, the more dams are needed to achieve the desired water level. A higher number of dams or filling the ditches ensures higher rewetting efficiency. In fens, the number of dams may be smaller, however, their locations are based on different principles than in raised bogs.

2.2.2. Removal of trees and shrubs

Artificial disturbance of the hydrological regime of peatlands and the expansion of trees are interrelated. Therefore, in peatland restoration a comprehensive approach is necessary, and all measures should be planned sequentially. If an effective rise in the water table is expected following blocking of the drainage system (particularly in areas where tree cover is not dense) a decision on the need for felling or thinning of trees should be taken during the planning process. Removal of trees may improve the results of peatland rewetting and promote faster recovery of the ecosystem; however, it is expensive, as it requires extra machinery and careful planning to minimize the ground damage. Moreover, often it is difficult for the public to accept such an activity, therefore it may require voluminous explanatory work.

Figure 4. *Manual removal of trees in a drained bog before rewetting (Sachara peatland, Lithuania, March 2020). Photo: Ž. Sinkevičius.*

As a part of the LIFE Peat Restore project, special purpose clearings were carried out in the Amalva, Sachara and Pūsčia peatlands (Lithuania, Figure 4). Similar work (clear cutting or thinning) was done in the Polish restoration areas in Słowiński National Park that had been severely damaged by drainage and peat extraction. Partial removal of shrubs and trees to prevent the overgrowth of a fen was carried out in the Engure Lake restoration area in Latvia. In the comparatively less degraded Suursoo-Leidissoo peatland (Estonia) and in the Baltezers and Augstroze peatlands (Latvia), the trees and shrubs were not cleared – it is expected that a certain proportion of the tree will die after rewetting.

An overview of the LIFE Peat Restore approaches concerning tree management in various project areas is given in Figure 5.

Many peatlands suffer from insufficient water provision in their catchment area, especially isolated kettlehole mires embedded in forest landscapes on mineral soil. In many cases in northeast Germany, originally surrounding deciduous forests had been converted into planted coniferous forests. Typically, in the latter, only tiny proportions of the annual precipitation benefit the groundwater due to higher interception and evapotranspiration while beneath deciduous trees, such as beeches *Fagus sylvatica* due to their smooth bark and lack of foliage in winter around 20% of the annual precipitation infiltrates into the groundwater (Müller 2009) and consequently in its catchment area also the peatland. In order to improve the water provision to such peatlands, forest conversion measures aim at shifting the dominance of often not site-typical coniferous tree cover to more deciduous trees (e.g. cutting conifers, planting deciduous trees, see *Chapter 4.1.4*).

Deciduous trees (especially birches in areas drained for a long time) or shrubs often establish

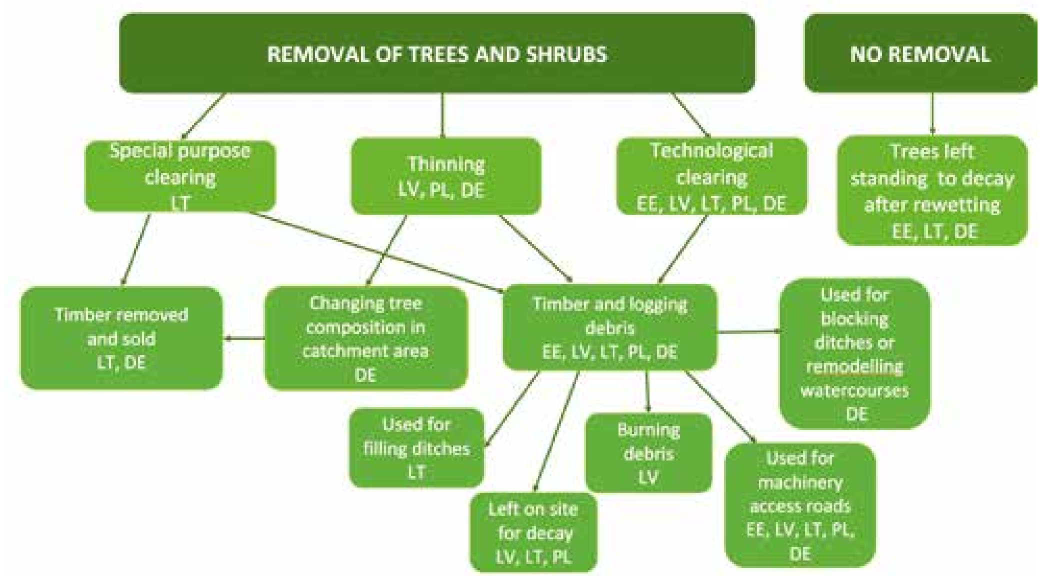


Figure 5. *An overview on different approaches on removing woody biomass from the peatland restoration areas in LIFE Peat Restore sites; more details given in this chapter and the following chapters.*

and form dense stands in drained peatlands. It may happen that even after raising and stabilising the water level, rapid regrowth often occurs from dormant buds below or above the peat surface. Therefore, repeated cutting of regrown sprouts may be necessary, especially if rewetting has not been effective enough due to lack of precipitation or due to other reasons during the initial phase after the implementation of restoration measures. When planning rewetting of such areas, this should be considered as potential extra costs.

In drained peatlands, thinning or removal of excess trees (above the natural tree density) combined with rewetting has a positive effect on the success of the restoration. In such cases, economically valuable trees can be selectively removed, leaving trees that are typical to natural mires, e.g. dwarf forms of Scots pine *Pinus sylvestris* (in bogs), as well as old trees that are important for biodiversity. In addition, it is advisable to leave the forest groves or groups of trees in higher elevations in peatlands (also on natural mineral "islands"), where it is not possible to achieve a high water level, as it would be necessary for the restoration of an open or semi-open mire. This principle was followed in the restoration of the Pūsčia peatland in Lithuania (see *Chapter 4.2.4*).

It is not always possible to remove all timber and logging debris from the restoration areas due to high cost, difficulties to agree with the owners of the surrounding lands, and other obstacles. It is possible to use "low-value" timber and branches from felled trees to fill some sections of the drainage ditches between the dams (this was practised, for example, in Amalva Sachara and Pūsčia peatlands, Lithuania). This measure can create favourable conditions for the re-establishment of *Sphagnum* mosses and other peat-forming vegetation in the ditches, which, in turn, are also important for water retention. Additional leftover timber can be placed in piles, which become a shelter for invertebrates and reptiles and left for biodegradation. This method was used in the LIFE Peat Restore areas in Słowiński National Park in Poland.

However, tree removal from peatlands as part of restoration is still subject to discussions among the peatland restoration experts, foresters, and local communities. Nevertheless, it may be an important part (but not mandatory) of the peatland restoration depending on the condition of the peatland to be restored, aims of restoration, technical possibilities to remove harvested timber from a restoration area, and economical substantiation including aspects of sustainability. The removal of shrubs and trees should be also seen in the light of public reactions to restoration measures: most shrubs and trees in a restoration site might die after rewetting, which may lead to incomprehension among the local community, visitors and other stakeholders. Similar reactions might occur when large scale tree removal prior to rewetting measures take place. Stakeholder engagement and communication should go hand in hand with restoration planning and implementation to explain to the public the purpose of the restoration and the reasons for the selected approaches.

2.3. Experimental restoration measures in post-harvested peatlands

Experiments on the restoration of post-harvested peatlands have started all over the world relatively recently, but several effective techniques have already been proposed, which are reviewed in various publications related to the restoration of peatlands (e.g. Joosten, Clarke 2002; Quinty, Rochefort 2003). Turning post-harvested peatlands into viable ecosystems is indeed a challenge if the bare surface of peat does not have any vegetation, is severely damaged and has changed its physico-chemical properties. In case the desired species do not establish spontaneously, reintroduction can be considered as an option.

Recently a new approach of peatland rehabilitation has been developed and adopted in several countries (e.g. Canada, Germany), which enables establishment and even utilisation of peat-forming vegetation (paludiculture) using modern technologies. Thus, not only valuable ecosystems are restored, but also renewable alternatives (biomass) to depleting raw fossil materials can be grown.

During the LIFE Peat Restore project, reintroduction of peat-forming vegetation was implemented using both *Sphagnum* spreading on bare peat (in Aukštumala peatland, Lithuania; see *Chapters 2.3.1, 4.2.6*) and installing vegetated floating islands in post-excavated water basins (in Słowiński National Park, Poland; see *Chapters 2.3.2, 4.2.2*).

2.3.1. Reintroduction of *Sphagnum* and other mire species

In post-harvested peatlands, restoration of the mire ecosystem with its key functions such as peat accumulation, carbon sequestration, re-creating and supporting biodiversity is highly recommended. This could at least partially compensate for the negative environmental impact caused by peat extraction. In the long term, only a properly restored hydrological regime in post-harvested peatlands suitable for the establishment of target mire vegetation can create favourable conditions for the recovery of the peat accumulation process. In case the desired species do not

Figure 6. *Sphagnum planting by volunteers in a post-harvested peatland in Aukšumala, Lithuania, in September 2019. Photo: L. Šveistytė.*

establish spontaneously, reintroduction can be considered, e.g. by direct seeding, planting pre-grown seedlings, transplanting sods from nearby donor mires, spreading *Sphagnum* sods (Figure 6), planting pre-grown plugs (Schumann, Joosten 2008; Joosten 2021). The most appropriate approach to be chosen depends on the peatland type, availability of donor material and various practical considerations.

During the last three decades, targeted reintroduction of peat-forming vegetation experiments was carried out: (1) in post-harvested peatlands, for example, in Canada (Bugnon et al. 1997; Quinty, Rochefort 1997, 2003), Germany (Beyer, Höper 2015; Wichmann et al. 2017), the United Kingdom (Money et al. 1995), Finland (Tuittila et al. 2003), Estonia (Karofeld et al. 2016; Purre, Ilomets 2018; Purre et al. 2020, 2021), Latvia (Pētersons et al. 2019), Lithuania (Jarašius 2015); (2) in drained, cultivated fens converted into meadows and pastures in Germany (Gaudig et al. 2014, 2018; Wichmann et al. 2017), Netherlands (Schrader (ed.) 2016); (3) on floating islands in shallow ponds in abandoned post-harvested peatlands in Germany (Blievernicht et al. 2013; Wichmann et al. 2017), Japan (Hoshi 2017); (4) in laboratory conditions and greenhouses in the United Kingdom (http://www.beadamoss.co.uk/; Caporn et al. 2017) and Germany (Beike et al. 2014).

Reintroduction of peat-forming vegetation is a costly and time-consuming method in peatland restoration, but it is justified if the hydrological restoration alone does not sufficiently support the formation of peatland vegetation. Such places are post-harvested peatlands that have remained unvegetated for a long time. In many cases, self-regeneration of peat-forming vegetation is not possible or is insufficient due to low water level. Raising the water level in the post-harvested peatland, its stabilization and maintenance are crucial for the establishment of peat-forming vegetation, therefore reintroduction of the target plant species must always be combined with rewetting.

Before re-establishment of peat-forming vegetation, a thorough analysis of the ecological conditions of the particular area, including investigation of peat and water properties, as well as the dynamics of water level must be carried out. Although the process of peat-forming vegetation establishment might differ depending on the specific site conditions, it usually consists of several common stages: planning, preparation of the site (drainage system, surface levelling), collection of donor material, establishment of donor material (e.g. sowing, planting, dispersal of vegetation fragments or sods), and maintenance of favourable hydrological regime.

2.3.2. Establishment of floating islands

Water bodies formed after peat extraction may improve landscape diversity and provide valuable habitats for many bird species. If they are small and shielded from wind effects, the peat-forming vegetation may naturally regenerate over time if the water level is favourable for its development. This is not, however, the case of large flooded former peat excavation basins that are exposed to the wind, created by large scale industrial peat extraction. In such cases, spontaneous regeneration is hindered by waving. Considering the problem, it is important to find a solution to enable the development of peat-forming vegetation in such water bodies.

Natural floating islands, i.e. floating fragments of mire vegetation may be found in dystrophic lakes. The idea of creating similar artificial floating islands is not new, though in most cases, they have been used for different purposes. Such islands have been built across the world: in most cases the purpose was to improve the water quality, to manage stormwater or to establish or diversify a habitat for birds (Headley, Tanner 2006; Xiuzhen et al. 2009; Van de Moortel et al. 2010; White et al. 2012; Wu et al. 2015; Yeh et al. 2015). This method is particularly effective in warm and humid tropical and subtropical climates. In such climate zones, the wetland vegetation grows throughout the year. Numerous examples of floating islands may be found in the United States, Japan and some countries in Southeastern Asia. Some countries in Europe have also constructed floating islands, including Germany and Lithuania (Live Lagoons Project). Many different types of materials are used to build floating islands including widely used, artificial materials for various constructions, coconut mats and wood. All sorts of floaters (buoyancy elements) are often used in the construction process to assure the islands' ability to float on water. Fast-growing wetland vegetation is often used to cover the islands; the plant species composition depends on the climate zone.

The LIFE Peat Restore project team in Poland carried out an experiment in a former peat-extraction water basin, where floating islands based on wooden constructions were anchored to the bottom of the water body and vegetated with the target plant species (Figure 7). It was decided to use natural materials, mostly wood, expanded cork and coconut mats. The constructed floating islands became inhabited by species typical of partly immersed peat communities. In the future, this method may also be used in other flooded post-harvested peatlands and find use in other types of water bodies. Details of the experiment are discussed in *Chapter 4.2.2*.

Figure 7. *The first island prototype developed during the LIFE Peat Restore project: in May 2017, just after planting the vegetation (A), and two years later, in summer 2019 (B). Poland, Wielkie Bagno. Photos: K. Bociąg.*

3.

MONITORING OF PEATLAND RESTORATION SUCCESS

Photo: M. Pakalne

3.1. Monitoring methodology

The process of peatland recovery following rewetting is long-lasting and may take several decades. The success of restoration depends on different factors, and efforts may not proceed exactly as planned. There is no common efficient and effective restoration technique or complete "blueprint" that fits all damaged peatlands. The restoration practice during implementation gives "…lessons that should be incorporated in subsequent work and future planning" (Joosten 2021). Therefore, well-designed monitoring of restoration is of great importance in learning lessons of implementation success or failure. There are some main principles one can consider in the monitoring of the ecosystem recovery process.

The monitoring programme, especially if the process may last for decades, should be adaptive in means it can be developed in response to new information, new technologies, in adopting new sampling and analytical methods to be used. The monitoring programme should be designed so that it may be quickly adapted to the deflections from the proposed state, to find the reasons and solutions to improve and move the process in the desired direction.

Lindenmayer and Likens (2010) presented a list of some critical components for effective monitoring programmes. Among others, they emphasized the preference of permanent plots instead of random sampling, constant updating and reviewing of data sets (including scrutinization for errors), availability of adequate, sustained and reliable funding. Also, it is important that the analysis of data enables trustworthy results to be significant statistically.

It is crucial to start monitoring before restoration and continue monitoring during the project for finding out whether goals are being achieved. The post-project monitoring informs about needs for additional actions or adjustments.

In restoring damaged peatlands, the monitoring of hydrology and vegetation are the most important indicators to be implemented. Depending on the site conditions (e.g. type of peatland, degree of degradation, level of heterogeneity) the design of the monitoring system may vary.

In the LIFE Peat Restore project sites, the monitoring system contained measurements of biota (vegetation mapping and changes in the plant species composition) and habitat conditions (water level and its fluctuations, precipitation, water and peat chemistry, air temperature, GHG). Joint vegetation, hydrological and GHG monitoring methodologies were developed and applied in all five project countries.

3.2. Vegetation monitoring

Vegetation monitoring aims to follow the peatland vegetation changes before and after the management actions, as plant communities respond both to long-term changes, such as climate change, and short-term management measures. Temporal changes in plant cover and composition is a widely used indicator for assessing restoration success. It concerns long-term recovery processes, as it is common in bringing a peatland ecosystem on a trajectory of recovery focusing on attributes, such as suitable physical and nutritional conditions, species composition, structural diversity and functionality of damaged peatlands. The recovery process of peatlands is not unidirectional and depends not only on the hydrological conditions but also is driven by peat and water quality dynamics.

Figure 8. *Tree diameter and height measurements in Suursoo-Leidissoo, Estonia. Photo: R. Pajula.*

In assessing the ecosystem dynamics more thoroughly, the most commonly used method is the recording of plant species present in permanent plots and the evaluation of their cover (Priede (ed.) 2017). The number and size of the sample plots may vary depending on the vegetation pattern, spatial heterogeneity and the size of the area. Plots should be marked with poles or in other ways to ensure that exactly the same location is found in the subsequent years. Also, the geographical coordinates of the plot centres or corners should be recorded. No universal monitoring method can be advised for all situations. Therefore, in each case, the situation should be assessed on site and a decision made as to where and how the monitoring sampling plots should be established. To produce comparable data on plant species richness, plot size and location have to be standardized (on a site level at least), and the taxonomic level of the inventory has to be fixed.

The data obtained can be statistically processed before restoration and during the vegetation succession after implementing the restoration measures. In order to monitor the vegetation dynamics, the LIFE Peat Restore team established a monitoring scheme that consists of permanent study plots (10 × 10 m). The number of these plots depends on the size and uniformity/heterogeneity of the area. These plots were used for estimation of trees (species, height, age, diameter; Figure 8), cover of shrubs, plant species composition and cover. Smaller (2 x 2 m or 1 x 1 m) subplots within the 10 x 10 m plot (Figure 9) were used to estimate the herbaceous plant and moss species composition and cover (see also the Estonian example in *Chapter 4.1.1*).

Figure 9. *Plant cover estimation in Suursoo-Leidissoo, Estonia. 10 x 10 m monitoring plot with smaller subplots, their borders marked with a tape. Photo: R. Pajula*

3.3. Vegetation mapping

Vegetation mapping, application of aerial photographs and satellite imagery are useful tools to monitor the spatial distribution of habitats and microhabitats, such as open water bodies, dry and wet spots, bare peat. Their location, extent and spatial configuration may change after restoration, therefore the information reflects the character of changes over a broader scale than plot-based vegetation monitoring, and both monitoring approaches may be combined.

The primary and preliminary information about the site state can be obtained from aerial photographs or remote sensing images. It is particularly important in cases when the area is large. The next step is to visit the site and find relations between the units distinguished on maps and actual habitat types (vegetation units).

Vegetation mapping of large heterogeneous areas, such as Suursoo-Leidissoo in Estonia (3343 ha), one of the LIFE Peat Restore areas, is challenging, as the vegetation forms a mosaic with transitions between the types. In such cases, an integrated method may be used for mapping the vegetation: data of the field studies together with maps data and remote sensing data (aerial photographs, satellite data, LiDaR data and drone images). In the case of Suursoo-Leidissoo, the main basis of mapping was the latest available orthophoto map compiled by the Estonian Land Board. To distinguish some vegetation types that were similar on orthophoto maps, *Sentinel* multispectral satellite data via *Sentinel Playground* (Sentinel Playground) and *Copernicus Open Access Hub* (Copernicus) were used. Also, data collected by drone (both the visual spectrum and multispectral data) were used. The normalized difference vegetation index (NDVI) map was calculated from the multispectral data. NDVI reflects well the cover of vascular plants and allows distinguishing the vegetation types. When mapping vegetation units that were distinguished (larger than 0.2 ha), relatively broad vegetation classes were used that indicated the trophic level of the mire communities and the presence of woody cover. The reason for choosing relatively broad vegetation classes was that they can be mapped more accurately and reliably throughout the area.

However, in many areas, especially in relatively small peatlands, the mapping may be simpler if the vegetation is rather homogeneous. Then it may be enough with a field survey using orthophoto maps or combined with some other maps (e.g. topographic maps or LiDaR data).

3.4. Hydrological monitoring

Monitoring of hydrological parameters in peatland ecosystems involves observing and recording water levels across the site. In case if management is planned, it may be important to monitor the peatland over a sufficiently long period to understand its "behaviour" in different weather conditions, including drought events and excess water periods.

The water level is an indicator that is widely used in assessing the recovery of the peatland vegetation and the entire ecosystem. It is one of the basic indicators in determining whether rewetting of the peatland has been successful (Priede (ed.) 2017). The water level has a significant impact on the peatland vegetation, its composition and structure, including trees.

There are several other important variables besides mean water level, such as water level fluctuation amplitude (especially during the vegetation period), minimum and maximum water level, first and third quartile, water level variation frequency (presented as the standard deviation

Figure 10. *Water level monitoring well and the process of downloading the hydrological monitoring data in Sachara peatland (Lithuania). Photo: L. Sendžikaitė*


Photo: A. Priede

of a mean), duration of spring high water level. From a hydrological point of view, the hydrological monitoring before starting restoration actions should last not less than three years, as one-year fluctuations may be strongly influenced by atypically low or high precipitation, extreme temperatures and other deviations that are generally not typical for the area.

The most appropriate approach is to use automatic loggers for water level monitoring (Figure 10). Data recording frequency of once or twice a day is sufficient for general hydrological monitoring. In the LIFE Peat Restore project, data loggers which register data within a two hours interval were used. Water level observations should be linked not only with rewetting and weather conditions, but are also used in interpreting ecosystem photosynthesis and transpiration in modelling the GHG measurements (see *Chapter 3.6*) results over the whole year.

In certain cases, for example, when the area is large, the data from the hydrometeorological stations recording data for national monitoring may be used. If the stations are located far away from the restoration area (over 20 km), a local meteo-station should be installed on the site. The minimum parameters to measure should be the amount of precipitation, air temperature, and photosynthetically active radiation (when GHG is measured on-site).

3.5. Monitoring of peat and water properties

Apart from hydrological and vegetation monitoring, an important aspect in assessing the peatland functioning and condition is the analysis of the physical and chemical properties of water and peat. Monitoring of chemical parameters indicates possible impacts and threats to which the peatland is exposed, especially when it is surrounded by fertilized arable lands. In the LIFE Peat Restore area in Poland, an important element of the impact on peatlands may be the vicinity of a brackish coastal lake. Determining and monitoring the chemical composition gives a possibility to determine the hydrogenesis of water and the ways of supplying objects with water (rainwater, groundwater, surface water). Moreover, it makes it possible to link the chemical composition of peatland waters with the water cycle, retention changes and water level fluctuations.

In many cases, especially for minerotrophic fens, it is appropriate to obtain data on inflow and peat water properties (pH, electric conductivity, Ca, Mg, N, P, C contents) and peat properties from the topmost (rooted) section of peat deposit (bulk density, ash content). The spatial variations and temporal dynamics of water chemistry are tightly related to plant species composition (Hájek et al. 2006).

3.6. Monitoring of greenhouse gas emissions

Successful rewetting of a drained peatland leads to a considerable reduction of GHG emissions into the atmosphere. GHG reduction occurs as the state of the ecosystem (increasing water levels and developing mire specific vegetation) improves. It takes time, thus GHG should be monitored before and after the restoration. In the LIFE Peat Restore project, GHG emissions were estimated before implementing restoration measures; assessing the impact of restoration on reducing GHG emissions was part of post-restoration monitoring.

There are different ways to estimate GHG emissions: to collect GHG data on site with direct measurements with manual chambers (Figure 11), or using Eddy covariance method for gathering GHG emission data from the atmosphere. While planning monitoring with direct measurements, either with chambers or Eddy covariance tower, it must be kept in mind that multiannual measurements are needed as GHG emissions may vary over a large range, even turning from carbon emitters to carbon sinks on different years due to variations in weather conditions. There is also a possibility to estimate GHG emissions indirectly with the GEST (*Greenhouse Gas Emission Site Types*) approach. All these methods can be used, they have their advantages and disadvantages, and the options must be considered before choosing a method.

In the LIFE Peat Restore project, GHG emissions were estimated before restoration actions using different methods. Direct GHG measurements with manual chambers were made on all 10 peatlands on 73 measurement points altogether (Table 2) on a selected number of vegetation types, while the GEST approach was applied for all types of restoration areas.

Manual transparent chambers were used for direct measurements. For quantifying long-term carbon accumulation of the site and aquatic carbon loss (e.g. DOC, DIC) additional measurements of peat accumulation and water carbon content on the site should be conducted. Engaging such variables in addition to direct GHG flux measurements allows assessing the true carbon accumulation and restoration success of the sites.

More details on greenhouse gas emissions in publication "Handbook on Assessment of Greenhouse Gas Emissions from Peatlands. Applications of Indirect and Direct Measurements by LIFE Peat Restore").

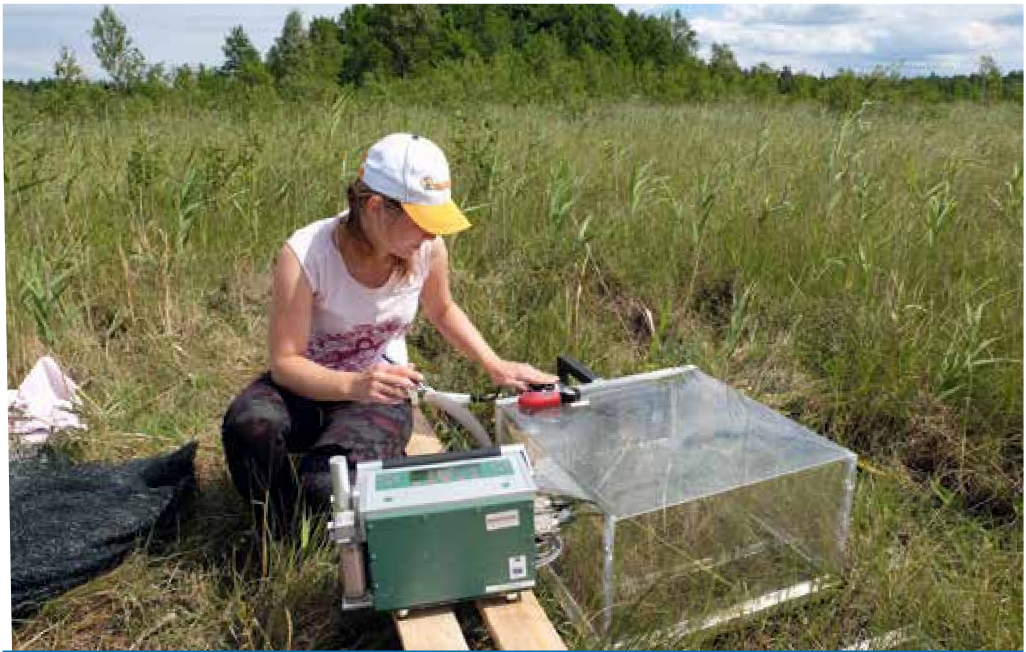


Figure 11. *Instrumental greenhouse gas measurements using a chamber in an alkaline fen in Suursoo-Leidissoo project area, Estonia. Photo: R. Pajula.*

The GEST approach was developed for assessing GHG emissions from damaged and rewetted peatlands using vegetation as a proxy. The concept is developed by the mire researchers group at the University of Greifswald (Couwenberg 2011; Couwenberg et al., 2011). As direct measurements of GHG emissions are laborious and expensive, this approach gives a possibility to evaluate GHG fluxes by interlinking vegetation types, water table depth, and peat properties and thickness.

Vegetation is a good indicator of GHG fluxes from peat soils as it reflects long-term water level conditions, affects GHG emissions via assimilate supply and aerenchyma and allows fine-scaled mapping. The methodology includes mapping of vegetation types characterised by the presence and absence of species groups indicative for specific water level classes. GHG flux values are assigned to the vegetation types following a standardized protocol and using published emission values from plots with similar vegetation and water level in regions with similar climate and flora (Couwenberg et al. 2008, 2011).

The vegetation seems to be well qualified for indicating GHG fluxes (Couwenberg et al. 2008, 2011) because:

GHG are significantly related to annual mean water level (Schaffers, Sykora 2000; Koska et al. 2001);


Photo: M. Pakalne

It is controlled by various other site factors that determine GHG emissions from peatlands, such as nutrient availability, soil reaction (pH) and land use (history);

It is itself directly and indirectly responsible for the predominant part of the GHG emissions by regulating CO_2 exchange, by supplying organic matter (including root exudates) for CO_2 and CH_4 formation, by reducing peat moisture and by providing possible bypasses for methane fluxes via aerenchyma ('shunt species'; Joabsson et al. 1999; Whalen 2005);

It reflects long-time water level conditions and thus provides an indication of average GHG fluxes on an annual time scale;

It allows fine-scaled mapping, e.g. on scales 1:2 500–1:10 000.

For more detailed information about using the manual chamber GHG measurement method and about the GEST approach for GHG assessment see the publication "Handbook on Assessment of Greenhouse Gas Emissions from Peatlands. Applications of Indirect and Direct Measurements by LIFE Peat Restore".

3.7. Overview on the monitoring of LIFE Peat Restore sites

Within the LIFE Peat Restore project, in total 10 sites were restored and monitored. An overview on the number and types of monitoring is given in Table 2.

Table 2. *Overview on the monitoring in the LIFE Peat Restore project areas*

Project sites	Number of vegetation monitoring plots	Number of hydrology monitoring wells/ piezometers	GHG measurements Number of sites
Suursoo-Leidissoo peatland	95	71 wells and 3 piezometric stations (each station with 5 wells at different depths)	12
Augstroze peatland	4	9	1
Engure Lake peatland	3	9	1
Baltezers peatland	3	9	1
Sachara peatland	5	5	1
Pūsčia peatland	5	6	1
Aukštumala peatland	-	8	1
Amalva peatland	5	7	1
Słowiński National Park	38	80	1
Biesenthaler Becken	7	5	1

4.

PEATLAND RESTORATION SITES

Photo: M. Pakalne

The LIFE Peat Restore project sites include minerotrophic (geogenous) and ombrotrophic (ombrogenous) mires. Minerotrophic mires, fens and transitional mires are primarily fed by groundwater that obtains minerals from the mineral soil. Ombrotrophic mires (raised bogs) obtain water and minerals exclusively from the precipitation. The intermediate stage, transitional and mixed mires, are partly fed by groundwater, partly by precipitation and surface runoff.

The sites and restoration actions applied and the preliminary results observed shortly after restoration are summarised in Table 3.

Table 3. *Peatland restoration methods and preliminary results in each LIFE Peat Restore project site*

Project sites	Restoration actions				Preliminary restoration results* in 2021	
	Building of dams	Removal of trees	Spreading of Sphagnum	Construction of floating islands	Rise of water level	Vegetation shift toward peat-forming vegetation
Suursoo-Leidissoo peatland (see Chapter 4.1.1)	Yes	No	No	No	Yes	Yes/partly unclear
Engure Lake peatland (see Chapter 4.1.2)	Yes	Yes	No	No	Yes	Still unclear
Baltezers peatland (see Chapter 4.1.3)	Yes	No	No	No	Yes	Yes
Biesenthaler Becken (see Chapter 4.1.4)	Yes	Yes	No	No	Yes/partly maybe still unclear	Still unclear
Augstroze peatland (see Chapter 4.2.1)	Yes	No	No	No	Yes	Yes
Słowiński National Park (Kluki, Ciemińskie Błota, Wielkie Bagno peatlands) (see Chapter 4.2.2)	Yes	Yes	No	Yes	Still unclear	Still unclear
Amalva peatland (see Chapter 4.2.3)	Yes	Yes	No	No	Yes	Yes/still unclear
Pūsčia peatland (see Chapter 4.2.4)	Yes	Yes	Yes	No	Yes	Still unclear
Sachara peatland (see Chapter 4.2.5)	Yes	Yes	No	No	Yes	Still unclear
Aukštumala peatland (see Chapter 4.2.6)	Yes	Yes	Yes	No	Yes	Still unclear

4.1. Fens, forested fens and transitional mires

Fens are mainly groundwater fed, with an addition of surface runoff and precipitation. They are mostly open or semi-open peatlands, in most cases with over 30 cm thick peat deposits and peat-forming vegetation. In intact and near-natural fens, sedges and brown mosses dominate. Shrubs and trees, usually in groups or as scattered individuals, are also common, while drained fens may be completely or partly overgrown with trees and shrubs, especially in fens heavily affected by drainage.

Fens develop wherever waterlogged conditions are maintained by groundwater supply, in part at least, by groundwater. Nowadays, the fens preserved in near-natural condition range in size from extensive fen complexes to small sites only of a few square metres. Fens frequently occur as a zone of variable extent, e.g. around lakes, in waterlogged depressions, on raised bog margins and in river floodplains. Fens may form complexes with mixed feeding regimes depending on the geological settings where the groundwater flows through. Fens vary from calcareous to weakly acidic, nutrient-rich to poor types, each with its own plant species composition, ranging from extremely species-rich to species-poor (Hájek et al. 2006).

Transitional mire is intermediate between two main types – eutrophic fen and oligotrophic bog, and they have the characteristics of both, sometimes closer to one, sometimes to the other. In transitional mires, a succession stage that follows the fen, the influence of groundwater has strongly diminished, and the impact of precipitation water starts to prevail. Drainage of fens can accelerate their development towards transitional mire. They usually occur on raised bog margins, on lakeshores and in inter-dune depressions. They are marked by the appearance of plant species that can grow in nutrient poor conditions (pH 4.5– 5.5).

Fens were widely distributed in the lowlands of Europe, especially in Northern and Eastern Europe. They are often used for agriculture, hay making and grazing, from very early times, but during the 19th and especially during the 20th century, most fens in Europe have been drained and converted into arable lands and forests. During centuries of agricultural use, the nature of fen ecosystems has changed and their biota impoverished. Many of those lying on thinner peat layers have lost their peat deposits in the course of lasting decades of management. Alongside human impact, the water level may drop down due to land uplift (e.g. as it is in Northwestern Estonia).

In all LIFE Peat Restore countries, the fen areas have significantly decreased due to drainage and conversion into other land use types (Ilomets 2017; Kotowski et al. 2017; Trepel et al. 2017). The lands that have been originally fens are still being used for crops, harvesting of highly productive hay on sown grasslands – land use types that require intensive fertilisation (Trepel et al. 2017). A great part of the former fens have ceased to exist, and many others suffer from drainage and continuous degradation. For example, in Estonia only 10% of rich fens are still in near-natural state (Ilomets 2017).

4.1.1. Suursoo-Leidissoo peatland, Estonia

Photo: R. Pajula

Location: Northwestern Estonia.
WGS84 coordinates: 59.180558, 24.011206, https://ieej.lv/peatrestore
Altitude: 13–18 m a.s.l.

Protection status: Suursoo-Leidissoo Special Protection Area,
Species conservation site for *Tetrao urogallus* (at the southeastern part of the project site),
Suursoo-Leidissoo Natura 2000 site, protected both under Habitats Directive and Birds Directive,
two ditches (Piirsalu and Kaldamäe) are protected as spawning areas for salmon and trout

Total area of the mire complex: 23 000 ha

Restoration area: 3343 ha, including alkaline fen, transitional mire, transitional mire forest, swamp forest and drained peatland forest

EU importance habitat types in the restoration area: Alkaline fens (7230), Transition mires and quaking bogs, (7140), Bog woodland (91D0*)

Implementation: Tallinn University (planning, monitoring, expertise), Projekteerimisbüroo "Maa ja Vesi" (technical design), OÜ Timberston (construction work)

Land manager: State Forest Management Centre, Estonia

DESCRIPTION OF SUURSOO-LEIDISSOO RESTORATION AREA

Suursoo-Leidissoo peatland restoration site is the eastern part of the huge (over 20 000 ha) mire complex in the northwestern Estonia. Before drainage, it was a wet and seasonally flooded alkaline fen with up to 4.8 m layer of fen peat. The area was traditionally used for hay making practised long before the 1880s when the first ditches were dug. Deeper drainage was established in the 1970s although the ditch network is not dense. Traditional hay making ceased in the 1970s. During the last 100 years, the drainage impact resulted in the water level dropping by about 0.2–0.6 metres. It resulted in the breakdown of the peat surface, especially near the ditches. Farther from the ditches, the water level had not dramatically dropped down leading to the development of a transitional mire (*Sphagnum* dominated, both open and forested, communities). Closer to the ditches, drained peatland forests formed where peatland plants are almost disappeared. Thus, after drainage, a very diverse vegetation pattern has developed (Figure 12).

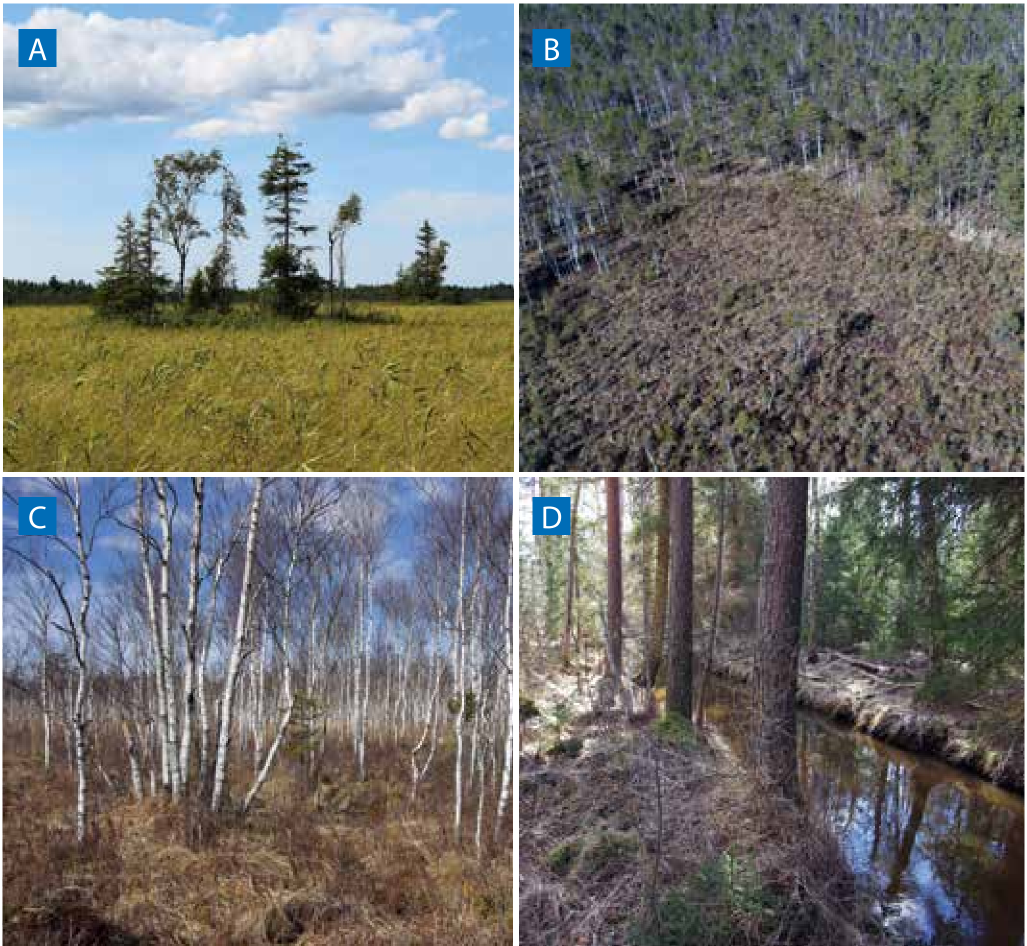


Figure 12. *Typical landscapes in the Suursoo-Leidissoo peatland: A – open, undrained calcareous fen with small treed islands; B – the border between shrubby transitional mire and densely treed areas; C – a fen with recently established young trees; D – drained peatland forest on the ditch banks. Photos: R. Pajula.*

WHY WAS THE RESTORATION NEEDED?

The drainage has induced two-directional vegetation change: (1) establishment of oligotrophic plant species, and (2) overgrowing with forest. The formerly open alkaline fen transformed into a mosaic of semi-drained pine, *Sphagnum* and shrubberies dominated peatland, in some parts – a deeply drained mixed forest on peat soil. An open fen has been preserved in ca. 18% of the area. The vegetation types on the Suursoo-Leidissoo restoration site are presented in Figure 13.

Alkaline fens are the most drained mire type in Estonia covering the lowest proportion of mire habitats. Suursoo-Leidissoo provided a great opportunity to restore this valuable vegetation type in a large area.

Rewetting scenario. Rising up the water table and keeping water longer on the peatland surface is the only way to restore peat formation and to prevent continuous degradation of peatland vegetation. Detailed inventory and modelling of hydrology, peat chemistry and peatland surface led to a conclusion that it is not possible to restore a calcareous fen in the whole area. The rest may be preserved or restored as an open transitional mire, a bog and wet forests (swamp forest, bog woodland). Bog development has already begun – the process continues, and the peatland surface has risen due to the growth of *Sphagnum* mosses. At this development stage, the vegetation depends mainly on precipitation, not from mineral-rich groundwater. Also, forest types (swamp forest, bog forest) will remain on the site. Re-wetting improves the condition of all existing mire types and thus makes the site a significant carbon sink. By blocking the ditches, the whole area may develop into a hydrologically coherent mire complex.

The non-intervention scenario. In a case of non-intervention, in a longer period of time (two and more decades) most of the area would turn into a drained peatland with absence or with a small share of peatland plants. In vegetation, mixed pine and spruce forest could dominate where due to low light availability sparse vegetation of minerotrophic forest plants may grow. Without rewetting, the *Sphagnum*-dominated vegetation developed due to slight drainage would gradually become similar to areas with heavier drainage impact closer to the ditches. Due to continuous peat decomposition, the whole drained peatland area has become a source of GHG emissions.

GHG emissions estimated by means of the direct GHG measurements (modelled data of 2018, 2019 and 2020) and by the GEST estimates. Although the emission values of vegetation types differ between direct measurements and GEST, for the total restoration site (3343 ha) the GHG emission sum turned out to be almost the same: 18 575.2 CO_2-eq/yr and 17 699.8 CO_2-eq/yr, respectively.

The calculations of future scenarios could be only done using the GEST approach. Due to shifts of vegetation types, during the next 10–30 years the emissions may decrease to about 13 000 CO_2-eq/yr in the rewetting scenario, and increase up to 30 000 CO_2-eq/yr in the non-intervention scenario. However, higher sequestration capability resulting from rewetting is expected, as the condition of the mire vegetation types improve. Thus, the carbon sequestration might increase more than the GEST prediction provides, because the GEST emission values derive from the pre-restoration status of the drainage affected vegetation types, not from vegetation in near-natural condition.

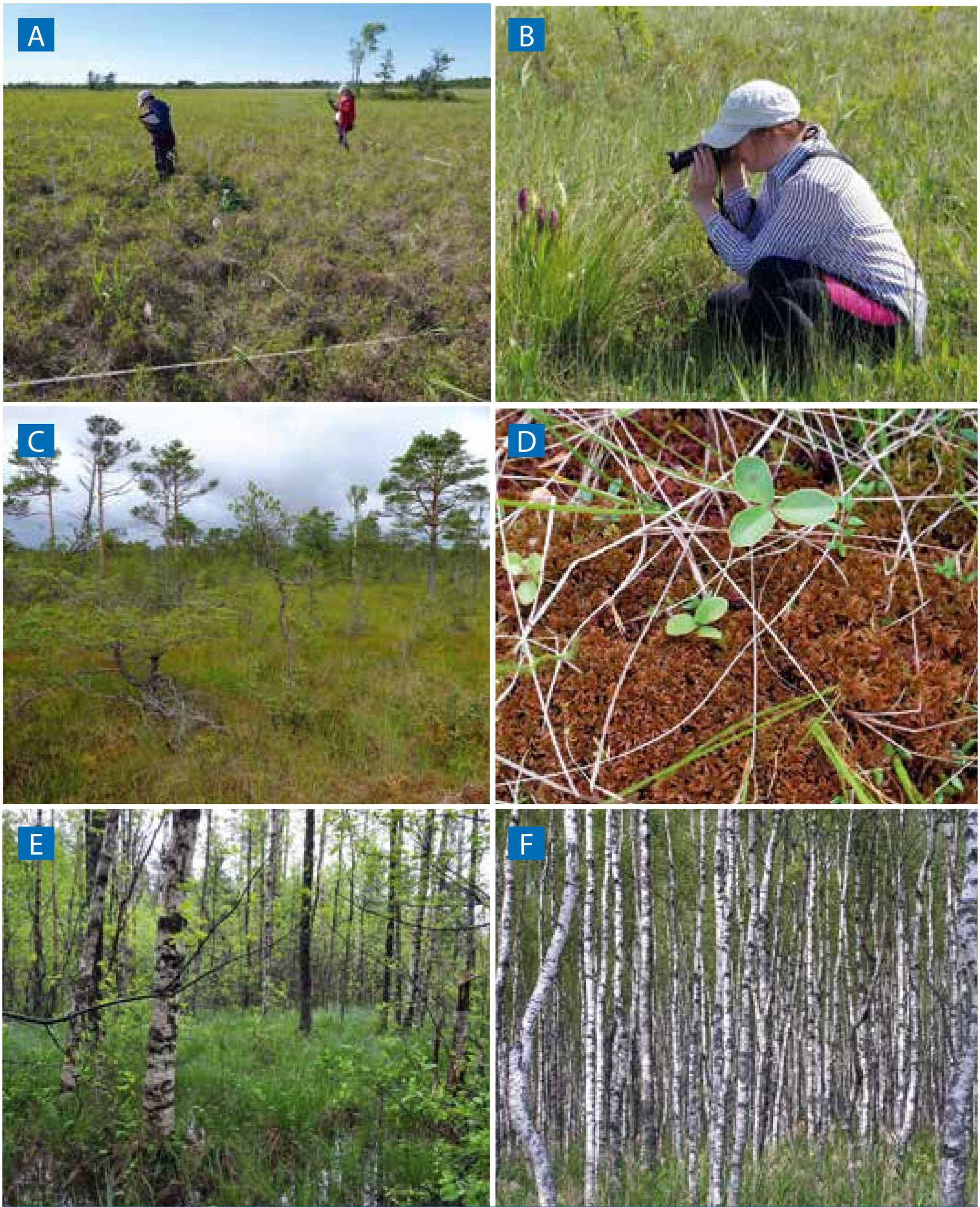


Figure 13. *Vegetation types in Suursoo-Leidissoo: A – an open fen in the northeastern part of Suursoo-Leidissoo peatland; the large amount of litter indicates the drainage effect (photo: R. Pajula); B – Dactylorhiza incarnata and D. ochroleuca, two threatened orchid species, growing in the open fen in Suursoo-Leidissoo (photo: L. Truus); C – transitional mire with sparsely growing pine trees (photo: R. Pajula); D – ground vegetation in the transitional mire (photo: L. Truus); E – minerotrophic swamp forest (photo: R. Pajula); F – minerotrophic fen recently overgrown with forest due to drainage impact (photo: R. Pajula).*

TARGET VEGETATION TYPES AND SPECIES

In the Suursoo-Leidissoo peatland, the original vegetation type before drainage was small-sedge alkaline fen. After assessing the structure and composition of the current vegetation, it was decided that it is not reasonable to restore the whole area as an open fen, as many parts of the peatland have already developed towards more oligotrophic conditions.

Areas with slight drainage impact are covered with a quite thick *Sphagnum* carpet – the initial stage of bog development (Figure 13C, 13D). Some parts of the peatland are overgrown with forest and are developing towards a minerotrophic swamp forest. It is expected that after rewetting large parts of the area may develop towards open or sparsely wooded woorded eutrophic and or mixed mire – a wetland type that has been significantly declined due to drainage (Figure 13E). Thus, after the hydrological restoration, the mire types developed due to drainage impact may remain in their areas, although their share may decrease, and the ecosystem functionality may improve. The only vegetation type that is expected to disappear in most of the area is drained peatland forest. An insight into the character of the vegetation types in the area is given in Figure 13.

The target plant species include small sedges (e.g. *Schoenus ferrugineus, Carex davalliana, C. panicea*, *C. flacca*), *Menyanthes trifoliata*, *Trichophorum alpinum, Myrica gale*, and brown mosses (e.g. *Scorpidium scorpioides, S. cossonii, Calliergonella cuspidata, Campylium stellatum, Warnstorfia* spp.). These species are important for the formation of fen vegetation. After rewetting, it is expected that some currently rare, scattered specialist species may become more frequent (e.g. *Primula farinosa, Parnassia palustris, Tofieldia calyculata* and orchids *Dactylorhiza incarnata, D. ochroleuca, Gymnadenia conopsea, Epipactis palustris*) (Figure 14).

The target species for swamp woods are *Alnus glutinosa* and *Betula pubescens* in the tree layer (with some individuals of *Pinus sylvestris*), and *Angelica sylvestris, Carex chordorrhiza, Caltha palustris, Cirsium oleraceum, Dryopteris cristata, D. carthusiana, Equisetum* spp., *Filipendula ulmaria, Calla palustris* in the ground vegetation.

The target plant species for transitional mire and for transitional mire forest are *Andromeda polifolia, Betula nana, Calluna vulgaris, Drosera rotundifolia, Eriophorum angustifolium, Vaccinium oxycoccos*. Presence of rare species, such as *Neottia cordata, Corallorhiza trifida* or *Hammarbya paludosa* and several *Dactylorhiza* species would increase the biological value of the area. Typical mosses for bogs are *Sphagnum* species (*S. angustifolium, S. capillifolium, S. fallax, S. fuscum, S. divinum, S. medium*), *Aulacomnium palustre* and *Polytrichum strictum* that have the key role in carbon sequestration in oligotrophic sites. In the forest tree layer, *Pinus sylvestris* with a crown coverage lower than 40% is expected.

The target bird species for open fen and transitional mire landscapes in Suursoo-Leidissoo are *Aquila chrysaetos*, *Circus pygargus, Falco columbarius, Grus grus, Lanius collurio, Numenius phaeopus, Lagopus lagopus. Tetrao tetrix* and *Tetrao urogallus* are the target species for *Sphagnum* dominated landscapes (transitional mires and bog woodlands).

PREPARATORY WORK

In the Suursoo-Leidissoo, the largest and most complex restoration site in the LIFE Peat Restore project, a detailed monitoring scheme during the pre-restoration stage was developed. This provided the baseline for understanding the changes in the future after restoring the water regime.

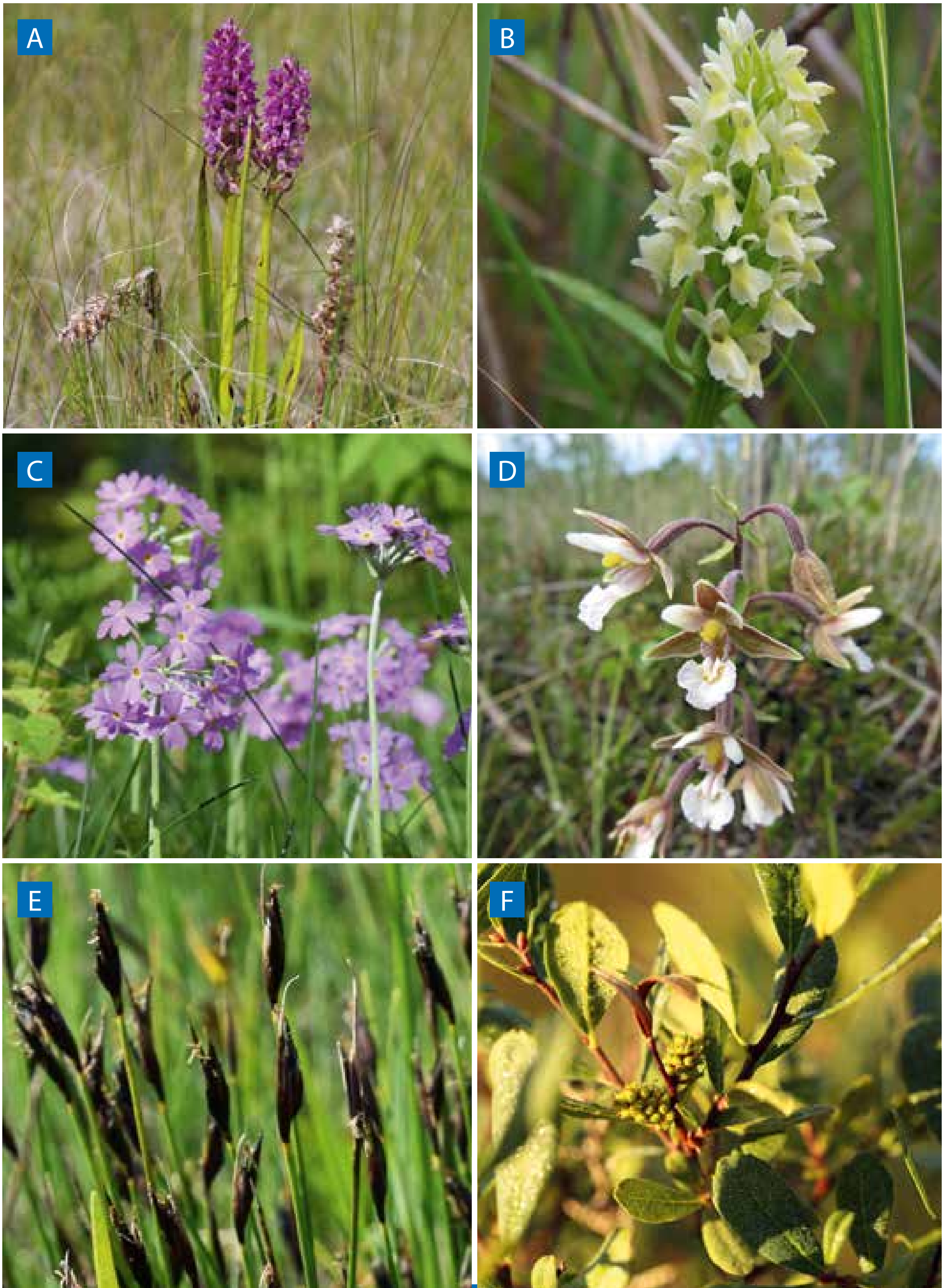


Figure 14. *Some of the target species of open alkaline fens: A – Dactylorhiza incarnata, B – Dactylorhiza ochroleuca, C – Primula farinosa, D – Epipactis palustris, E – Schoenus ferrugineus, F – Myrica gale. Photos: L. Truus (A–C, E), A. Priede (D) and M. Pakalne (F).*

It also expands theoretical knowledge on the functioning of fen ecosystems and allows correcting mistakes that may occur in restoration. Further analysis of monitoring data may provide novel basic knowledge and be applied in restoring other groundwater-fed peatland ecosystems.

The vegetation monitoring was carried out in permanent sample plots with different size subplots (depending on functional plant type: trees and shrubs, dwarf shrubs, herbaceous plants, and bryophytes) (Figure 15).

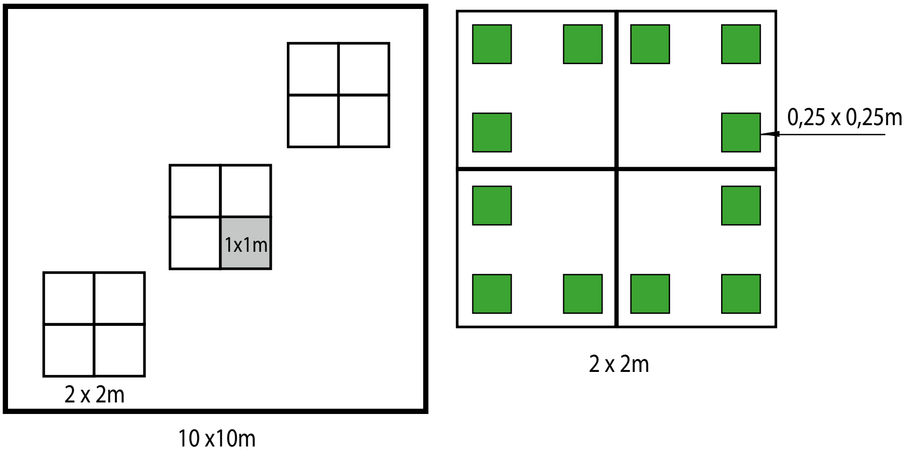


Figure 15. *The monitoring design for different plant groups: 10 x 10 m for trees and shrubs; 2 x 2 (each with 1 x 1 m subplots) for dwarf shrubs and herbaceous plants; 0.25 x 0.25 m for bryophytes.*

Figure 16. *Four monitoring plots on a transect that crosses the ditch in the northeastern part of the Suursoo-Leidissoo peatland, the best preserved alkaline fen in the area. Photo: R. Pajula.*

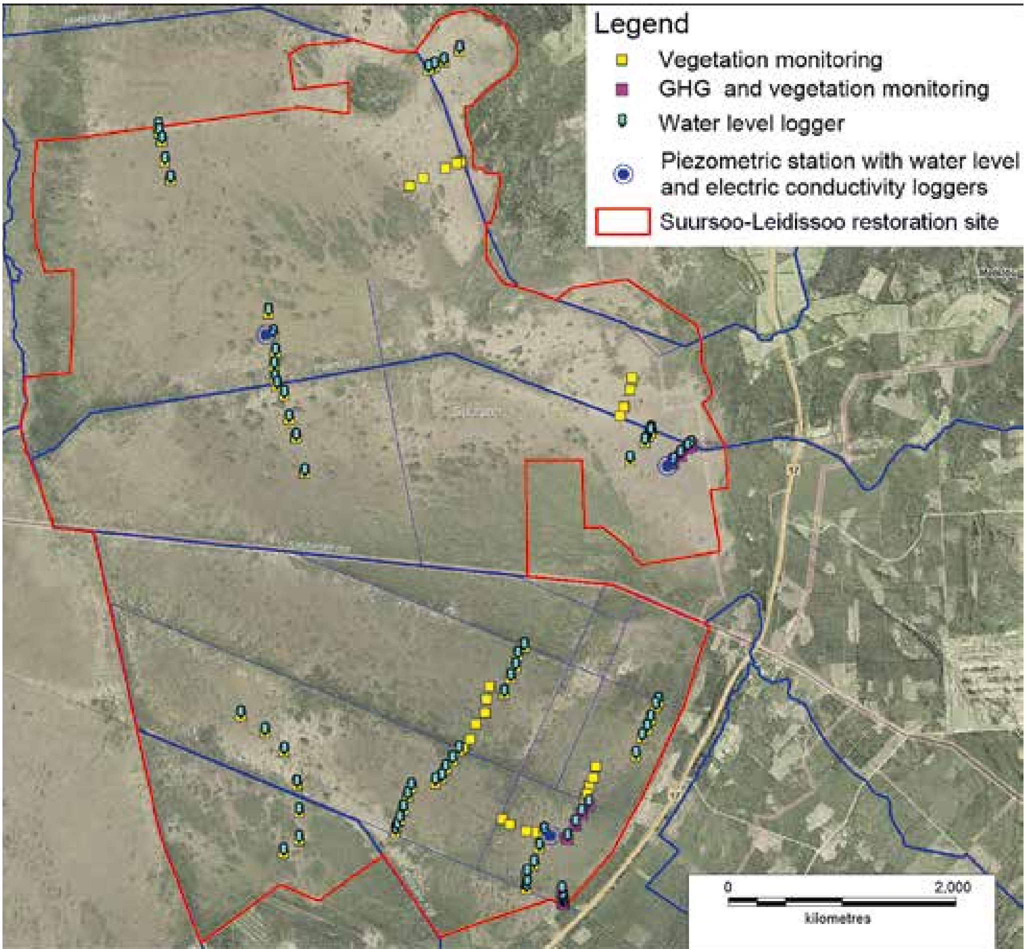


Figure 17. *Monitoring network on Suursoo-Leidissoo restoration area. Map: R. Pajula.*

In total, 95 monitoring plots for trees and shrubs, 285 plots of 2 x 2 m (1140 plots of 1 x 1 m) for vascular plants, and 3420 plots for bryophytes were established (Figure 17). Coverage (%) of each plant species was estimated. For trees (>1 m tall), diameter, height and age class was measured. Monitoring plots were located along transects across the ditches (Figure 16). All other parameters, such as water level and water chemistry, peat bulk density and ash content, peat water chemistry and GHG were measured close to the vegetation plots. Also, the relative height of microforms (hummocks, tussocks) was measured in each plot.

A water level monitoring system of water level loggers was installed (71 loggers and three piezometric stations) for gathering water level fluctuation data (Figure 18A). Loggers registered data within a two hours interval from June 2018 until December 2021. Water level data were modelled and combined with temperature and precipitation data and clustered with vegetation analyses data (Lode 2020, 2021A, 2021B).

Vegetation mapping over the whole project site (3343 ha) was performed using relatively broad vegetation classes that indicate the trophic status of the mire communities and the presence of forest. The type "drained peatland forest" was defined using the degree of drainage; it was identified using the composition of moss and herbaceous species and water table depth as indicators. The main challenge was the mosaic-like character of the vegetation and transitions between the types.

Maps on different scales available at the Estonian Land Board were used for vegetation mapping, including LiDaR data about the vegetation height. Additionally, drone images in the visual spectrum were used. A multi-rotor drone *DJI Phantom 4 pro* with pre-planned automatic flights (missions) was utilised for data collection. Hundreds of individual images were combined into a georeferenced photo mosaic, a photomap. Resolution (pixel size) of the photo maps depending on the flight height was 2–4 centimetres. This is enough to reflect the pattern of microstructures and the pattern of the dominant plant functional types.

Monitoring of bird populations was carried out in the Suursoo-Leidissoo restoration site: before restoration actions in June 2018 and in June 2021, two months after rising up water level. Number of nesting bird pairs counted and results were given according to the habitat preference of bird species (species of forests and shrubberies vs. species of open landscapes). The fen and bog monitoring methodology of the Estonian Environmental Agency was used (KESE 2020). Comparison of two inventories shows the first results of rewetting.

GHG budget was estimated in the Suursoo-Leidissoo restoration site during three years (2018, 2019, 2020) in five vegetation types before hydrological restoration. Altogether, there were 48 measurement points located in 12 sites (Table 2, Figure 17). Measured CO_2, CH_4 and N_2O emission data were recalculated into CO_2-equivalents, and the mean annual emissions modelled[1].

Drone equipped with a multispectral camera (*Sensefly eBee Sequoia*, Figure 18C) was used for mapping of normalised difference vegetation index (NDVI). The camera simultaneously recorded photos in four spectral bands (green, red, near-infrared, red-edge) that allows it to generate multispectral vegetation indices. It was used to quantify the amount of green biomass and the photosynthetic capacity of plant cover. The higher leaf area index (LAI) and photosynthetic capacity, the higher is the carbon sequestration rate to the plant biomass. In case of peatlands, NDVI value reflects the cover of vascular plant vegetation. NDVI maps reflect vegetation patterns and allow estimation of carbon uptake by vegetation.

Drone photos used for vegetation mapping. Drone (UAV) flights covered all vegetation monitoring plots and their surroundings. Photos made during the flights together with plant cover estimations were used for compiling the vegetation maps.

In the vegetation periods (from May to October 2018–2020), drone monitoring proceeded once a month simultaneously with instrumental GHG measurements in all GHG measurement sites (see *Chapter 3.6*). The aim was to relate NDVI pattern of communities with direct, instrumental GHG measurements. The possibility of using the index as an indirect GHG indicator over a larger area was tested.

A digital elevation model was developed with a water flow network to understand the hydrology of the site. In peatland restoration, one of the first steps is to create the projection of the current water movement paths and the topography of the site – mire surface slopes and flow accumulation lines

[1] Details are given in the separate publication "Handbook on Assessment of Greenhouse Gas Emissions from Peatlands. Applications of Indirect and Direct Measurements by LIFE Peat Restore".

Figure 18. Some examples of actions in Suursoo-Leidissoo peatland:*:*

A – data downloading from the water level logger (photo: L. Truus);

B – building a greenhouse gas measurement station (photo: R. Pajula);

C – sending an SenseFly eBee Sequoia drone in flight to take multispectral images (photo: K. Sepp).

of water. The surface elevation model was created on the basis of the elevation map (based on LiDaR data by the Estonian Land Board and SAGA GIS software). The situation after blocking the ditches was modelled to predict the target water level. This model was the basis for selecting the rest-on measures and developing a technical design. We modelled surface slopes, flow accumulation and channel network, and catchment basins for the pre-restoration and post-restoration situations.

Modelling indicated that the ditch network has considerably changed the surface topography due to peat compression and decomposition, and the mire surface has sunk near the larger ditches. At the same time, there is active peat accumulation and *Sphagnum* growth in the watersheds at larger distances from the ditches. The local surface slopes have been altered, surface gradients increased and flowline lengths decreased. As a result, the water quickly reaches the ditches, and the peatland becomes drier. In the past, the overall slope was inclined towards the north-west direction (Figure 19A), towards the Vihterpalu River at the western border of the project site. The surface of the peatland was flatter, and the water path to the river was long.

Modelling of the post-restoration situation was based on a solution that the ditches would be blocked by dams and the sinks behind the dams would be filled in. Then, a surface model was created (Figure 19B). The model showed that the water level may rise by 0.3–1 m in the ditches after damming. Consequently, mire water level gradients towards the ditches may decrease by the same amount, thus significantly raising the water level in at least 50–150 m wide zone from the ditches. At longer distances from ditches, the runoff conditions and the water level may change to a lesser extent. According to the model, the tree density may decrease after damming due to raised water level. This may also decrease evapotranspiration and, in turn, foster the rise of water level.

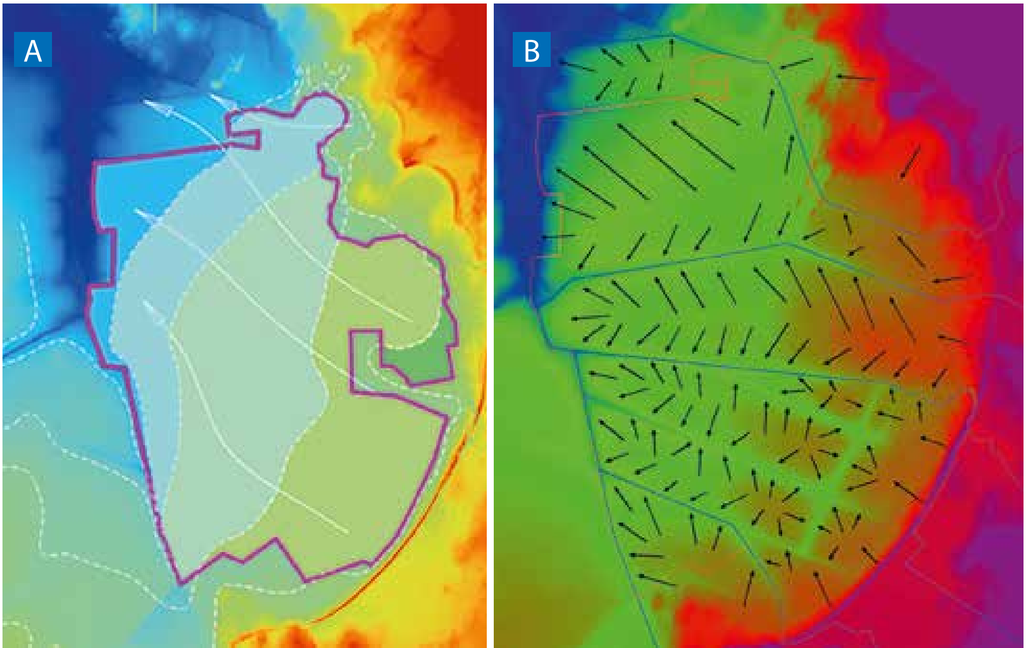


Figure 19. *Suursoo-Leidissoo peatland surface topography and water flow lines (arrows). A – situation before drainage; B – situation before restoration. Map: R. Pajula.*

When developing the technical design, the contracted technical design company took into account the slope of the peatland surface and water flow directions modelled during the pre-restoration studies. Additionally, the widths and depths of ditches measured and also longitudinal profiles of larger ditches were levelled by specialists of the same company.

The dams were designed on the basis of a widely used, well-approbated approach (Similä et al. 2014; Priede (ed.) 2017; Salm et al. 2020), according to which the length of the dam wings was proportional to the surface evenness. All dams in the area have the same basic design (Figure 20A), but the lengths of the wings vary from 10 to 40 m depending on the ground topography. The dams were planned after every 15 (20) cm change of ground level along the ditches. According to the surface slopes around the ditches, the length of the planned dams was calculated. The total length of ditches where peat dams had to be built was ca. 37 km.

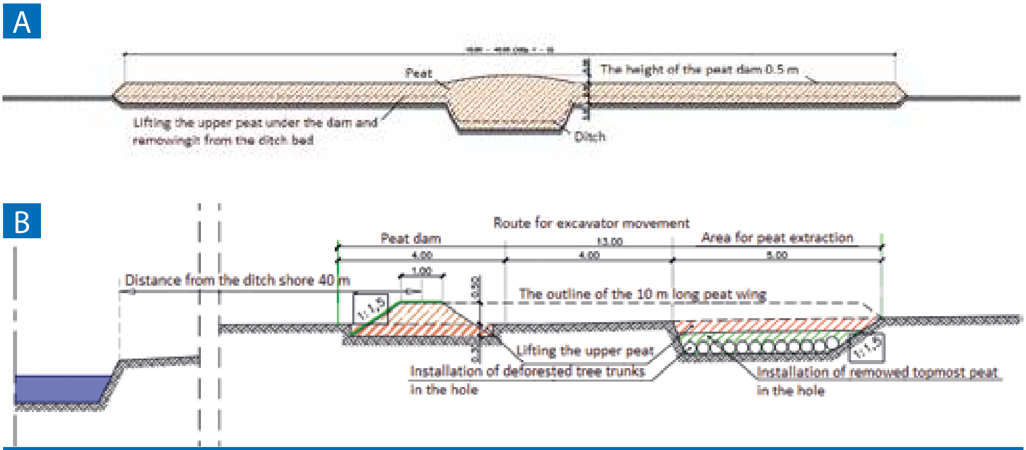


Figure 20. *Cross-sections of peat dam (A) and peat dike (B) in the technical design. Drawing: Projekteerimisbüroo "Maa ja Vesi".*

Exceptional solutions had to be applied in two cases: the Piirsalu and Kaldemäe streams, as it was not allowed to block the ditches with dams because they are protected as spawning rivers of salmon and trout. As a technical solution, it was decided to build peat dikes on both sides of ditches to prevent drainage impact to the peatland surface. In order to slow down the flow of high water behind the dikes, 10 m long wings perpendicular to the dikes (Figure 20B) were built at every 250 metres. Peat dikes have the effect that the outflow of water from the mire surface slows down without closing the water body.

RESTORATION AND MONITORING RESULTS

Peat dams and dikes were built from October 2020 to March 2021 (Figure 21–24). Altogether, the technical design envisaged the construction of 173 peat dams and 12.3 km of peat dikes. All construction work was carried out as planned.

Figure 21. *An excavator used for dam building. The paths for movement were first cleared of trees. Metallic footers help the heavy (15–20 t) machinery move on soft peat soil. Photo: R. Pajula.*

Figure 22. *A peat dike built along the Kaldemäe stream, autumn 2020. Photo: R. Pajula.*

Figure 23. *Construction of a peat dike running along the Piirsalu stream. Photo: R. Pajula.*

Figure 24. *Opening of the old bed of Kaldamäe stream for fish migration. Photo: R. Pajula.*

Figure 25. *Water in the drained peatland forest in May 2021, two months after blocking the ditches. Photo: R. Pajula.*

Figure 26. *Raised water level behind the peat dike running along Piirsalu stream in spring 2021. Photo: R. Pajula.*

The peat used for the construction of peat dams and peat dikes (Figure 23–26) was taken locally from the peat deposit creating holes in the mire surface. The holes were relatively small (2–3 full excavator buckets). More peat was needed to build peat dikes; for this purpose, elongated holes were created (with a maximum size of 5 x 10 m and with a depth up to 1 m). Distance between the holes was kept at least 2 m to prevent the formation of flow channels. The distant slope was designed for sloping 1:1.5 to allow the fallen animals to escape from holes.

To restore the drained areas around the straightened Kaldamäe stream, the ditch was redirected to the old bed, thus opening it for fish migration (Figure 24). Both dikes and dams were well visible in the satellite images (Figure 27B), therefore *Sentinel* satellite images were used to monitor the progress of the work, as the project team could not be present all the time.

NDVI mapping revealed important relations between NDVI values and vegetation cover and composition (Figure 27A). The highest NDVI (in mid-summer) values (0.7–0.8) were found in forested areas, especially those dominated by deciduous trees. Drained fens with the dominance of *Molinia caerulea* or high bushes have moderate to relatively high NDVI values (0.6–0.7). Sedge (*Carex lasiocarpa*, *C. davalliana*, *Schoenus ferrugineus*) dominated fens in near-natural condition have low to moderate NDVI values (0.3–0.6). *Sphagnum* dominated bog or transitional mire communities have the lowest NDVI values (0.3–0.5) in the Suursoo-Leidissoo site.

In the case of Suursoo-Leidissoo peatland, NDVI negatively correlates with wetness and values of natural mire vegetation types. Lower NDVI value indicates more natural and valuable communities, while higher NDVI value reflects lower naturalness and stronger impact of drainage. This pattern is caused by the circumstances where plant growth and the amount of green biomass in natural mires is limited by high soil water table. Surface aeration in drained mires has increased nutrient availability, therefore the total biomass, vascular vegetation cover and leaf area index (LAI) are higher.

Vegetation types also differ according to the natural state and NDVI values. Concerning the "internal diversity" of vegetation types, the index appears to reflect mainly coverage of vascular plants. It indicates that within the type higher NDVI values reflect stronger drainage impact, as in the case of Suursoo-Leidissoo.

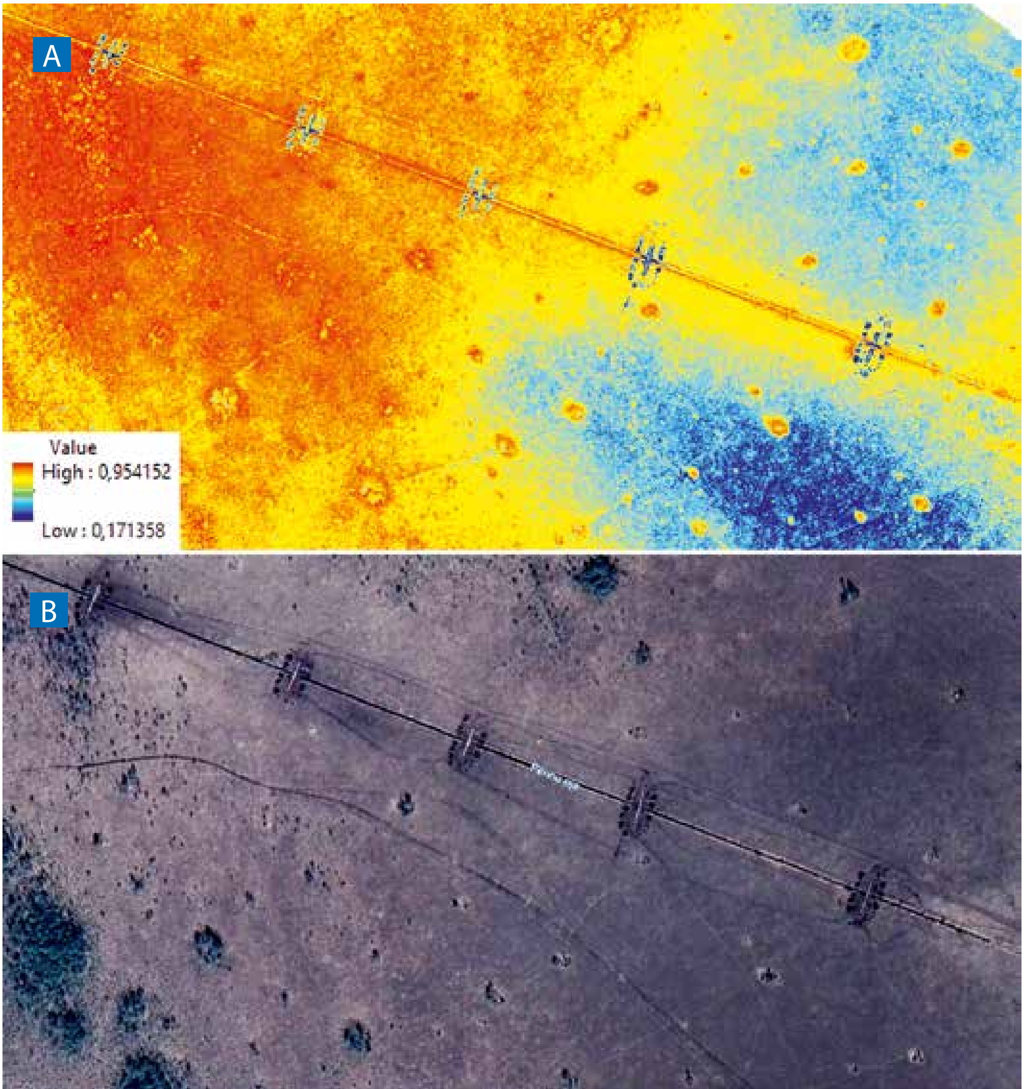


Figure 27. *NDVI map (A) from July 16, 2021 compared to Google Earth satellite photo (B) from May 4, 2021, the eastern part of Suursoo-Leidissoo project peatland with a fen and Pennu ditch with recently built dams. Lower NDVI values (blue) indicate near-natural alkaline fen communities; higher values (red and orange) indicate more drained fen with dominance of Molinia caerulea. NDVI map (A): R. Pajula.*

The seasonal distribution of NDVI showed a clear pattern: the highest values are in mid-summer (July), while the lowest in spring and autumn. This is caused by the seasonal distribution of green biomass.

Before restoration, the main vegetation types were distinguished: alkaline fen (602 ha), minerotrophic peatland forest (297 ha), transitional mire (823), bog woodland (859 ha), drained peatland forest (733 ha) (Figure 28). The period since rewetting was not sufficient to observe any significant changes in vegetation types. This is caused by the seasonal distribution of green biomass.

Figure 28. *Distribution of vegetation types on the Suursoo-Leidissoo project site before restoration.*

An analysis of hydrological conditions in relation to the weather data and vegetation composition was done. Water level fluctuations in relation to air temperature and precipitation during a three year period (2018–2020; see Lode 2020, 2021A and 2021B) was modelled. It was found that the length of the vegetation period and the length of the hydrological minimum period were highly different in these years significantly depending on interannual variations in air temperature and the amount of precipitation. Depth of the minimum water level and the length of the hydrological minimum period varied a lot depending on the degree of drainage. Years with extremely dry weather affected most areas with a heavier drainage effect where the water level dropped significantly.

Drop of the mire water level in the summer period is the main reason initiating vegetation changes in drained mires, and vice versa – rising up the water table resulting from restoration, periods with minimum water levels become shorter, and the water level becomes higher.

The summer of 2018 was dry and hot, while the year 2019 was with abundant precipitation. Vegetation periods of two years were the same length but the hydrological minimum period was a week shorter in 2019 than in 2018. During the dry periods, groundwater level dropped down differently: up to -40 to -80 cm in 2018, and up to -20 to -50 cm in 2019, depending on the vegetation type and the distance from ditches.

Results of the GHG measurements and modelling demonstrated that the areas most affected by drainage were the largest emitters of GHG. GHG emissions were strongly correlated with site hydrology, especially with water level fluctuations. GHG emissions from different vegetation types depended on weather conditions and greatly varied between years and between dry and wet seasons. The main results are presented and analysed in the separate publication "Handbook on Assessment of Greenhouse Gas Emissions from Peatlands. Applications of Indirect and Direct Measurements by LIFE Peat Restore".

The first results of the hydrological restoration were indicated by the groundwater level rise just after the dams and dikes were built. One-site surveys and drone monitoring demonstrated that all dams on the ditches and along fish brooks worked well keeping water on the mire surface (Figure 29). It is obvious that the duration of the high water period in spring may last up to the end of June. It is common in fens that in July the water table drops down. Importantly, the high water table (even overflood) should not stop earlier; before restoration measures, the water level dropped down already in May (Figure 30).

Figure 29. *Aerial view of the ditch crossing in the eastern part of the Suursoo-Leidissoo restoration site in spring 2021 after the construction of the dams. The small pools are holes where peat was taken for dam building. Photo: R. Pajula.*

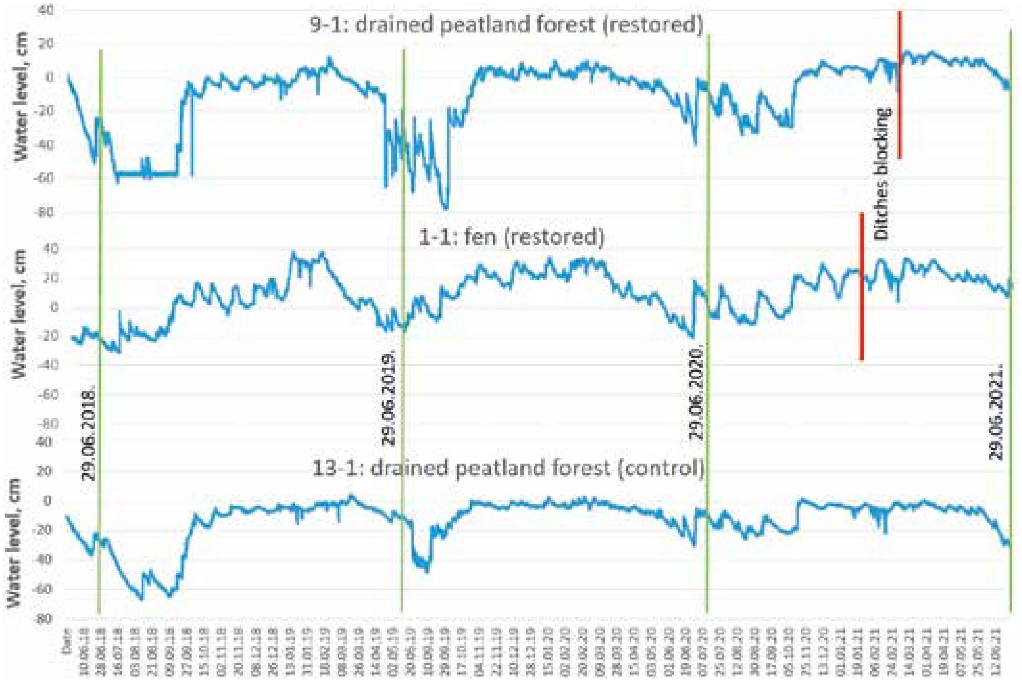


Figure 30. *Comparison of water table curves in Suursoo-Leidissoo project site in calcareous fen (plot 1-1), in drained peatland forest with raised water level (plot 9-1) and in drained peatland forest with no water level rise up (plot 13-1, control, not dammed) before and after blocking of ditches (red lines). Green lines represent the same date (June 29th) in three years (2018, 2019, 2020) before blocking of ditches until midsummer 2021.*

The first effects of rewetting on vegetation were noticed in late spring (May, June) as the soil remained wet for a long time. Vegetation response to rewetting takes time, as the water level raised just in March 2021. The expected dying of trees has begun in areas with the highest water level: some spruces fell down, and needles were drying on others. This may gradually lead to lower tree density.

The first observations after blocking the ditches showed that plants dominating in the drained forests (e.g. *Vaccinium vitis-idaea*, *Hylocomium spendens*, *Rhytidiadelphus triquetrus*) are dying and being replaced by mire plants. In sites where routes for excavators are cleaned, the previous vegetation of the drained sites was destroyed. Besides raising the water level, the removal of surface cover in heavily drained areas is a prerequisite for the establishment of peat-forming vegetation. Recovery of mire vegetation was visible in late spring 2021 when several vascular plant species (*Carex* spp., *Myrica gale*) were sprouting in masse. At a very early stage after rewetting, the brown mosses (e.g. *Drepanocladus* spp.) already covered the wet peat surface.

The first inventory of the breeding birds in the Suursoo-Leidissoo project area was carried out before building dams (in 2018). The results showed that the bird species were typical for heavily degraded fens and transitional mires, as the area was before restoration. Only about one quarter of the breedings bird pairs were typical for open mire landscapes, among them three species of waders: common snipe *Gallinago gallinago,* green sandpiper *Tringa ochropus* and Eurasian woodcock *Scolopax rusticola*. Less than 10% of the total project area was suitable for birds preferring open mire habitats; the rest of the area was occupied by bird species occurring in forests and shrubs. It was expected that rewetting may considerably improve the conditions for mire bird species.

A positive effect of rewetting on the bird populations was already notable three months after rewetting. The building of dams was finalised in March 2021, and the first changes in bird populations were recognised during an inventory in June 2021. The second bird inventory in spring 2021, just after the water level rose up, did not show an increase of open landscape bird species, however, the number of pairs of waders in the open area rose. The number of *Tringa ochropus* pairs increased more than four times. The waders were attracted by the muddy and wet surface exposed during the restoration work. After rewetting, a large number of cranes in the area were observed (Figure 31). Also, there was a remarkable abundance of frogs in the small pools where peat was taken to make dams.

Figure 31. *Common crane Grus grus. Photo: R. Jakaitis.*

CONSTRAINTS AND SOLUTIONS

In the Suursoo-Leidissoo peatland, it was initially planned to raise the water level in all ditches and streams by building peat dams. On the same day when the LIFE Peat Restore project started (July 1, 2016), two streams (ditches), Piirsalu and Kaldamäe in the restoration area were officially designated as protected spawning streams for salmon and trout.

This induced the Estonian project team to face a nature conservation conflict as, on one side, restoring degraded peatlands is a priority according to the national legislation. On the other side, building dams and raising the water level in protected fish spawning areas is prohibited. For that reason, the initial restoration plan had to be changed. After almost two years of lasting discussions with conservation officials, a compromise was found. The solution was rewetting the area but leaving ditches open for fish – building off building peat dikes along the ditches (streams) on both sides (Figure 23, 27). By building dikes, the surface waters cannot easily flow to the stream but stay on the peatland. As the hydraulic conductivity of the sedge dominated peat is low, the water can hardly infiltrate through the dikes. It was decided to construct the peat dikes not closer than 40 m from the ditch to prevent washing out of peat into the ditches. The height of the peat dikes over the surface is 50 cm, and the width on the top – 1 m (Figure 20B).

Photo: M. Pakalne

4.1.2. Engure Lake peatland, Latvia

Photo: J. Dzilna

Location: Western Latvia
WGS84 coordinates: 57.266751, 23.146529, https://ieej.lv/peatrestore
Altitude: 0.8–3 m a.s.l.
Protection status: Area in Engure Lake Nature Park (Natura 2000 site code: LV0302800), Ramsar site No. 738

Total area of the mire complex: 12 580 ha

Restoration area: 106 ha, including 86 ha of alkaline fen, favourably affected by blocking the ditches (two dams) and 20 ha where trees and shrubs were removed

EU importance habitat types in the restoration area: Calcareous fens with *Cladium mariscus* and species of the *Caricion davallianae* (7210*), Alkaline fens (7230)

Implementation: University of Latvia (planning, monitoring, expertise), Lake Engure Nature Park Fund (clearing of trees and shrubs); E Būvvadība (technical designs, construction work)

Land manager: JSC "Latvia's State Forests"

DESCRIPTION OF THE ENGURE RESTORATION AREA

Engure Lake Nature Park comprises different types of wetlands. The largest area in the nature park is covered by Engure Lake, a coastal freshwater lake (4046 ha) that is surrounded by reed beds, fens, swamp woodlands, dry forests on coastal dunes. The lake is separated from the Gulf of Riga by a narrow (1.2–2 km) stretch of sandy, forested dunes. About 6000 years ago it was connected to the Baltic Sea, but then gradually separated and became a lake. In the early 19th century, the lake was at least twice as big as its area today. Due to the lack of hay meadows and pastures, it was decided to lower the water level to obtain agricultural lands and to reduce the floods. In 1842, the Mērsrags Canal, which still connects the lake and the sea, was dug. As the water level dropped by 1.5 m, the area of open water decreased by one half. Large areas of the lake bottom became exposed – muddy bottom on the western shore, and sandy bottom on the eastern shore. As the lake became smaller, large areas of wet meadows, fens and reed beds developed on its new shores, while some areas gradually overgrew with the forest.

On the eastern shore of the lake (LIFE Peat Restore project area), alkaline fens have developed in shallow depressions (Figure 32, 33), on a sandy bottom that has overgrown mostly with sedges (*Schoenus ferrugineus*, *Cladium mariscus*, *Carex elata*). Since the fens are very young (ca. 170 years), the peat layer is very thin or absent. During the second half of the 19th century and the first half of the 20th century, a large proportion of the exposed lake bottom was used for hay mowing and grazing for many decades. Nowadays, the formerly grazed and mown fens are abandoned and are overgrowing. Grazing and mowing are re-established only in some areas on the eastern shores of the lake (outside the LIFE Peat Restore project area).

Figure 32 . *A typical species in the calcareous fens in the Engure Lake area – Ophrys insectifera. Photo: M. Pakalne.*

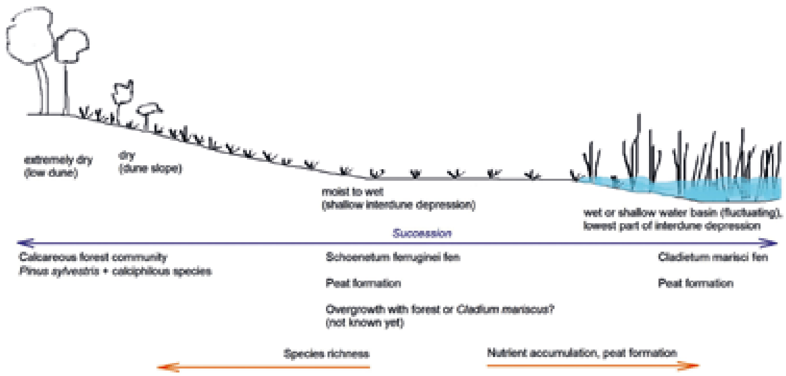


Figure 33 . *Vegetation and an overview on the succession and fen development in the Engure fens. Drawing: A. Priede.*

WHY WAS THE RESTORATION NEEDED?

In the early 20th century, some fens around Engure Lake were drained by shallow, hand-dug ditches that helped to make shorter the high inundation periods in the fen depressions, also in the LIFE Peat Restore project area on the eastern shore of the lake. In the early 21st century, the drainage impact was not significant, however, it contributed to increased fluctuations of the water table in the fens. Before restoration from 2017 to 2019, the water table in the fen depression was highly fluctuating due to natural conditions (sandy bedrock), however, the fluctuations were even sharper due to drainage. In combination with drainage effect, cessation of traditional management caused gradual transformation of fens into woodland (Figure 34). This has led to replacement of peat-forming *Schoenus ferrugineus*, *Cladium mariscus* and brown mosses dominated vegetation by plant communities of drier conditions (*Molinia caerulea* dominated vegetation). In a few decades, this may result in interruption of peat-formation, decline of rare, protected fen habitats and species, and establishment of a calciphilous, mesophytic pine forest community.

Figure 34. *Overgrowing fen with grey alder Alnus incana and Scots pine, Pinus sylvestris before clearing of shrubs. Photo: A. Priede.*

Rewetting as a scenario. To prevent further deterioration of the ecosystem, it was decided to block two drainage ditches in the northern part of the area. On the basis of hydrogeological modelling and exploring the site conditions in the field, it was assumed that it will help to retain the water in the fen depression for a longer period, preventing rapid runoff that, in turn, promotes establishment of trees. Two scenarios were developed: raising the water level for 20 and 25 cm, both with similar potential effect on vegetation. Finally, it was agreed to implement the 20 cm scenario. According to the modelling results, it may directly affect 80–90 ha of fen, however, should not cause damage to the surrounding forests on mineral soils.

The non-intervention scenario. In a case if rewetting and clearing of shrubs would not be applied, in a longer period of time (two and more decades) a large proportion of the open fen area may overgrow with forest. This would cause local extinction of typical alkaline fen vegetation, including numerous rare, threatened species and lead to disruption of peat formation.

GEST estimates on GHG reduction: after restoration no change in GEST-types was expected, and emissions may not change significantly. Therefore, the calculated GWP is identical in all scenarios, 32.2 t CO_2-eq annually and 1610.0 t CO_2-eq in the next 50 years.

TARGET VEGETATION AND SPECIES

The target vegetation is sedge-dominated vegetation of calcareous fens, either dominated by *Schoenus ferrugineus* (small-sedge vegetation of base-rich fens) (Figure 35) or *Cladium mariscus* (Figure 36). Observations during the last 30 years (Pakalne 1994; Roze 2015; Pakalne, Priede 2019) show that still in the 1980s the area was dominated by sparsely vegetated open water pools or *Schoenus ferrugineus* dominated fen (Figure 37). Since then, the fen has been either overgrown with *Schoenus ferrugineus* (Figure 38) or invaded by *Cladium mariscus* in the wettest depressions – that may be, in this case, the climax vegetation.

Figure 35. *Schoenus ferrugineus – one of the dominant plant species in the Engure Lake project area. Photo: M. Pakalne.*

Figure 36. *Cladium mariscus in a calcareous fen in Engure Lake Nature Park. Photo: M. Pakalne.*

Figure 37. *The fen area with sparse hummocks of Schoenus ferrugineus, Phragmites australis and open water in 1988. Photo: M. Pakalne.*

Figure 38. *Calcareous fen dominated by Schoenus ferrugineus in the same area in 2020. Photo: M. Pakalne.*

The target vegetation in the Engure Lake peatland is either small-sedge vegetation with calciphilous plant species dominated by *Schoenus ferrugineus*, or *Cladium mariscus* dominated tall sedge fen (Figure 35–38). Besides *Schoenus ferrugineu*s, typical vascular plant species of the small-sedge fen are *Carex panicea*, *Phragmites australis* (sparse cover), *Lycopus europaeus*, *Potentilla erecta*, *Epipactis palustris*, *Primula farinosa*, *Eupatorium cannabinum*, *Cirsium palustre*, and mosses *Drepanocladus revolvens*, *Scorpidium scorpioides*, *Fissidens adianthoides*, *Campylium stellatum* (Figure 39). The most common accompanying species in *Cladium mariscus* dominated fen are *Phragmites australis*, sedges of *Carex flava* group, *Myrica gale*; in shallow depressions with open water – *Utricularia intermedia, U. minor*; the moss layer is dominated by *Scorpidium scorpioides* and *Drepanocladus revolvens*. In both vegetation types, the tree and shrub cover is sparse, composed of Scots pine *Pinus sylvestris* and common juniper *Juniperus communis*, or absent.

Figure 39. *Some of the target plant species of calcareous small-sedge fen vegetation in Engure fens: A – Liparis loeselii, B – Gymnadenia conopsea, C – Scorpidium scorpioides, D – Primula farinosa, E – Campylium stellatum, F – Fissidens adianthoides, G – Dactylorhiza incarnata, H – Dactylorhiza maculata. Photos: M. Pakalne (A, B, C, D, G, H), L. Strazdiņa (E, F).*

The vegetation shift in Engure and some similar areas in Latvia, i.e. transformation from *Schoenus ferrugineus* dominated to *Cladium mariscus* dominated vegetation (Pakalne, Priede 2019) has raised a discussion on the need to apply mowing to support *Schoenus ferrugineus* dominated vegetation. However, the experimental mowing in some plots in Engure and Ķemeri National Park (A. Priede, *per. com.*) has not so far proved that this is an effective measure. Further experimental mowing and monitoring of the effects on longer term are needed, therefore this as an insufficiently tested method was not applied on a larger scale in the project (only small experimental mowing plots, should be continued after the project to observe the long-term effect).

PREPARATORY WORK

Prior to applying restoration measures within the LIFE Peat Restore project, Engure Lake Nature Park had a site management plan (Blanka (ed.) 2011), valid until 2025. However, it did not foresee any measures to restore alkaline fens habitats, which are among the key biodiversity elements in the nature park and among the largest and most representative alkaline fens in Latvia. According to the national legislation, updating the site management plan requires applying the full procedure including inventory of the entire area of the nature park, focusing not only on fens, but also other habitat types and species groups. The LIFE Peat Restore team did not have resources and capacity for this. The project budget for fen restoration was limited, focused on the priority area on the eastern shore of the lake. However, it was considered that proper planning and involvement of the key stakeholders is necessary, therefore a detailed management plan for the project area was developed. That included the fens and hydrologically related surrounding area, an area covering 238 ha (LIFE Peat Restore 2018).

The planning phase included habitat/vegetation mapping based on field surveys in combination with orthophoto maps and hydrogeological modelling (done in 2017–2018)

Figure 40. *Clearing of shrubs in the Engure fen was done manually using a brushcutter (February 2020). Photo: K. Libauers*

supplemented with field surveys of the area including ditches. The modelling was based on data on the drainage basin, rainfall amount and surface relief. As a result, two scenarios (two different maximum water levels resulting from blocking the ditches) were developed: raising the average water level at 0.20 m and at 0.25 m, for each the potential impact was assessed. During the plan development stage, three stakeholder meetings were held including field visits (the land manager JSC "Latvia's State Forests", the national authority Nature Conservation Agency, and two directly involved LIFE Peat Restore project partners: University of Latvia and Lake Engure Nature Park Fund). As a result, a management plan for the target area was developed and agreed by all involved parties by the end of 2018.

The plan proposed construction of two plastic dams with potential rewetting impact on 86 ha area in the northern part of the project area (Figure 46) and clearing of 33.4 ha of overgrown fen: 23.1 ha as a priority (during the project), and 10.3 ha after 2025. In the long term, the plan proposed establishment of extensive, regulated grazing in the entire 238 ha area, of which 65 ha are calcareous fens (after the end of LIFE Peat Restore. by attracting other funding).

The preparatory work included official, written agreement with the land manager JSC "Latvia's State Forests" as well as development and approval of the technical design. These procedures took approximately two years.

RESTORATION AND MONITORING RESULTS

In the Engure Lake peatland, cutting of trees and shrubs (23.1 ha) was selective (Figure 40). Older pines, groups of pines and healthy junipers were preserved, as they serve as important biodiversity and landscape elements (Figure 42). As agreed with the land manager, trees with a diameter above 12 cm may not be removed, which was strictly followed. The young trees and shrubs were cut using hand tools (chainsaw, brush cutter), collected in heaps and burned on

Figure 41. *Volunteers help to remove the shrubs from the fen (February 2020). Photo: A. Priede.*

Figure 42 . *The Engure fen after clearing of shrubs in June 2021. Photo: A. Priede.*

the ground. The work was done in winter (January–February 2020). The work was partly done by volunteers (ca. 3.5 ha), thus also sharing and gaining practical experience and discussing the need for such management in similar fen areas (Figure 41).

Two plastic piling dams were installed on the shallow ditches where a rapid runoff of water from the fen to the lake was observed. Thus, it was decided in the very early stage of the project that blocking the ditches may help to retain the water and to improve the water regime in the fen. The location of ditches was different from most situations in peatland restoration areas (often difficult to access), as here it was possible to access the ditches by machinery (forest road on stable mineral soil,

Figure 43. *Installing the plastic piling in the Engure restoration area. Photo: M. Pakalne.*

Figure 44. *Plastic dam in the Engure restoration area in August 2021, more than half a year after building. Photo: A. Priede.*

Figure 45 . *Vegetation monitoring in Engure peatland. Photo: K. Libauers.*

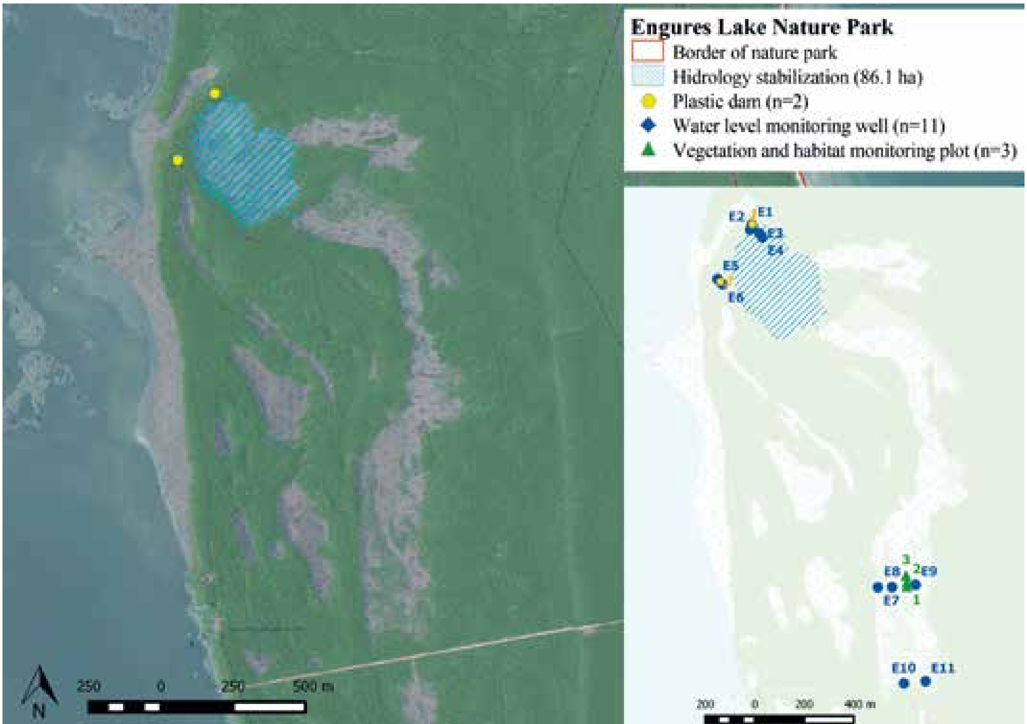


Figure 46 . *Water level and vegetation monitoring points in the Engure restoration area. Map: L. Strazdiņa.*

only removal of some fallen trees was needed). Since the ditches were dug in mineral soil, it was not possible to apply the well-adapted ditch damming method: peat dams (no peat material was locally available). Therefore, plastic piling was chosen as the most appropriate, cost-effective solution for the local situation. Two dams were built here in November 2020, on small ditches running out of the fen (Figure 43, 44).

The upper part of the soil was sandy and light in colour. About half a meter deeper begins a clayey, allerite layer. The work was done by a small excavator and two workers. The location of the dam was marked and the construction area was fenced with tape. The excavator excavated a trench about 10 m long with a depth of half a meter. The workers placed a section of plastic piling onto the trench and set a piece of wood on it. Then, the excavator pushed the piles onto the ground using the bucket (Figure 43). Each section of the plastic pile was connected to a wooden board, and a plastic protection strip was placed on the surface (Figure 44). The length of the plastic piles on the sides of the dam is 1.5 m, in the central part of the dam the length is 2 metres. In the middle of the dam, there is a meter long recess for water drainage. The height of the dam is about 20 cm above the ground. Upon completion of the work, the trench around the dam was filled with the excavated sand. The dam building was completed in November 2020.

To assess the restoration success, during the planning stage (in 2018), vegetation monitoring plots and water table monitoring wells (Figure 47) were established (the map depicting the location of monitoring points is given in Figure 46).

Figure 47 . *Water level monitoring well. Photo: A. Priede.*

Water table monitoring wells equipped with automatic data loggers were installed in April 2018, more than two years before installing the dams (building was completed in November 2020). Water table was automatically measured by loggers once per hour (except for the periods when the shallow groundwater was frozen).

Vegetation monitoring (Figure 45) in permanent plots was carried out every year during the summer season since 2018 according to the joint methodology agreed among the project partners (see *Chapter 3.2*). In Engure, three large plots (10 x 10 m) and 30 subplots (1 x 1 m) were established. The first monitoring results suggest that after removal of shrubs and trees, there is a positive effect on the plant cover, giving more space for the mire vegetation to develop. It also favours the growth of orchid species, such as *Liparis loeselii.* Still, the vegetation development greatly depends on the water level fluctuation during the vegetation period as dry periods interchange with flooded bryophyte layer after heavy rainfalls. As in the monitoring area, the water level has not been raised by building of dams, substantial changes in the plant cover have not been

Figure 48. *Water level fluctuations in the Engure restoration area (the water level is presented above the sea level), from December 2020 to June 2021. In 2020, improvements were made to the measurement system with additional equipment that displays more accurate and reliable data, therefore only this period is presented here.*

observed. Still, the tendency remains that the calcareous fen vegetation with *Schoenus ferrugineus* is being replaced by *Cladium mariscus*.

In the Engure area, precipitation is the main determinant of the water level in the fen. The groundwater level is unstable and rapidly reacts to precipitation events. After heavy rain or snowmelt, especially in spring season, it can be very wet with standing water, but during the summer the groundwater level may drop considerably, leading to temporary desiccation of the fens.

In the first half of 2021, precipitation was significantly higher than in 2020. The highest precipitation was observed in January (40.2 mm) and May (84 mm). In the water level monitoring wells E10, E11 installed in the farthest places from the fen, the lowest groundwater level in the period from 2018 to 2020 recorded was 1.12 m below the surface, while the highest water level in the same period was 70 cm below the surface (Figure 48). The water level in the wells located closer to the mire was much higher. For example, in well E8 the maximum recorded level was 3 cm above the ground. Wells E2 and E5 were located closer to ditches and to Engure Lake, thus the water level in these wells had a larger amplitude.

CONSTRAINTS AND SOLUTIONS

Study of the calcareous fen vegetation shows that in the course of time *Schoenus ferrugineus* community is being replaced by *Cladium mariscus* dominated vegetation. This is a natural process that cannot be stopped. Removal of trees and shrubs should be done on a regular basis after the end of the LIFE project with some years interval (e.g. five to ten years), as young trees will establish and offsprings from the cut tree stumps will regenerate.

4.1.3. Baltezers peatland, Latvia

Photo: M. Pakalne

Location: Southwestern Latvia
WGS84 coordinates: 56.67966, 22.62252, https://ieej.lv/peatrestore
Altitude: 123–125 m a.s.l.

Protection status: Area in Baltezers Mire Nature Reserve (Natura 2000 site code: LV0531100)

Total area of the mire complex: 228 haa

Restoration area: 41.5 ha

EU importance habitat types in the restoration area: Transition mires and quaking bogs (7140), Western Taiga (9010*), Bog woodland (91D0*

Implementation: University of Latvia (planning, expertise), E Būvvadība (technical designs, construction work)

Land manager: JSC "Latvia's State Forests"

DESCRIPTION OF BALTEZERS PEATLAND

Baltezers Mire Nature Reserve is located in the Saldus Hilly Area of Austrumkursa Upland in the western part of Latvia. The largest area in the nature reserve is covered by forests (142.1 ha), while mire covers 41.1 ha, Baltezers Lake – 35 hectares.

The nature reserve is located in a relief depression formed by the activity of the glacier ca. 16 000 years ago. Baltezers Lake occurs in a glacio-karst depression, and the mire developed as the wet relief depression overgrown with peat-forming vegetation and gradually filled up with peat. Peat started accumulating about 5000 years ago at the end of the Atlantic period and the beginning of the warmer subboreal period. A raised bog with a dome in the central part developed. The average depth of peat is 2.3 meters, while at the deepest point the peat is 3.7 m thick (Ābelīte (ed.) 2019).

Figure 50. *Drainage ditch in Baltezers peatland before rewetting. Photo: A. Priede.*

In 1985, the peatland was characterised by raised bog and transitional mire peat deposits (Ābelīte (ed), 2019), i.e. acidic, poorly decomposed peat. Today, the raised bog vegetation is largely replaced by calciphilous plant species. There are numerous plant species, such as small sedges and brown mosses, that never occur in acidic raised bogs. This phenomenon was caused by the Brocēni cement factory, located about 2 km from the nature reserve. From 1938 to the 1980s, it produced a large amount of cement dust that was emitted into the air, i.e. 14 000–28 000 t of limestone particles per year (Ābelīte (ed), 2019), from which a considerable proportion was deposited in the nearby Baltezers peatland and Baltezers Lake. Today, the cement factory is equipped with effective filters which stop the release of limestone particles into the environment. The cement dust deposition in the bog has facilitated the decomposition of the upper peat layer and enriched it with nutrients, causing turnover of the vegetation, i.e. conversion from raised bog vegetation to calciphilous transitional mire vegetation.

WHY WAS THE RESTORATION NEEDED?

During the first period of Latvia's independence (1918–1940), a national scale peat extraction propaganda encouraged farmers to cut peat for soil improvement, bedding and heating. Apparently, such intentions also affected Baltezers peatland. At that time, the peatland was partly drained and prepared for peat cutting in an approximately 30 ha large area. Drainage works included digging of ditches and establishment of roads to transport the peat. Peat extraction in this area has not commenced, at least not in large amounts. The impact is still in place as ditches (Figure 50) and old, highly decomposed piles of peat.

Rewetting scenario. To prevent further degradation of the ecosystem, it was decided to block the drainage ditches all around the Baltezers peatland. On the basis of hydrogeological modelling and exploring the site conditions in the field, it was assumed that it would help to retain the water in the mire and improve the mire condition, carbon sequestration capability and support mire vegetation.

Non-intervention scenario. If rewetting would not be applied, in a longer period of time (two and more decades) a large part of the open mire area might overgrow with forest.

Estimated GHG reduction after rewetting: after rewetting the total emissions may be lower for 66.3 t CO_2-eq than in baseline situation, i.e. in the rewetted peatland the emissions may be 241.79 t CO_2-eq annually and 12 089.7 t CO_2-eq in the next 50 years.

TARGET VEGETATION AND SPECIES

As the original raised bog vegetation, due to the impact from cement factory by limestone particles from cement dust, has been irreversibly transformed into transitional mire vegetation, target species include peat-forming species such as *Sphagnum warnstorfii*, *Eriophorum polystachion, Carex rostrata, Carex flava, C. pulicaris, Trichophorum alpinum, Scorpidium scorpioides, Bryum pseudotriquetrum, Campylium stellatum, Parnassia palustris, Succisa pratensis, Scorpidium scorpioides*. It is important to maintain this habitat for *Ophrys insectifera*, a very rare orchid species in Latvia.

Since there is no longer the impact of cement dust deposition, the target vegetation would include also the original raised bog species, e.g. *Eriophorum vaginatum, Trichophorum cespitosum, Drosera anglica, D. rotundifolia, Sphagnum magellanicum, S. fuscum, S. rubellum, Andromeda polifolia, Calluna vulgaris*. At present, the bog species occur only in patches or on hummocks among the transitional mire vegetation.

Figure 51 . *Some of the target plant species in Baltezers peatland: A – Sphagnum warnstorfii, B – Trichophorum alpinum, C – Carex rostrata, D – Parnassia palustris, E – Andromeda polifolia, F – Tomentypnum nitens, G – Scorpidium scorpioides, H – Sphagnum fuscum, S. rubellum, Vaccinium oxycoccos. Photos: M. Pakalne (A, B, C, D, E, H), L. Strazdiņa (F, G).*

PREPARATORY WORK

Within the LIFE Peat Restore project, in 2019 a site management plan was developed for Baltezers Mire Nature Reserve, valid until 2031 (Ābelīte (ed.) 2019). It proposed hydrological restoration by blocking the ditches including detailed locations of the peat dams (Figure 52). The proposed actions were based on field inventories done by certified habitat and species experts. Hydrogeological modelling was done by a qualified expert hydrogeologist.

The preparatory work including the development of the management plan and hydrogeological modelling, development and approval of technical designs, and agreement with the land manager JSC "Latvia's State Forests" took approximately two years.

During the planning stage, vegetation monitoring plots and water level monitoring wells were established (Figure 52). The vegetation and water level monitoring was commenced two years before restoration, in 2018. Vegetation monitoring (Figure 53) in permanent plots was carried out every year during the summer season according to the joint methodology agreed among the project team (see *Chapter 3.2*). In Baltezers Mire, three large plots (10 x 10 m) and 30 subplots (1 x 1 m) were established.

The water level was automatically measured by loggers in nine wells of which three were located near the dam and the other wells in a transect in the direction from the ditch to the central part of the mire. The measurement interval was once an hour.

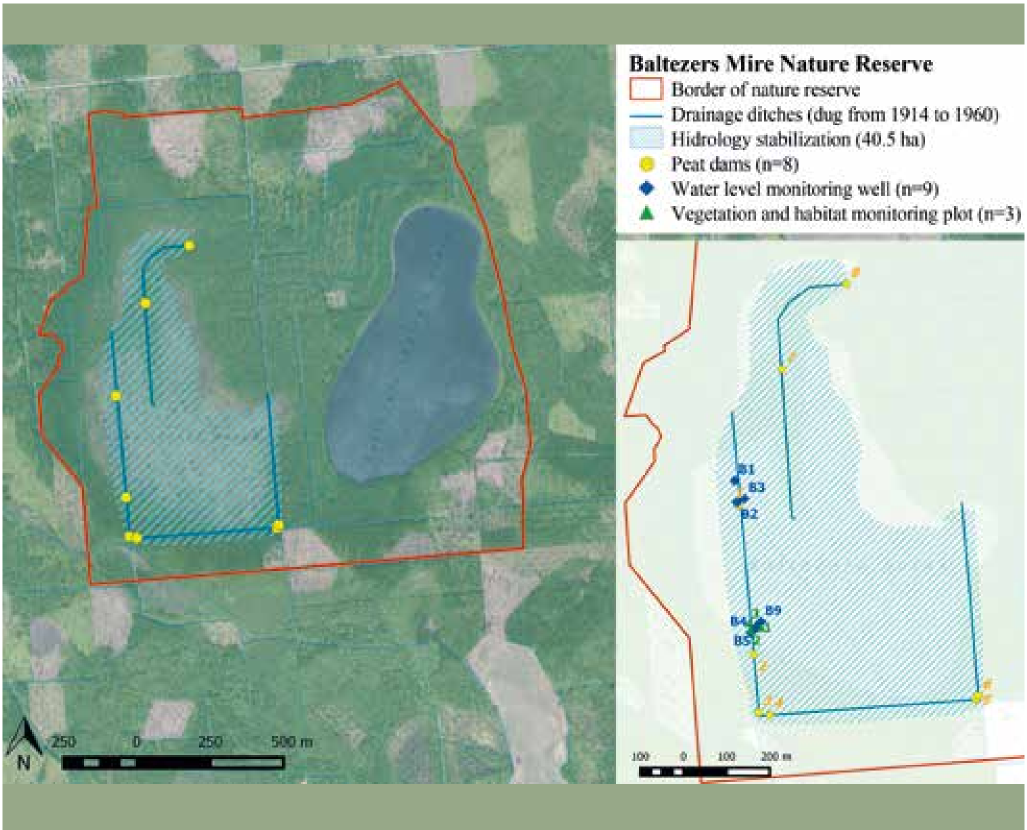


Figure 52 . *Water level and vegetation monitoring points in Baltezers Mire.*

RESTORATION AND MONITORING RESULTS

The building of peat dams on ditches was used as the most effective way to raise and stabilise the water level as well as to retain the water in the mire (Dēliņa, Ģederts 2013). In total, eight peat dams were built (Figure 55), as proposed in the management plan. Two dams were built on the ditch in the northern part of the mire, two dams are located on the western side, and four dams perform their function on the ditch at the southern margin of the mire. The modelled area that may be favourably affected by hydrological restoration reaches 40.5 hectares. The dam building was done by two light, relatively small size excavators, equipped with wide caterpillar tracks, which prevent the excavators from getting stuck in the mire. The excavators were small, capable of manoeuvring through a forested peatland without removal of many trees and damaging the ground vegetation and peat layer. In densely forested parts of the peatland, excavators moved with difficulty; one excavator even slightly damaged its tracks. To improve the movement of machinery, the road was prepared using a chainsaw to cut smaller trees and shrubs on the way.

The peat for building the dams was taken from the near surroundings of the dam locations without creating holes on the ground (Figure 54). The peat layer to the southern part of the mire (four dams located there) was thinner than that near the ditches in the northern part. At this point, the depth of the ditch is twice as much as along the central part of the bog which caused some changes in the practical implementation.

Figure 53. *Vegetation monitoring in Baltezers Mire was carried out by experienced experts. Photo: M. Pakalne.*

Figure 54. *Dam building process in Baltezers Mire. Photo: A. Priede.*

As known from the earlier experience in Latvia (Nusbaums 2008), after rewetting, such shallow hollows where the peat surface is temporarily damaged overgrow with the typical mire vegetation within a few years.

The construction of the dams was completed in October 2020, the earthworks took two days. Since then, the groundwater level at the site began to stabilise.

After building dams, a rise in water levels and stagnation in water flows in the ditches upstream from the dams were observed (Figure 55). The main task of the dams has been achieved: the water is retained in the mire and, in a longer time, will stabilise, i.e. the average water table has risen and the well-pronounced fluctuations, as before rewetting, were becoming smooth (Figure 56).

The lowest groundwater level during the monitoring period was observed in the well B2 installed close to one of the ditches – 42 cm below the mire surface. As a result of rewetting, it reached 11 cm below the surface in the first half of 2021 (the stabilisation to be further observed). The intensity of precipitation after the dam construction also helped to reach the desired water level faster. In the first half of 2021, precipitation was significantly higher than in the same period of 2020. The highest precipitation was observed in May 2021 (39.6 mm) and June (34 mm).

After building dams on the drainage ditches in Baltezers Mire, it was observed the area near the ditches is becoming wetter indicating that the conditions suitable for peat formation are re-established, followed by reappearing of mire species (e.g. *Drosera* sp.) in the drained areas (Figure 57).

CONSTRAINTS AND SOLUTIONS

Overall, the restoration work including the planning stage did not face any unexpected problems. When building dams in Baltezers Mire, in some locations the construction work using the peat from the adjacent mire was problematic, as it was highly saturated with water. Consequently, to build the dams as planned in the technical design, a much larger amount of mud was used than other dams in this mire. When entering the mire through the wooded part, one of the excavators got damaged but it could be repaired and did not cause any serious delays.

Figure 55 . *Accumulation of water in ditches between the peat dams, June 2021. Photos: M. Pakalne.*

Figure 56 . *Water level fluctuations in Baltezers peatland before and after the building of dams. In 2020, improvements were made to the measurement system with additional equipment that displays more accurate and reliable data, therefore only this period is presented here.*

Figure 57 . *In the early stage after the dam building, the drainage ditches in Baltezers peatland were gradually overgrowing with Drosera anglica. Photo: M. Pakalne.*

4.1.4. Biesenthaler Becken, Germany

Photo: M. Scharping

Location: Northeastern Germany, Federal State of Brandenburg
WGS84 coordinates: 52.748113, 13.592512, https://ieej.lv/peatrestore
Altitude: 40–55 m a.s.l. (referring to three project peatlands)

Protection status: Biesenthaler Becken (Biesenthal Basin) Nature Reserve (990 ha)
Natura 2000 site (960 ha), Natura 2000 site code DE3247301

Area: 15.5 hectares of three separate peatlands within the nature reserve (except BB-3)

Restoration area: In total 15.5 ha of 3 drained mires (BB-1, BB-2, BB-3): 4 ditch fillings with clay and partly wood; 43 ditch fillings with peat and wood; at BB-1 for raising the water level in natural stream 1 river bottom slide 50 m (with peat, wood and mineral soil) and along 600 m structuring of the river with peat and wood; forest conversion in 2 ha catchment area of BB-3

EU importance habitat types in the restoration area: Bog woodland (91D0*) dominated by birches, and other vegetation on peat (alder forest, reeds)

Implementation: NABU Germany (overall implementation, expertise), Wasser- und Bodenverband "Finowfließ" (technical planning)

Land manager: NABU-Stiftung Nationales Naturerbe

DESCRIPTION OF BIESENTHALER BECKEN

Due to the complex glacial and post-glacial processes that have resulted in diverse geomorphological patterns, the relatively small Biesenthaler Becken (Biesenthal Basin) Nature Reserve is rich in various habitat types and vegetation forms. The area is dominated by forests and grasslands on mineral soils and by lakes and peatland vegetation such as alder forests, willow shrubberies, sedges and rushes, reeds and wet meadows in the depressions.

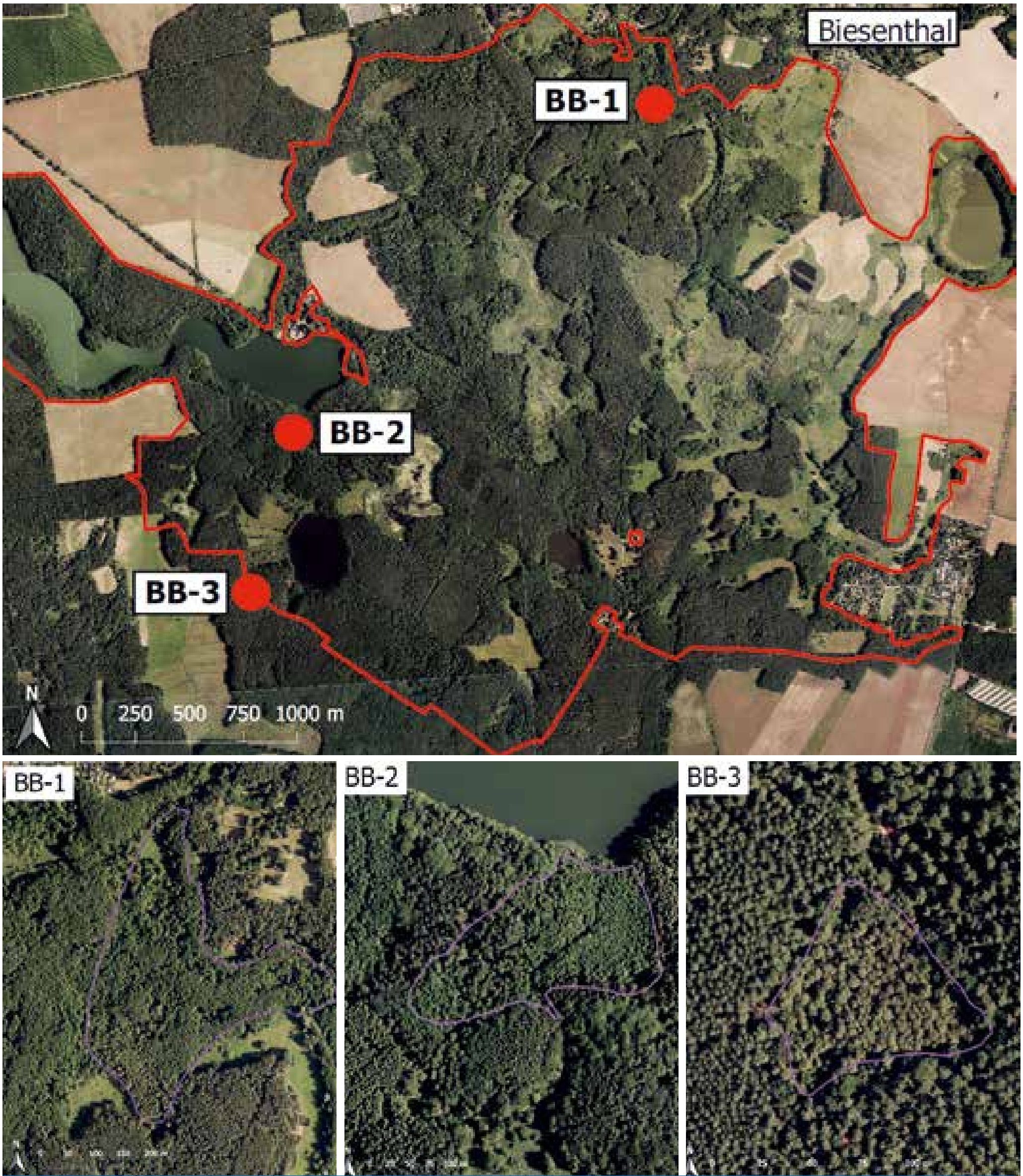


Figure 58. *The German project area (red – protected area Biesenthaler Becken; source: "Landesamt für Umwelt Brandenburg"; https://www.govdata.de/dl-de/by-2-0; dl-de-by-2.0) and location of the three project sites with marked borders (Basic Geo Data: © GeoBasis-DE/LGB 2018). Maps: S. Breiden.*

In the long-term (1961–2010), the annual average air temperature and precipitation is +8.9 °C and 520 mm, respectively. According to the Köppen classification, the climate is moist-continental.

Three drained, mainly wooded peatland areas were selected as the LIFE Peat Restore restoration sites (Figure 58). The **restoration area BB-1** covers 10.5 hectares. It is situated to the west of the sandy Heideberg plateau and is crossed by the lowest reaches of the small Pfauenfließ stream before it enters the Finow River. The fen (BB-1 restoration area) has developed from a terrestrialising (overgrown) lake and gradually transformed into a mire with a percolation regime that is indicated by sedge-brown moss and partly *Sphagnum* peat layers, in parts interrupted by lake sediments. The mean peat thickness is ca. 4.75 m, with a maximum depth of 9 m in the central part.

Based on the historical soil data, 60 years ago the BB-1 area was used as grassland with numerous small ditches draining the peatland into the Pfauenfließ River and the other neighbouring rivers: Rüdnitzer Fließ and Finow. After abandonment, large parts of the fen grassland turned into black alder *Alnus glutinosa* forests. Moorbirch *Betula pubescens*, Scots pine *Pinus sylvestris* and willows *Salix* spp. cover a smaller proportion of the area (example view on the title page of this chapter). Only a little open fen vegetation patch has survived. As a consequence of drainage leading to water levels of 40 cm below the surface (Figure 64, below; the mean level around 8 cm below surface), the peat layer is strongly decomposed up to 50 cm depth.

The **restoration area BB-2** covers approximately 3.5 ha and is situated between Plötzensee Lake and Hellsee Lake. The peatland is drained by the artificial Plötzenseefließ watercourse bringing water from a larger catchment area to Hellsee Lake. The mean peat thickness of this terrestrialisation peatland, characterised mainly by alder peat layers above the lake sediments, is 4.3 m with a maximum depth of 7.75 metres.

The BB-2 area was not used for agricultural purposes during the last 100 years, however, it was moderately drained for forestry by digging the artificial Plötzenseefließ watercourse leading to the mean water levels in a range between 11 and 20 cm, with the lowest levels between 60 and 70 cm below the surface. The uppermost 20 cm of peat is strongly degraded. Although the naturally prevailing black alder kept its dominance (Figure 59), the lower water levels allowed the growth of non-site typical species such as *Fagus sylvatica*.

The restoration area BB-3 is situated in a drainless depression to the west of Plötzensee Lake and covers around 0.7 hectares. The genesis of this strongly degraded kettlehole peatland remains unclear, as strong peat compaction prevented reaching the mineral ground beyond 2 m depth. Based on the historical data, the BB-3 area was also never used for agricultural purposes. During the last 100 years, it was a forestry area. For the latter purpose, a central ditch cut all through the small peatland destroyed the sealing layers between the peat body and the mineral soil that are characteristic for kettlehole mires. This perforation led to a strong decline of the water level, with a recent mean of around 95 cm and a maximum of around 125 cm below the surface. This resulted in strong peat decomposition and loss of the original Moorbirch-*Sphagnum* vegetation in most area.

As briefly introduced in *Chapter 3.6*, the GEST (*Greenhouse-Gas-Emissions-Site-Types*) approach was applied in the LIFE Peat Restore project. According to the GEST approach, in Biesenthaler Becken, several vegetation units were identified following Succow and Joosten (eds.) (2001). These more fine-scaled units were assigned to six different GESTs on peat (two of them are open peatland GESTs, and four – forested peatland GESTs, see Table 4).

Figure 59 . *A typical example of alder carr vegetation with the dominance of black alder Alnus glutinosa in the BB-2 area (Carex elongata-Alnus glutinosa-community, water level "very moist", see Table 4), July 2020. Photo: J. Etzold.*

Table 4. *Vegetation and site conditions assigned to six GESTs in the German project areas*

Area	Vegetation unit	Habitat type (Annex I of the Habitats Directive)	Site conditions: water/trophic/ "acidity" level	GEST	Area (ha)
BB-1	*Filipendula ulmaria-Urtica-dioica-Cirsium oleraceum* community	-	Moist/ eutrophic-rich/ subneutral to alkaline	Moist reeds and (forb) meadows	0.05
BB-1	*Carex nigra-Caltha palustris-Filipendula ulmaria*-community	-	Very moist/ eutrophic-rich/ subneutral to alkaline	Very moist meadows, forbs and small sedges reeds	0.16
BB-1	*Carex remota-Alnus glutinosa-Fraxinus excelsior-/ Carex acutiformis-Salix cinerea*-communities	-	Moist/ eutrophic rich/ subneutral to alkaline	Moist mesotrophic/ eutrophic forests and shrubberies	4.8
BB-2	*Carex remota-Alnus glutinosa-Fraxinus excelsior* community	91D0* (only part with *Betula pubescens*)	-		1.58
BB-2	*Carex acutiformis-Salix cinerea*-community	-	-		0.07
BB-1	*Carex elongata-Alnus glutinosa*-community	-	Very moist/ eutrophic rich/ subneutral to alkaline	Very moist mesotrophic/ eutrophic forests and shrubberies	3.58
BB-2	*Carex elongata-Alnus glutinosa*-community	91D0* (only part with *Betula pubescens*)	-		1.77
BB-1	*Betula pubescens-Alnus glutinosa* community		Wet/mesotrophic-medium/acidic	Wet mesotrophic/ eutrophic forests and shrubberies	2.01
BB-3	*Rubus fruticosus-Betula pubescens*-community	91D0*	Moderately moist/ mesotrophic very poor/acidic	Moderately moist mesotrophic/ eutrophic forests and shrubberies	0.65

WHY WAS THE RESTORATION NEEDED?

All three project areas had been strongly altered by drainage showing distinct signs of degradation. The original mire vegetation and habitats have declined in extent or were subject to succession towards other vegetation types adapted to the drier conditions.

As mentioned before, in the past the BB-1 area was covered by open fen grassland, but due to a dense drainage system it is nowadays dominated by black alder forests and the uppermost peat layers are degraded.

The moderate drainage of the BB-2 area led to the aforementioned peat degradation and also a shift in the plant species composition.

In the BB-3 area, the central ditch cutting through the sealing layers into the mineral soil fulfilled its goal, deeply draining and degrading the former kettlehole mire with its Moorbirch-*Sphagnum* vegetation.

Despite the fact that before rewetting most of the ditch system was poorly functioning and partly overgrown, it still drained the peatlands. Without restoration efforts (**non-intervention scenario**), peatland degradation would have continued for decades with respective GHG emissions and further loss of the remaining valuable peatland habitats and water retention capability. Therefore, in the **rewetting scenario**, it was planned to implement restoration measures to improve the hydrological situation in all three peatland areas, thus stopping or decreasing the peat decomposition and re-establishing the peat formation process.

Estimated GHG reduction after rewetting: a reduced GWP may be around 6.5 t CO_2-eq/year after restoration.

TARGET VEGETATION AND SPECIES

With the targeted water level rise near the soil surface at the BB-1 and BB-2 sites, wetter conditions may result in the desired vegetation shift towards peat-forming vegetation. In general, the forest stand may become thinner due to fewer trees coping with the wetter conditions, while the herbaceous mire vegetation may increase its cover. In the long-term, nutrients could be demobilized leading partly from eutrophic to mesotrophic conditions favourable for mire specialist species.

It may be expected that after rewetting, among the wooded parts, the formerly driest sites covered with vegetation assigned to the GEST "Moist mesotrophic/eutrophic forests and shrubberies" will be largely transformed into "Very moist mesotrophic/eutrophic forests and shrubberies".

The rather acidic "Wet mesotrophic/eutrophic forests and shrubberies" dominated by *Betula pubescens* with their still near-natural species composition will most probably stabilise. It may be expected that the conditions for species such as *Potentilla palustris, Valeriana dioica*, tall sedges and *Sphagnum* species may improve (Figure 60).

While possibly expanding their cover, similarly few open sites will turn from the GEST "Moist reeds and (forb) meadows" into "Very moist meadows, forbs and small sedges reeds" that may host mire specialist species.

For the small kettle-hole peatland BB-3, it remains unclear whether blocking of the central ditch excavated in the mineral ground and the forest conversion measures in the small catchment area will result in a significant rise of the water level, i.e. whether the current *Rubus fruticosus-Betula pubescens* community (water level "moderately moist") could transform into a *Sphagnum sp.-Betula pubescens* community (water level "moist"), in this case, considered a target community with mire species.

Figure 60. *Some of the target species in Biesentahler Becken. A – Sphagnum squarrosum, B – Carex acutiformis. Photos: A. Priede.*

PREPARATORY WORK

Technical design and further preparation

Soil analyses (including stratigraphic drillings), hydrological assessment, detailed vegetation mapping, forest inventory (to obtain structural parameters and estimation of the wood biomass of the particular forest types) were carried out for all three project areas in 2017 and 2018. Historical soil data from an official database (HUA, 1953–1972) were used.

Based on the hydrological measurements, mapping of the drainage system and with help of land-based laser levelling tools and a digital elevation model, water flow directions and present water levels were assessed. According to these findings, the feasibility of the restoration goals was fine-tuned, and the aspired water levels were determined.

After a long assessment and planning period, in March 2019, a contractor finalised a detailed technical design for the restoration of each site. The technical design contained overview maps, descriptions and specifying sketches for each type of measure (see examples in Figures 61–63). Constraints that had to be overcome during this phase are described in the *subchapter* "Constraints and solutions".

The technical designs were the precondition for the official approval procedure by the relevant authorities. The final approval was issued in January 2020. The following tender procedure resulted in awarding a contract to a restoration company in August 2020 that started the restoration works two months later (October 2020).

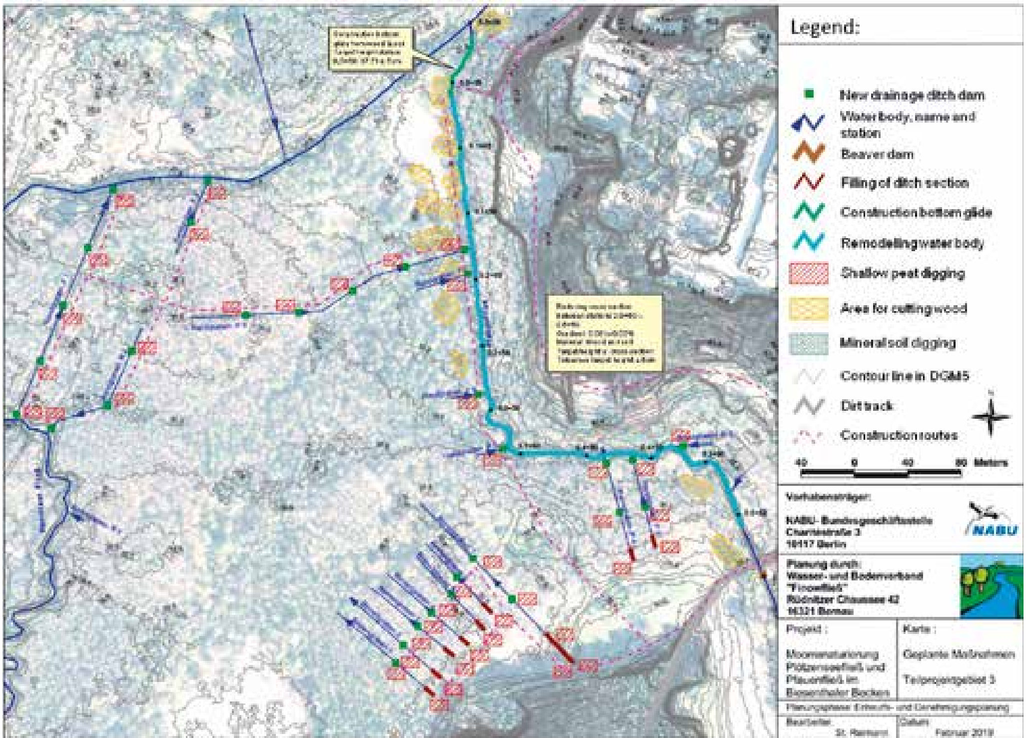


Figure 61 . *The technical design for peatland restoration of the largest site BB-1 in Biesenthaler Becken with nearly 40 planned ditch fillings and water rise measures along the Pfauenfließ River. Map: S. Reimann.*

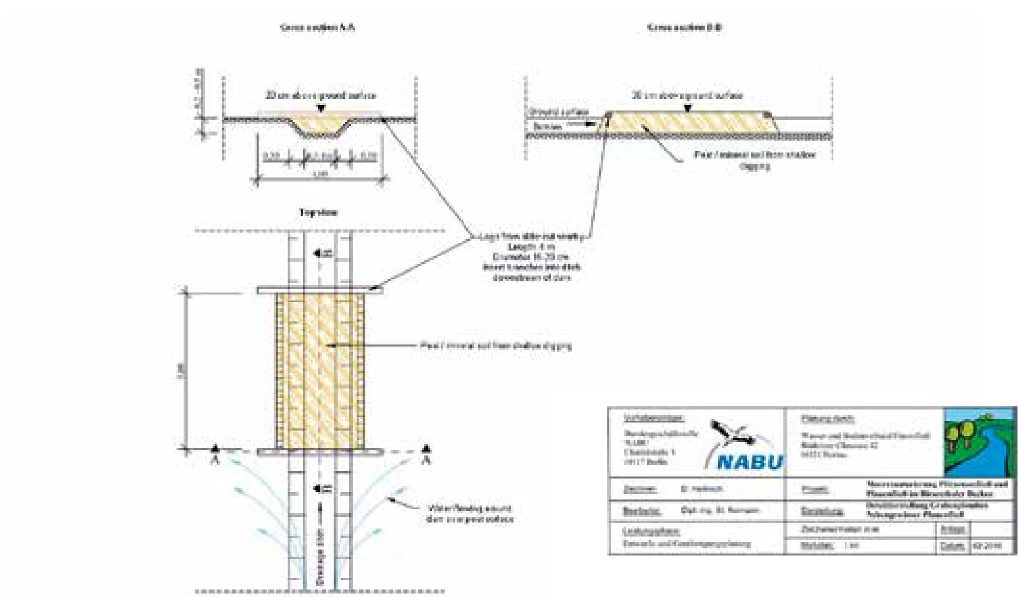


Figure 62 . *An example of smaller drainage ditch dams, constructions made of peat or mineral soil and wood (BB-1 area). For BB-2 area dams only differ by larger dimensions. Drawing: S. Reimann, D. Hellmich.*

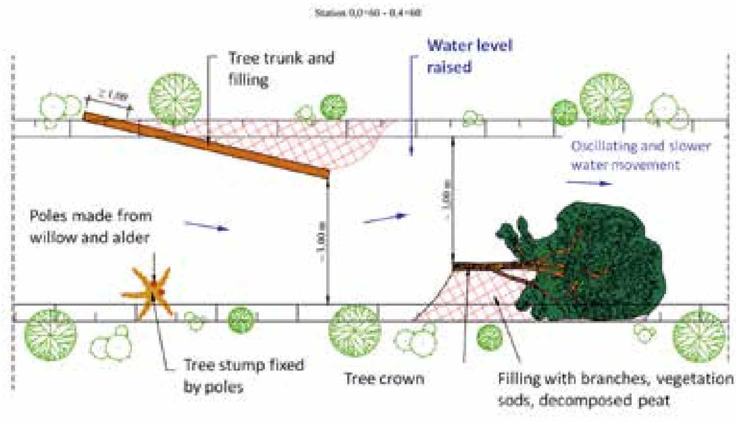


Figure 63 *Sketch on reducing the cross-section of the small Pfauenfließ River at site BB-1 to raise the soil. Drawing: S. Reimann, D. Hellmich.*

RESTORATION AND MONITORING RESULTS

In July 2018, permanent hydrological monitoring in five groundwater wells (in all three restoration sites together) and three gauges in the streams at BB-1 and BB-2 were installed. The measurements were continued to the date of this publication in 2021.

The results of BB-1, the largest restoration area among the sites in Germany, are shown in Figure 64.

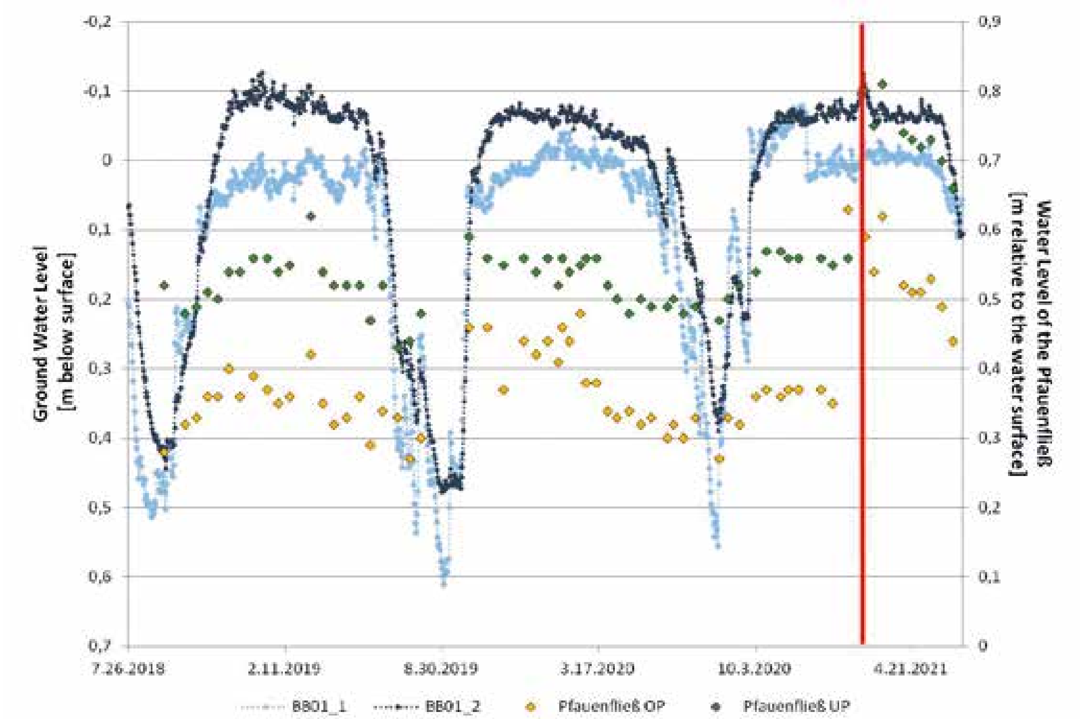


Figure 64 . *Example for hydrological monitoring of BB-1 area; groundwater data (in two wells BB01_1 and BB01_2) and water level position of the Pfauenfließ River (…OP and …UP); red line – date of intervention. Graph: A. Herrmann.*

To reach the restoration goals in all three peatland areas, the drainage ditches were blocked in ca. 50 locations. Depending on the width of the drainage ditch and the amount of water flow, the ditches were blocked using different techniques. For blocking the ditches, mostly peat, mineral soil and wood from the nearest surroundings was used. Additionally, in the largest restoration area BB-1, for raising the water level of the Pfauenfließ River in a 600 m stretch, the bottom was reshaped and diversified with soil and wood structures to reduce the river's cross-section (Figure 63). To improve the water provision to the BB-3 area, forest conversion measures, such as removal of the previously planted Scots pines *Pinus sylvestris* and replacing them with deciduous broadleaved tree species, were conducted in its catchment area.

In the small kettlehole peatland BB-3, both ends of the central drainage ditch penetrating the sealing layer were closed with clay brought into a trench of 2 m depth (Figures 65, 66). The clay was transported from an artificial soil filling from a distance of less than 5 km away. In contrast to the simple clay filling of the upper 10 m of the ditch, the end in direction of the water flow received additionally a "catchment ditch" rectangular to the ditch forming together a "T-shaped" clay-filling (Figure 66).

In the BB-3 area, the hydrological monitoring revealed still no significant rise of the water level eight months after the measures.

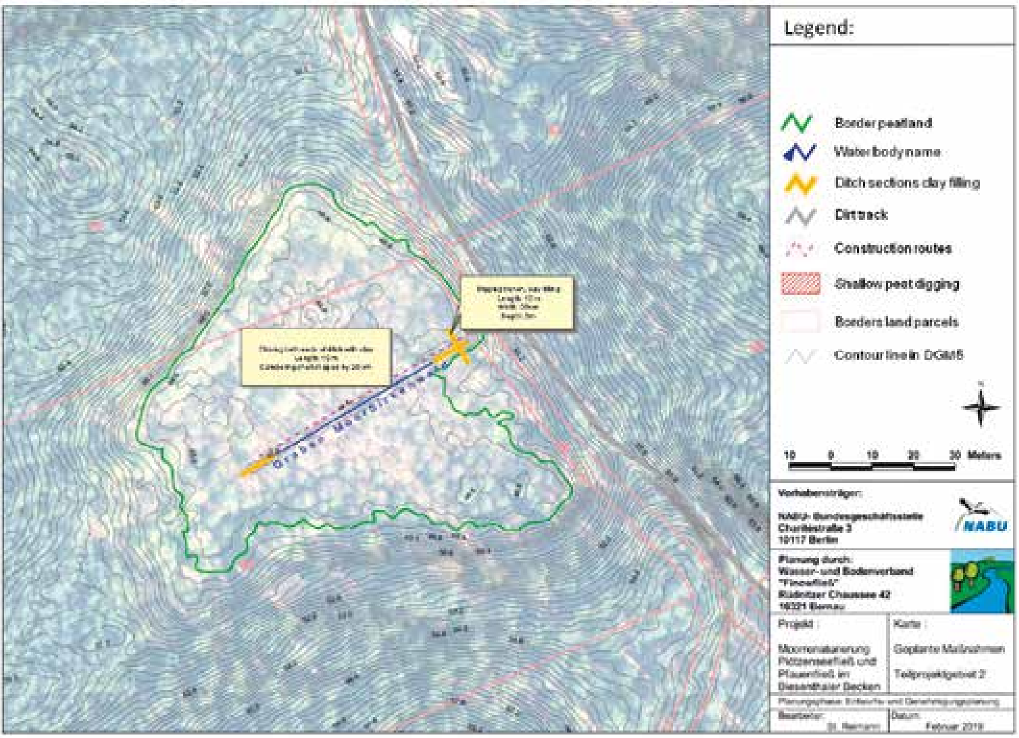


Figure 65. *The technical design for peatland restoration of the BB-3 area in Biesenthaler Becken; both ends of BB-3's central drainage ditch and in the main direction of the water flow also an orthogonal "catchment ditch" were filled with clay up to a depth of 2 m. Map: S. Reimann.*

Figure 66.
In the main direction of the water flow, the end of the BB-3's central drainage ditch and a T-shaped "catchment ditch" were filled with clay up to a depth of 2 m (October 2020). Photo: J. Etzold.

In the BB-2 area, the Plötzenseefließ artificial watercourse draining a 3.5 ha large former terrestrialisation mire with a black alder carr was around 3 m wide. Here, distributed over a stretch of ca. 260 m, five dams were constructed. Each has a length of around 10 m and a width of over 4 m (differing only in their dimensions from the general technical design in Figure 62). At both ends, logs of up to 7 m length cut in the nearest surroundings were placed orthogonally to the ditch to stabilise the filling material. Due to a more pronounced slope, for the two uppermost ditch fillings clay transported to the site was used (Figure 67). The material for the three lower dams was besides wood locally gathered degraded peat from shallow peat diggings .

The hydrological monitoring revealed a significant raise of the water level eight months after the measures and a reduction of fluctuationsAt the southern margin of the BB-1 peatland area, in autumn 2020 nine smaller ditches, less than 2 m wide, were closed by around 20 dams (Figure 61).

Figure 67. *One of the two dams made of clay and trunks blocking the Plötzenseefließ (BB-2), October 2020. Photo: J. Etzold.*

Figure 68.
The excavator starts with the filling of a ditch at the margins of the Pfauenfließ peatland BB-1 (October 2020). Photo: J. Etzold.

Also, due to lower amounts of flowing water, these dams were constructed smaller, with shorter logs at both ends and around 5 m in length (Figure 62). The filling material was, where applicable, soil from the nearby mineral border and mainly degraded peat from shallow peat excavated next to the dams.

The central parts of the BB-1 area were wetter than expected by the initially contracted company using an 8 t excavator. Despite its low soil pressure of only 150 g/cm^2, as it was equipped with wide bucket chains (Figure 68), the company did not dare to finalize the rewetting measures at this site. Another specialised company continued the restoration work at the beginning of 2021 with better adapted machinery, a small excavator (1.7 t) driving where necessary on wooden pallets (Figure 69). The work was eased by the winter conditions with frozen soil.

At more than 20 locations, the ditches in the central and northern part of the restoration area draining into the Pfauenfließ River and the two other adjacent rivers (Figures 61, 69) were blocked by wood and peat constructions.

Figure 69.
A small excavator driving on pallets was used in the BB-1 area. This type of vehicle used logs, branches, mineral soil and peat to close ditches flowing into the Pfauenfließ River and the two other adjacent rivers (February 2021). Photo: J. Etzold.

Figure 70. *The excavator installing the so-called bottom glide shortly before the mouth of the Pfauenfließ into river Finow; woody materials, mineral soil and peat was used (February 2021). Photo: J. Etzold.*

Figure 71. *A view downstream along the bottom glide (work completed, February 2021). Photo: J. Etzold.*

Furthermore, for raising the water level in the Pflauenfließ River and in the peatland upstream, the construction works had to preserve the ecologically important continuity of a natural watercourse, i.e. dams could not be built on the natural stream. Near the mouth of the Pflauenfließ River, before entering the Finow River, a 60 m long so-called bottom glide was constructed in order to raise its water level. For this purpose, logs were installed transversely as steps at a defined height and the spaces in between were filled with branches, peat and mineral soil (Figures 70–71).

Additionally, around 500 m upstream from the bottom glide tree trunks, other plant material, peat and mineral soil were placed into the river (Figure 72). That reduced the cross-section of the stream and thus higher water levels could be reached. In contrast to the original plan (Figures 61, 63), more mineral soil was inserted into the river. This allowed reducing the disturbance to the peatland and exposure of the peat by shallow peat digging.

Figure 72. *To increase the water level in the Pfauenfließ River, structures like logs, branches and soil material were placed in an irregular manner reducing the cross-section of the watercourse (February 2021). Photo: J. Etzold.*

The hydrological monitoring revealed a significant rise in the water level four months after the measures and a reduction of fluctuations (Figure 64).

As an additional measure to improve the hydrological situation in the small kettlehole (BB-3), forest conversion in its nearly 2 ha large catchment area was done. Here, the dominant tree species is the non-site typical Scots pine *Pinus sylvestris* planted for forestry purposes. Beneath conifers such as pines, the rate of groundwater formation is insignificant. This is in contrast to stands of deciduous trees such as beech where due to their smooth bark and lack of foliage in winter about 20% of the annual precipitation benefits the groundwater and thus in its catchment area also the peatland (Müller 2009).

As the first step of this forest conversion measure, the cover of pines was considerably reduced by logging (by 40 to 60% of the total crown cover). Afterwards, to support the development of deciduous forest vegetation, deciduous tree species such as beech and oak *Quercus* spp. were planted (around 600 seedlings). This was done in wooden fences to protect seedlings against deer browsing (Figure 73). Also, the natural regeneration of deciduous trees is easier in these fences. The fences will be maintained for 5–8 years by local NABU representatives until trees have grown out of the browsing range. Then, they may decay on site or if still in good condition set up on other sites to support forest conversion there (long experience in areas owned by the NABU-Foundation for National Natural Heritage).

Figure 73.
As one of the measures with a potentially favourable effect on site rewetting, a large proportion of Scots pines were removed and replaced by seedlings of deciduous broadleaved species (e.g. beeches and oaks). This measure was chosen, as a higher cover of deciduous trees is more favourable for groundwater formation (February 2021). Photo: J. Etzold.

CONSTRAINTS AND SOLUTIONS

The NABU-Foundation for National Natural Heritage is the owner of almost all LIFE Peat Restore restoration areas in Germany (except for two small parcels). Agreements with the owners of these two land parcels had to be reached, as restoration measures affected their property. Agreeing on the compensations with both landowners was a time-consuming process and included land exchange and financial compensation. This process led to the finalisation of the technical design only in March 2019 and caused delays in the overall implementation of the restoration measures by one year, as the agreements with the landowners were also preconditions for submitting the planning documents for approval to the authorities of the Barnim district and the federal state of Brandenburg.

For the two largest sites, BB-1 and BB-2, it was necessary to ensure that the neighbouring lands would not be potentially affected by the rewetting of the target area. As a precaution, the developers of the technical design carefully considered alternatives to avoid such impacts.

Furthermore, to prevent concerns of the local population regarding rewetting measures close to the Biesenthal town, an informative meeting was held in 2019 within the framework of the environmental committee of the city assembly of the Biesenthal municipality. The ecosystem services of peatlands and the project's restoration plans were presented, stressing also the international attention the Biesenthaler Becken gained through the LIFE Peat Restore project.

In general, awareness-raising and stakeholder involvement are of the utmost importance for successful project implementation. Several authorities on two administrative levels were involved in the approval procedure of the restoration plans. It was led by the water authority of the federal state of Brandenburg which had to involve environmental and historic monuments protection authorities on the federal state level and water, environment, historic monuments protection, and building authorities on district level. The final approval was given in January 2020. The bureaucratic procedures lasted over more than nine months.

According to the German Federal Law on Nature Protection, such restoration measures can only be conducted outside of the vegetation and breeding season between October and February, tender procedures for contracting companies were launched in early summer 2020, leading the restoration measures to be started in October 2020.

As lessons learnt, sufficient time has to be devoted for preparatory actions prior to actual peatland restoration. Accordingly, project duration has to consider enough time for monitoring the effect and success of the restoration measures. This is often challenged with projects of five-year duration. The need for time buffers became even more obvious facing extreme situations like the COVID-19 pandemic.

Furthermore, requirements for tender procedures have to be chosen carefully, including as many as possible quality criteria besides the prices for a detailed weighing of offers. Applying companies should be encouraged to carefully check sites and technical specifications and possible difficulties. This might avoid delays due to the wrong estimation of their capabilities dealing with the difficult "too wet" peatland conditions.

4.2. Raised bogs, bog woodlands and industrially exploited bogs

Raised bogs develop in relief depressions by ground paludification, commonly first undergoing the groundwater-fed fen and then the transitional mire stage. Raised bogs may also result from terrestrialisation of lakes, as they gradually overgrow and undergo several development stages. Most often, the bottom below the peat is formed by weakly permeable deposits such as clay, aleirite, moraine and sandstone.

In the region covered by the LIFE Peat Restore, raised bogs may be dome-shaped or of the plateau type. In most cases, the surface of an active raised bog is dome-shaped, either with one or several domes (cupolas). The dome can reach a relative height of 7–8 m in comparison to the mire margin. The dome develops, as the water stays longer in the central part of the raised bog and thus the *Sphagnum* species grow faster. The peat layer is so thick that the groundwater is not any more accessible for the plant roots. The plants obtain water only in the form of precipitation, therefore bogs are called ombrotrophic (rain-fed). The raised bog peat is mostly composed of *Sphagnum* mosses and cottongrass and is poorly decomposed (5–20%).

The peat reaction is acidic (pH 3–4). The total amount of mineral substances ranges between 2 and 4%. The vegetation is dominated by oligotrophic plant species that have low demand for nutrients.

Many active raised bogs are characterised by a complex of bog pools and hollows that interchange with ridges and hummocks (Figure 73). Also, lakes may occur in the raised bogs.

Figure 73. *Raised bog with pools. Photo M. Pakalne.*

The most common micro-relief feature of raised bogs is the alternation of relatively dry hummocks and ridges with wet hollows, lawns and carpets and open-water bog pools.

Active raised bogs may be open, with sparse tree cover or may include areas of bog woodland.

The plant communities are relatively species-poor, however, they host numerous highly specialised species occurring only or almost only in bogs. The vegetation is dominated by *Sphagnum* species that have a crucial role in the development of the bog microstructures and peat development. Several *Sphagnum* species, such as *Sphagnum magellanicum*, *S. fuscum*, *S. angustifolium* form the hummocks in raised bogs. Between the hummocks, there are hollows where bryophytes, such as *S. cuspidatum, S. flexuosum* and *S. tenellum* are common. On hummocks and ridges, there is a significant cover of dwarf shrubs, most commonly *Calluna vulgaris, Empetrum nigrum, Vaccinium oxycoccos, Andromeda polifolia*. Some sedges, most commonly *Eriophorum vaginatum* or *Trichophorum cespitosum*, occur in raised bogs as co-dominant vascular plant species on drier microstructures, while S*cheuchzeria palustris, Rhynchospora alba* and *Drosera anglica* occupy the depressions. Near the bog pools, *Rhynchospora alba, Scheuchzeria palustris, Carex limosa*, together with some *Sphagnum* species (*Sphagnum cuspidatum, S. majus, S. tenellum)* occur.

Among the LIFE Peat Restore project areas, intact and slightly drained raised bogs were well represented in the Augstroze peatland, Latvia, while heavily damaged raised bogs were found in Lithuania (Amalva, Pūsčia, Sachara, Aukštumala) and in Słowiński National Park, Poland (Kluki, Ciemińskie Błota and Wielkie Bagno). Bog woodlands, either near natural or highly degraded, were found in all the aforementioned areas, mostly at the margins of bogs.

Photo M. Pakalne.

4.2.1. Augstroze peatland, Latvia

Photo M. Pakalne.

Location: Northeastern Latvia
WGS84 coordinates: 57.537500, 25.023100. https://ieej.lv/peatrestore
Altitude: 77–119 m a.s.l.

Protection status: Area in Augstroze Nature Reserve (Natura 2000 site code: LV0000110)

The total area of the nature reserve: 1880 ha

Restoration area: 147.8 ha of raised bog (Madiešēni Mire)

EU importance habitat types in the restoration area: Active raised bogs (7110*), Degraded raised bogs still capable of natural regeneration (7120)

Implementation: University of Latvia (planning, monitoring, expertise), E Būvvadība (technical designs, construction work)

Land manager: JSC "Latvia's State Forests"

DESCRIPTION OF THE AUGSTROZE RESTORATION AREA

The Augstroze restoration area includes four raised bogs and other types of wetlands (lakes, transitional mires and quaking bogs, bog woodlands, swamp forests), among which Madiešēni Mire is the largest one. The largest proportion of Madiešēni Mire is an excellent example of an active raised bog, and it is among the largest raised bogs in Latvia. This is a typical raised bog with an extensive ridge-hollow complex. The central part of the mire is a vast maze of bog pools (Figure 74). Among other raised bogs within the Augstroze Nature Reserve, Madiešēni Mire is the only one where the intact bog landscape, hydrology and vegetation of the mire, though not in the whole area, has been altered by drainage.

Figure 74. *Intact part of Madiešēni Mire. Photo: M. Pakalne.*

Why was the restoration needed?

The northern part of Madiešēnu Mire was drained in the period from 1983 to 1998 by a ditch network. In 2019, these ditches (Figure 75) still had a significant negative impact on the raised bog causing degradation over a large area: low water table, compaction of the upper peat layer, decline of *Sphagnum* cover, enhanced growth of dwarf shrubs and trees. Before restoration, several drainage ditches, except for those in the forests on the bog margin, were overgrown. Still, many of them functioned well and had a negative impact on the bog ecosystem.

Rewetting scenario. To prevent further deterioration of the ecosystem, blocking the drainage ditches was selected as an appropriate measure. This should ensure water retention in the bog contributing to the recovery of peat-forming raised bog vegetation, especially *Sphagnum* cover, peat accumulation and carbon sequestration.

Non-intervention scenario. In a case of non-intervention, the desiccation of the raised bog in the drained part would continue and the degraded peatland would continue to be a source of considerable GHG emissions.

Estimated GHG reduction after rewetting: the total annual emissions within the next 50 years is by one half smaller than in the baseline situation, i.e. 346.53 and 17 326.3 t CO_2-eq without the forest biomass, and 346.42 and 17320.6 t CO_2-eq with the forest biomass.

Figure 75. *A drainage ditch in the Augstroze restoration area, August 2019. Photo: A. Priede.*

TARGET VEGETATION AND SPECIES

The target vegetation in the degraded part of the Madiešēni Mire after rewetting is the typical raised bog species complex. The target plant species after peatland restoration include species of raised bogs such as dwarf shrubs *Calluna vulgaris, Andromeda polifolia, Chamaedaphne calyculata, Vaccinium uliginosum, Vaccinium oxycoccos*; herbaceous plants *Eriophorum vaginatum, Rhynchospora alba, Drosera rotundifolia, D. anglica, Scheuchzeria palustris.* The target bryophyte species are *Sphagnum magellanicum, S. rubellum, S. fuscum, S. majus, Polytrichum juniperinum, Aulacomnium palustre, Mylia anomala, Kurzia pauciflora, Dicranum undulatum, Cladopodiella fluitans* (Figure 76).

PREPARATORY WORK

To find the best solution and to agree with the involved stakeholders, a management plan for the Augstroze Nature Reserve was prepared according to the national legislation. It included habitat mapping and inventory of the drainage system, selecting the restoration measures and their location. To understand the effects of drainage ditches and their blocking, a hydrogeological model was developed. It is a computer-based model based on values such as drainage basin, rainfall amount and surface relief. Based on this model, 25 peat dam locations (Figure 77) were selected to block the water flow, to raise the water table and prevent its sharp fluctuations. The preparatory work included an agreement with the land manager JSC "Latvia's State Forests" and the development and approval of technical designs. The entire planning stage from the first inventories to implementation took almost two years.

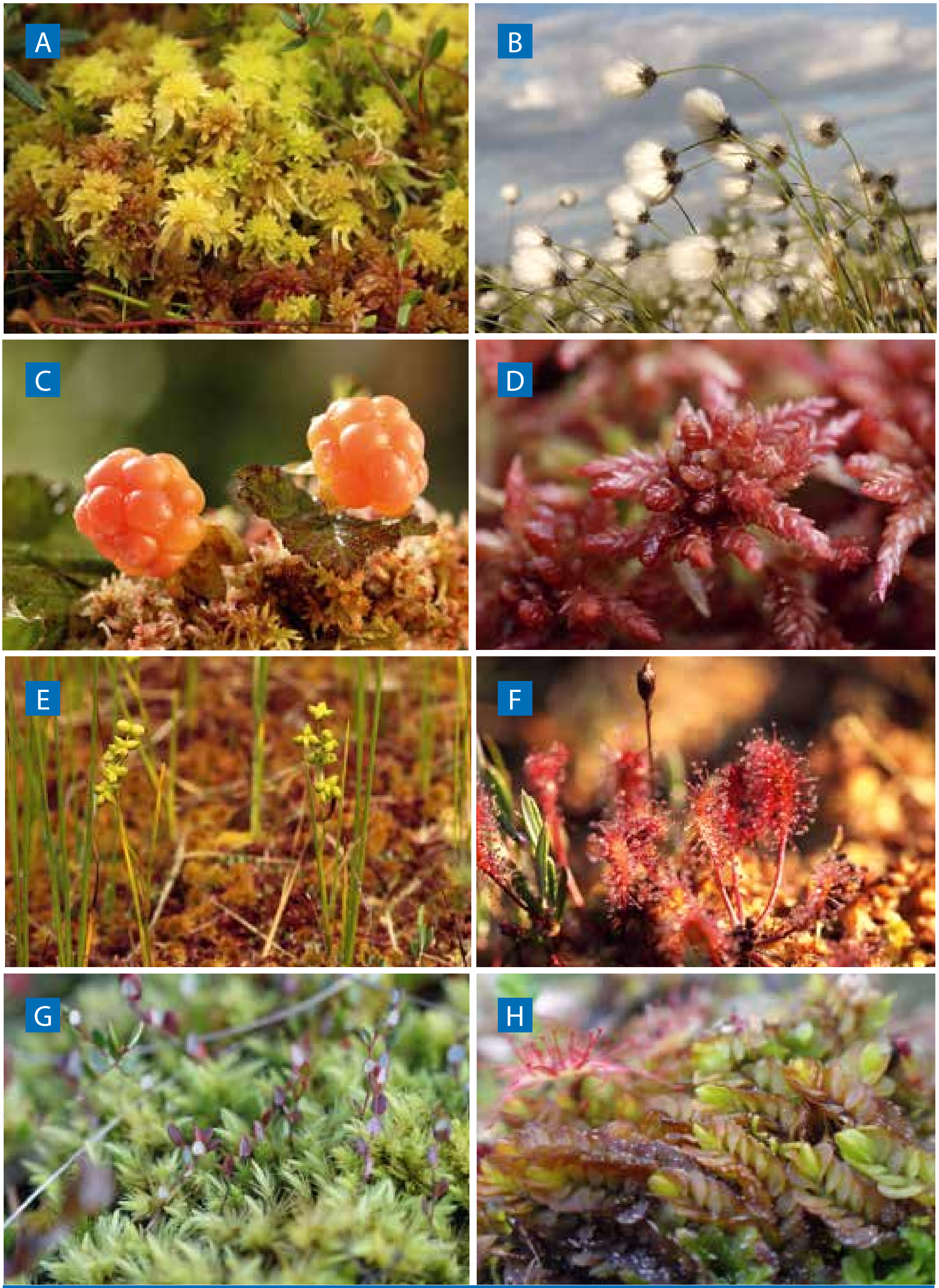


Figure 76. *Some of the target plant species in raised bogs: A – Sphagnum carpet, B – Eriophorum vaginatum, C – Rubus chamaemorus, D – Sphagnum magellanicum, E – Sphagnum fuscum and Scheuchzeria palustris, F – Drosera anglica, G – Aulacomnium palustre, H – Mylia anomala. Photos: M. Pakalne (A–F), L. Strazdiņa (G, H).*

RESTORATION AND MONITORING RESULTS

According to the hydrogeological modelling results, the rewetting measures (peat dams on the ditches) would create a favourable effect on at least 147.8 ha of the drained bog (Figure 77).

Prior to the building of dams, dam locations and tracks for movement of machinery were marked, and the trees and shrubs on the tracks cleared. Light mini-excavators (Figure 78) equipped with wide tracks, relatively small in dimensions, were used for building dams. According to the legal restrictions of the particular protected area, the works could be performed at the end of summer, in autumn or in winter, outside the bird nesting season. Experience from the LIFE Peat Restore and earlier peatland restoration projects in Latvia shows that using this type of excavator results in low surface pressure and causes minor damage to the vegetation and the upper peat layer during work and movement of machinery.

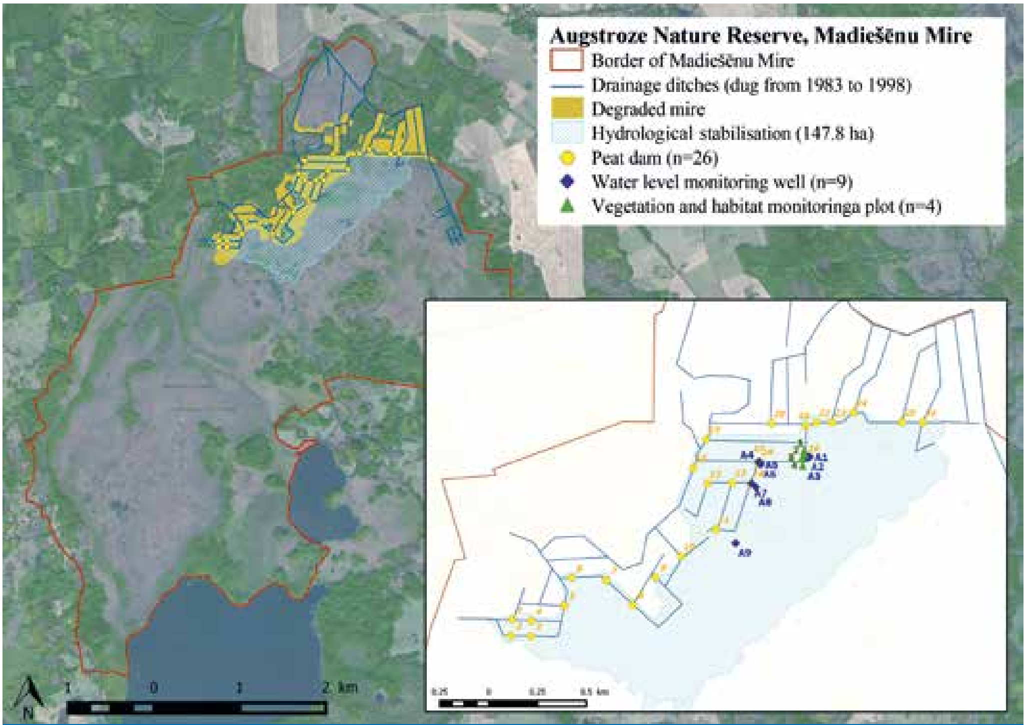


Figure 77. *Augstroze restoration area with dam location, the transect of water level monitoring wells and the hydrological regime stabilisation area (147.8 ha) according to hydro-geologica l modelling. Map: L. Strazdiņa.*

In total 25 dams were built in the Augstroze restoration area. The dams were built in October 2020 using peat from the surrounding bog surface near to the ditch where small, shallow hollows were excavated and peat dams created. The banks of the hollows, at least on one side, should be gently sloping to prevent the trap effect on wild animals. Prior to the construction of the dams, in the place where peat was taken for dam building the topsoil (peat and vegetation) was removed by the excavator bucket reaching the intact layer of the peat. The dams were built layer by layer and compacted with an excavator bucket. After that, an extra layer was placed on the top of the dam that secures the designed height, as the peat is gradually compacting while stabilising. Therefore, after building the dam, the surface was higher than the surrounding area and wider than the ditch to prevent water infiltration or leaking around the dam. As the last, the topsoil with vegetation was placed on the top of the dam (Figure 79) preventing erosion of the dam and supporting the establishment of bog vegetation on the dam surface.

Figure 78. *The excavator is building a peat dam. Photo: M. Pakalne.*

Figure 79. *The constructed dam is solid enough to stand on it. Photo: M. Pakalne.*

During the planning stage, vegetation monitoring plots and water table monitoring wells were established. Monitoring started two years before restoration, in 2018. Vegetation monitoring was carried out every year during the summer season using the joint methodology agreed upon among the project partners (see *Chapter 3.2*).

To monitor the effectiveness of the dams, water monitoring wells were installed in the Madiešēni Mire to record changes in the groundwater level throughout the project (Figure 80). Water level monitoring is carried out in nine wells that are located in three transects with different distances from ditches. The water table was automatically measured by loggers once per hour (except for the periods when the shallow groundwater was frozen) (Figure 81).

Figure 80. *Water level monitoring using loggers. Photo: M. Pakalne.*

Figure 81. *Water level data were downloaded and further processed several times per year. Photo: M. Pakalne.*

After blocking the ditches, the largest increase in water level was observed in the ditches and near the ditches, where the water became stagnant. The observations during the first months after rewetting, i.e. after the construction of the dams, showed that the sharp water level fluctuations near the ditches have stabilised (Figure 87). The formerly dry peat near the ditches is now saturated with water.

In the monitoring wells, the fastest water level increase takes place in those closest to the ditches and dams. For example, in the A1 and A5 monitoring wells blocking of ditches caused an almost immediate increase in water level. In the well closest to the ditch (A1), the lowest water level in the period from 2018 reached 66 cm and the highest groundwater level was 19 cm below the surface in 2021, which was achieved due to the construction of peat dams. The intensity of precipitation also helped to reach the desired groundwater level significantly faster and to keep it stable for a longer period of time. In the first half of 2021, precipitation was significantly higher during the same period in 2020. In 2020, the highest precipitation was observed in May (120.4 mm) and June (62 mm). The average water level in this monitoring well has increased by 26 cm compared to the period before the construction works. This reflects the correct choice of dam design, their operation and efficiency.

The vegetation response to the rise of the water table is slower, and it will take some years until the establishment of the target vegetation. The dam surfaces have not dried out because a layer of living bog vegetation (sods) were applied during the construction work.

Soon after blocking the ditches, dying of *Calluna vulgaris*, the dominant species in the drained area, was observed. Near the dams, new shoots of *Calluna vulgaris, Andromeda polifolia, Rubus chamaemorus* (Figure 82) and bryophytes *Dicranum scoparium, Sphagnum rubellum, Sphagnum cuspidatum* re-established (Figure 83).

The monitoring results suggest that restoration has had a positive effect on the hydrological condition of the degraded bog that is the first step toward recovery of the peat-forming vegetation and stabilisation of the entire system (Figures 84–86).

Figure 82. *Sphagnum cuspidatum, a typical raised bog species in wet hollows, re-grows in the blocked ditches. Photo: M. Pakalne.*

Figure 83. *Sphagnum patches emerge on bare rewetted peat near the dams half a year after rewetting. Photo: K. Libauers.*

Figure 84. *A ditch in the Augstroze peatland in August 2019. Photo: A. Priede.*

Figure 85. *The same ditch in June 2021. Photo: M. Pakalne.*

Figure 86. *One of the peat dams on a drainage ditch, August 2021. Photo: A. Priede.*

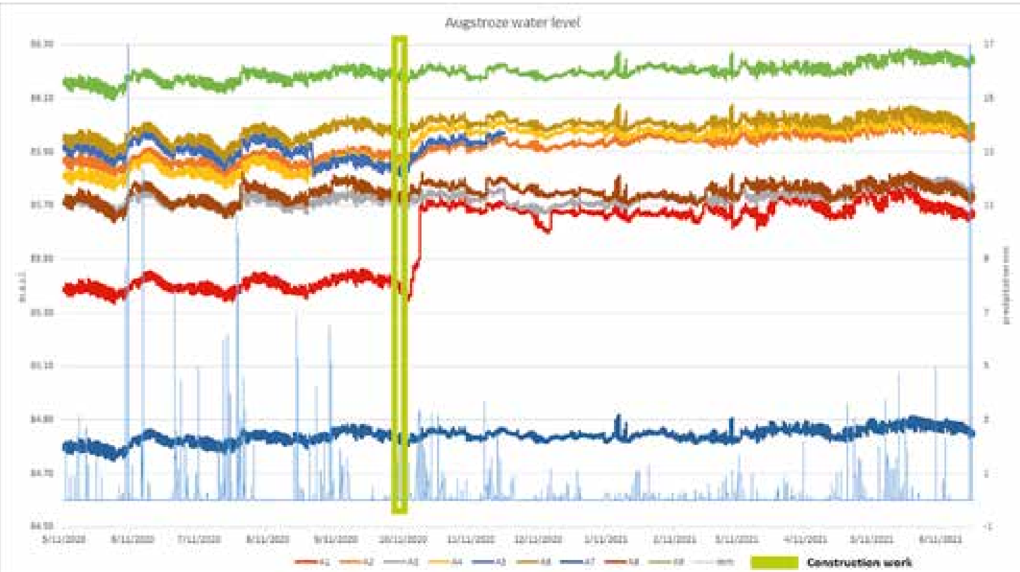


Figure 87. *Water level fluctuations before and after blocking the ditches in the Augstroze peatland.*

CONSTRAINTS AND SOLUTIONS

During the construction works in areas like Augstroze, one should be aware that an excavator can partially get drowned in the peat due to the driver's carelessness and due to the weight of the excavator. The construction company must use light excavators that move easily on the mire surface. The previous peatland restoration experience in similar areas proves that the selection of appropriate machinery, suitable for the particular area, is highly important to prevent extra costs and damage to the mire.

In the Augstroze restoration area, the dams were built by two small excavators. The work was done in four days. Moving to the dams was slightly delayed by the ditches on the way. To get over them, they had to make temporary bridges made of peat. On the last day when all the dams were almost built, for one of the excavators, the hydraulic mechanism got broken and it could no longer lift the bucket. Fortunately, there was a heavy machinery repair shop in the nearby town and the problem was solved in a short time.

Photo M. Pakalne.

4.2.2. Słowiński National Park, Poland (Kluki, Ciemińskie Błota and Wielkie Bagno peatlands)

Photo: K. Bociąg

Location: Northern Poland, https://ieej.lv/peatrestore
Kluki – WGS84 coordinates: 54.6735667, 17.3217763. Altitude: 0–32 m a.s.l.
Ciemińskie Błota – WGS84 coordinates: 54.6719369, 17.3611309. Altitude: 0–28 m a.s.l.
Wielkie Bagno – WGS84 coordinates: 54.6933525, 17.5041384. Altitude: 1–36 m a.s.l.

Protection status: Areas in Słowiński National Park
Special Area of Conservation (SAC): Ostoja Słowińska (PLH220023)
Special Protection Areas (SPA): Ostoja Słowińska (PLB220003)
Słowinski Biosphere Reserve

The total area of the national park: 18.069 ha

Restoration areas: 808 ha (Kluki – 262 ha, Ciemińskie Błota – 91 ha, Wielkie Bagno – 455 ha)

EU importance habitat types in the restoration area: Active raised bogs (7110*), Degraded raised bogs still capable of natural regeneration (7120), Transition mires and quaking bogs (7140), Bog woodland (91D0*)

Implementation: Naturalists' Club (based in Świebodzin, Poland)

Land manager: Słowiński National Park

DESCRIPTION OF THE PROJECT PEATLANDS IN THE SŁOWIŃSKI NATIONAL PARK

In the LIFE Peat Restore project, three bogs within the borders of Słowiński National Park (SPN), Gardno-Łebsko Lowland, were included: Kluki, Ciemińskie Błota and Wielkie Bagno (Figure 88). These peatlands started to develop around 10 000 years ago, i.e. shortly after the continental glacier withdrew. The central parts of these peatlands represent raised bogs with domes, while the marginal parts are transitional mires. They are transformed and degraded by human activity: the peat was mined here since the end of the 18th century, especially in Wielkie Bagno. The latter is still being used for peat extraction outside the borders of the national park. All three peatlands are heavily drained, with numerous canals and drainage ditches, and in Wielkie Bagno post-harvested areas are also present.

The vegetation of these bogs is strongly altered and only partially retains its natural mire-type nature. Currently, most of the peatland area is covered by bog woodland dominated by Scots pine *Pinus sylvestris* and swamp forests dominated by birch *Betula pubescens* at different stages of degradation due to drainage. The herbaceous undergrowth is mostly dominated by the purple moor-grass *Molinia caerulea*. Strongly degraded pine woodlands are also common, with only a small share of peat-forming vegetation in the undergrowth. On the margins of peatlands in the vicinity of the birch-dominated swamp forests, a birch-oak forest develops. Open bog vegetation covers a comparatively small area, but the most valuable element of it is the *Erico-Sphagnetum medii* community. The post-harvested areas are overgrown with the regenerative types of vegetation dominated by moss species, however, the peat-forming vegetation has not recovered in large parts of the disturbed peatlands. Desiccation of some non-forested areas causes encroachment of trees, mostly pine and birch.

There are a few large post-excavation basins in Wielkie Bagno, in the area of peat mine Krakulice, located at the border of SPN, in the southern part of the peatland. They were created as land reclamation measures during the last 20 years and are characterized by poor vegetation succession (Figure 89).

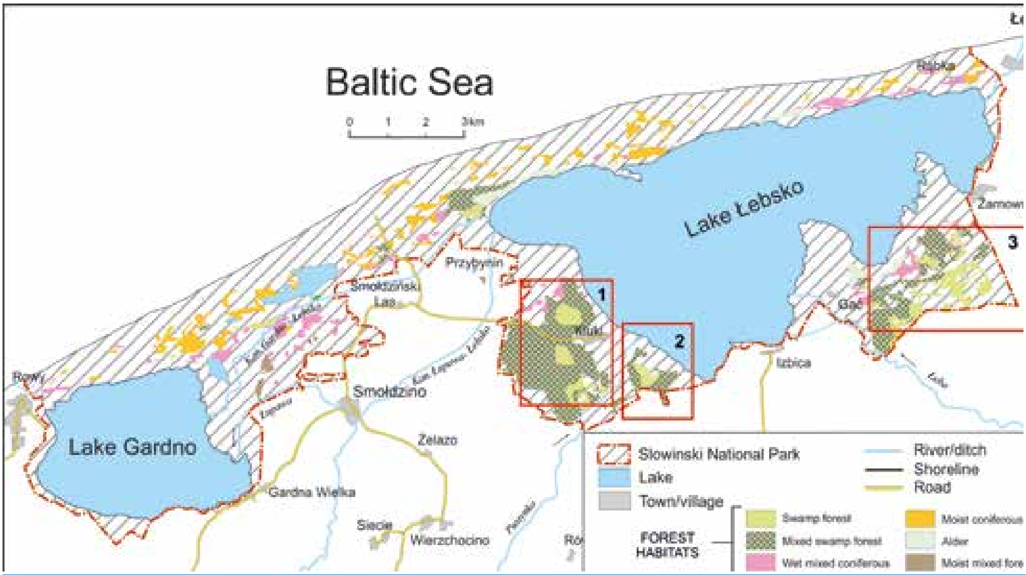


Figure 88. *Peatlands covered by the LIFE Peat Restore project in Słowiński National Park, Poland: 1 – Kluki; 2 – Ciemińskie Błota; 3 – Wielkie Bagno..*

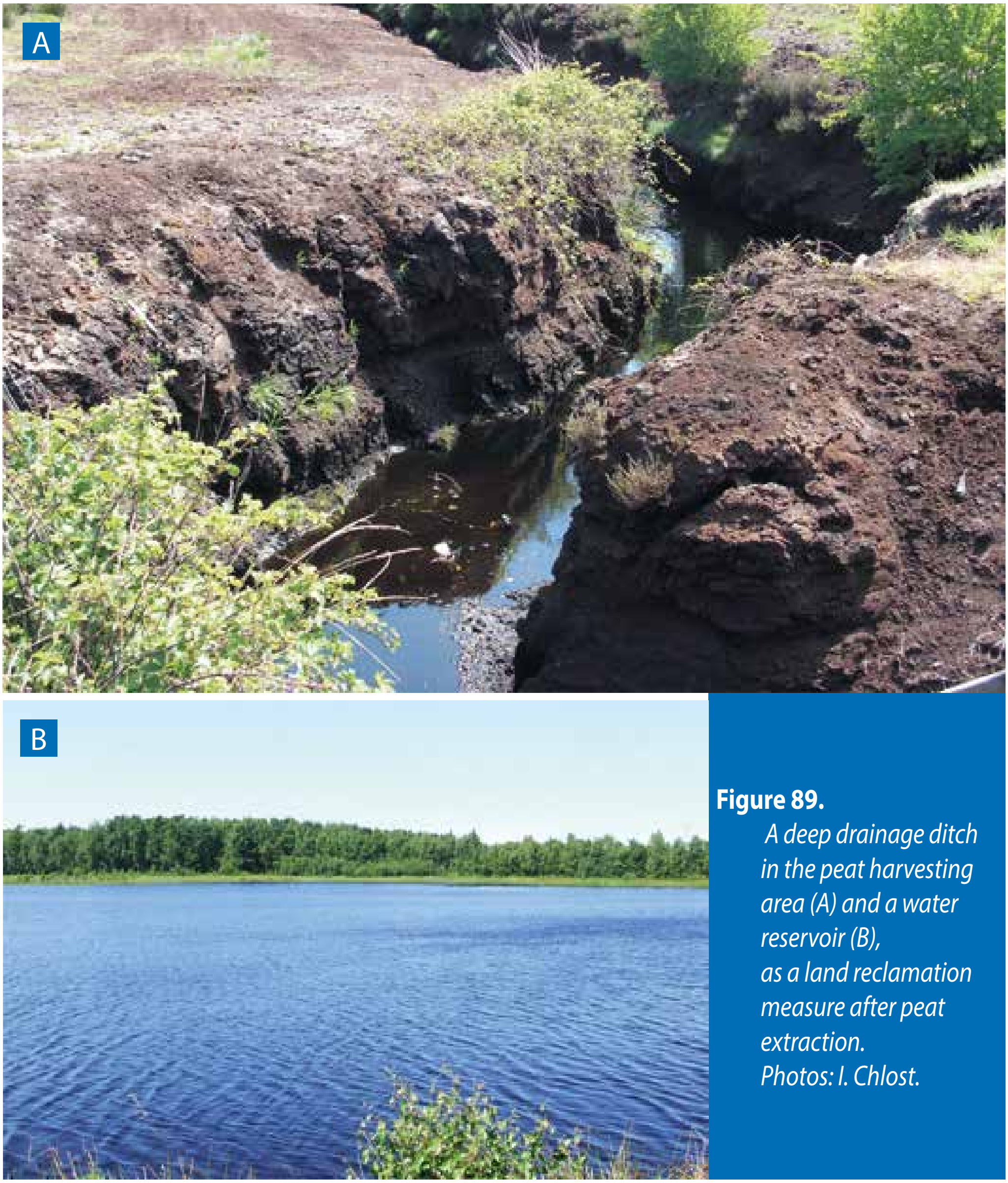


Figure 89. *A deep drainage ditch in the peat harvesting area (A) and a water reservoir (B), as a land reclamation measure after peat extraction. Photos: I. Chlost.*

WHY WAS THE RESTORATION NEEDED?

The peatlands of the Gardno-Łebsko Lowland have been intensively drained for over 250 years. Part of the area was converted into meadows and pastures, and peat has been exploited since the 19th century. Intensification of drainage on a large scale was carried out in the first decades of the 20th century. The drained transitional mires and raised bogs were also partly afforested for wood production purposes. Drainage of peatlands carried out in the 19th and 20th centuries resulted in a complete change in the conditions of supply and drainage of these sites, modifying the water balance. These include, on the one hand, additional water supply by the inflow of water from the outside (for example, through transit channels), and, on the other, more important and destructive for the persistence of peatlands – escape (outflow) of water outside the given site. At the same time, the proportion between rainfall and evaporation was disturbed, as the losses were due to increased evaporation from open water surfaces in canals, drainage ditches and post-mining excavations. Since the establishment of Słowiński National Park in 1967, the drainage network has not been maintained and some ditches have overgrown. Even though some of the ditches still drain surplus water beyond the boundaries of the areas deteriorating their water balance.

Drainage and peat decomposition resulted in degeneration of mire vegetation including overgrowing by trees and shrubs. *Erico-Sphagnetum medii* community, typical open bog vegetation of this area, is the most endangered. Drainage prevents the regeneration of peat-forming vegetation in the post-harvested peatlands. Also, the bog woodlands degrade. In the large post-excavation water basins, the succession of the vegetation is prevented by intensive waving due to wind exposure. Such weather conditions are frequent in the coastal area.

Rewetting scenario. To prevent further deterioration of the peatlands within the borders of Słowiński National Park, blocking of drainage ditches was crucial to implement on all three project sites. In areas with the heaviest drainage impact, i.e. overgrown by trees and shrubs, trees had to be removed (see *Chapter 2.2.2*). It was done to (1) slow down the succession of the most valuable non-forest peat bogs towards forest communities, (2) halt continuous drainage-caused degradation, and (3) improve the light conditions for the development of ground vegetation including *Sphagnum* species in areas where the vegetation has already entered the forest phase, as well as in post-excavation areas where the trees growing on dykes shade the peat bog ground vegetation.

In order to test the techniques of support mire vegetation development in large post-excavation water basins, an experiment with floating islands was carried out on one of the large reservoirs in the southern part of Wielkie Bagno (the surroundings of Krakulice mine).

Non-intervention scenario. Without active intervention, there would be further degradation of the peatlands: increase in drainage, lowering of groundwater level, unfavourable changes in habitats and vegetation.

Estimated GHG reduction after rewetting: annual emission (expressed as GWP) from the project area in the baseline scenario is estimated as 16 541 t CO_2-eq. According to the restoration scenario, it is foreseen to reduce it to 12 886 t CO_2-eq, i.e. by 3665 t CO_2-eq (22%). This is a reduction from 13,35 to 10,40 t CO_2-eq/ha, i.e. by 2,95 t CO_2-eq/ha.

TARGET VEGETATION AND SPECIES

The target vegetation in the three restoration areas in Poland is typical raised bog vegetation (Figure 90), mostly *Erico-Sphagnetum medii* community, and pine woodlands. The target species are those characteristic for the particular types of vegetation (including rare, endangered species in Poland) such as *Erica tetralix*, *Drosera rotundifolia, D. anglica*, *D. intermedia*, *Rhynchospora alba, Trichophorum cespitosum, Rubus chamaemorus, Sphagnum magellanicum, S. rubellum, S. fuscum*.

It is also important to retain or improve the conditions for peat-forming, moss dominated vegetation in the post-excavation areas (Figure 91). Such plant communities are dominated by *Sphagnum cuspidatum*, *Eriophorum angustifolium* and *Molinia caerulea* on low-lying and therefore the wettest depressions developed after peat extraction, while the terrain elevations and drained places are covered by *Sphagnum* spp., cotton-grasses and dwarf shrubs of the *Ericaceae* family.

Within post-excavation basins and on floating islands quaking bog vegetation may develop, composed of *Sphagnum* species, *Eriophorum angustifolium, Carex rostrata* and *Calla palustris*.

Figure 90. *The target vegetation types and species of raised bogs: A – open raised bog vegetation (Erico-Sphagnetum medii community) in Wielkie Bagno, B – pine woodlands in Wielkie Bagno; C – Erica tetralix; D – Sphagnum magellanicum. Photos: K. Bociąg.*

Figure 91. *The target vegetation and target plant species in Wielkie Bagno: A – Rhynchospora alba; B – Drosera intermedia; C – moss communities regenerating of wet post-harvested peatlands. Photos: P. Pawlaczyk, M. Pakalne.*

PREPARATORY WORK

In Poland, the LIFE Peat Restore project was implemented by Klub Przyrodników, a non-governmental organisation, on lands owned by the SNP, on the legal basis of a formal agreement between both involved parties.

Most of the conservation measures were implemented in the national park, a protected area with a restrictive legal regime. The legal regulation in Polish national parks generally forbids all human activities on its territory with some exceptions. One of these exceptions is conservation measures: they are allowed if included in the park's 20-years management plan. If the management plan has not been developed yet, as in the case of Słowiński National Park, the actions must be proposed in co called "conservation tasks" (simplified and provisional plan for 1–5 years), issued by the Ministry of Climate and Environment. The project measures were included in the "Conservation tasks for Słowinski National Park for 2017–2019" and "Conservation tasks for Słowinski National Park for 2020–2022".

The ditch blocking needs preliminary "water consent" based on the water condition assessment. The consent is issued by Polish Waters, the national water management authority. According to the procedure, it is necessary to prove that hydrological conditions will change only on the lands within the national park and will not have an impact on the lands owned by other parties. Since 2019, for "reconstruction of drainage ditches" (which may also include blocking of outflow) the building permit is no longer required by the Polish law.

The restoration of post-excavation water reservoirs was implemented in the water body outside the borders of the national park, nevertheless, SNP is the manager of the reservoirs. Installing floating islands needed an official agreement with the national park.

All measures were justified and classified as "necessary for conservation of Natura 2000 habitats", thus, despite the location inside the Natura 2000 site, no specific impact assessment procedures were required.

The preparatory work included, as described above, an agreement with SPN including multiple consultations with SPN and companies that have practical experience, especially in the field of designing, construction and earthworks.

During the preparatory stage, hydrological and chemical monitoring protocol was specified. The monitoring was designed to record changes in surface and groundwater levels and the physical and chemical characteristics of these waters before and after building dams in the area. As part of hydrological monitoring, 80 measuring points have been established (Table 5), including self-recording devices: 63 piezometers with divers to monitor temperature and changes of groundwater level, and 17 limnigraphs to monitor water levels and temperature of surface water (in ditches, canals and post-excavating water basins).

Table 5. *Number of self-recording devices for the level of surface and groundwater at individual sites*

Device type	Site		
	Kluki	Ciemińskie Błota	Wielkie Bagno
Piezometer	22	17	24
Limnigraph	3	3	11
Total	**25**	**20**	**35**

Since 2017, the water levels have been recorded twice per day. Water level data were summarised after the end of each hydrological year (the period from 1 November of one year to 31 October of the following year). Once a month, the flow in the ditches from which water escapes beyond the peatlands was measured, and tests of the physical and chemical properties of water were carried out *in situ*: temperature, oxygen, water pH and conductivity (Figure 92). In addition, hydrologists performed seasonal hydrological mapping to determine retention in peat bogs and drainage ditches. Groundwater samples were taken for laboratory tests. In the laboratory, the following parameters and ions were determined: N_{tot}, P_{tot}, HCO_3, Na^+, NH_4^+, K^+, Mg^{2+}, Ca^{2+}, Cl^-, NO_3, PO_4^3, SO_4^2.

Additionally, one self-recording meteorological station was installed in SPN, which represented all restoration sites. Data on precipitation, air temperature, wind direction and speed were obtained from this station. Peat hydration measurements and vertical profiles were also made.

Hydrological monitoring also covered a few post-excavating reservoirs, on which limnigraphs were installed to measure the water table fluctuations. Occasionally, the basic physical and chemical properties of water were measured, including oxygen contents, pH and electric conductivity. Due to the lack of data, depth measurements were also made in the reservoirs (Figures 93, 94). The obtained results were the basis for designing the floating islands as a method of initiating re-establishment of mire vegetation in this part of Wielkie Bagno.

Figure 92. *Field work: A – installation of piezometers; B – reading data from divers; C – water flow measurement; D – reading the water level from the gauge; E – in situ measurements of surface water parameters; F – collection of peat cores. Photos: I. Chlost (A, B ,D, F); M. Pawłowska (E), I. Bubak (C).*

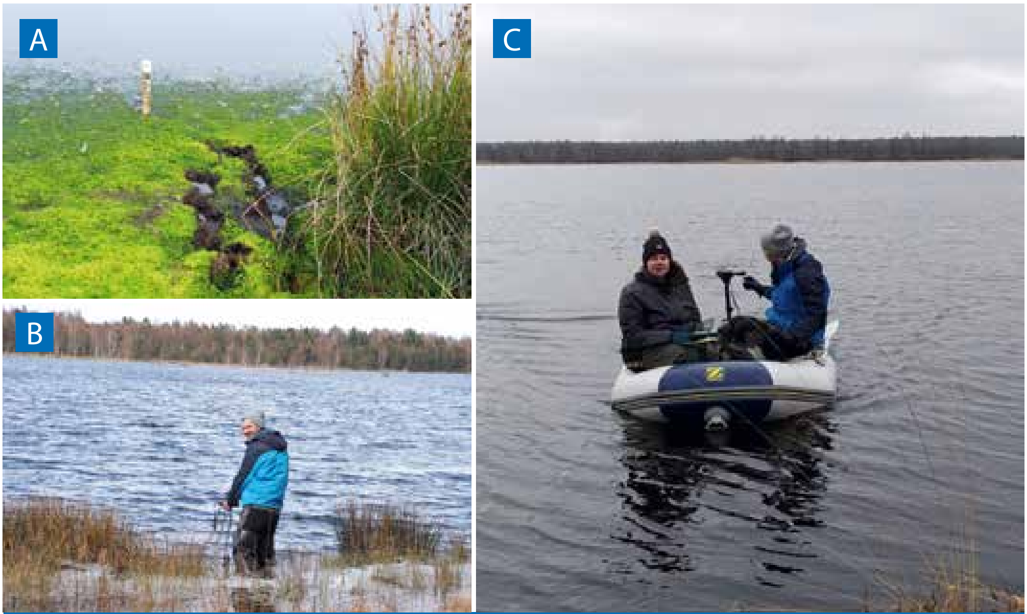


Figure 93. *Field work: A – a piezometric pipe with a water level recording device; B – measurements of the physical and chemical properties of water; C – depth measurements in post-excavating water basins. Photos: I. Chlost (A, B); M. Czereda (C).*

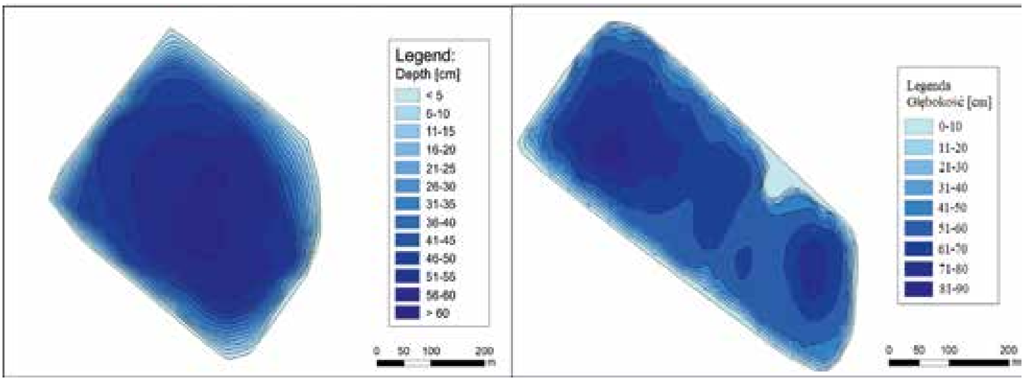
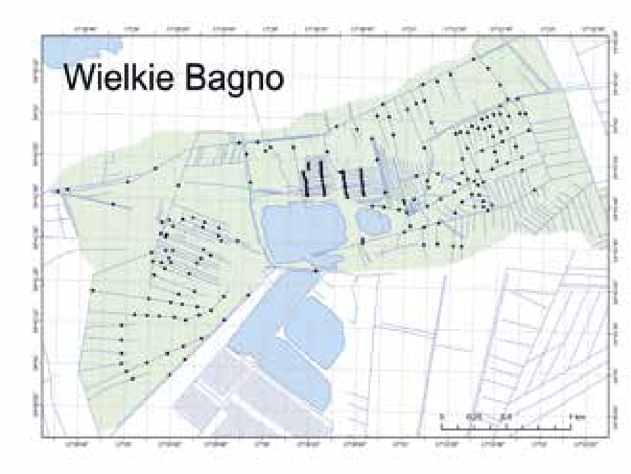
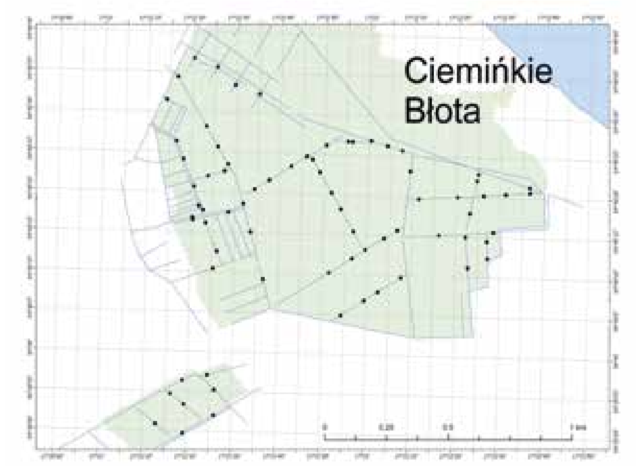


Figure 94. *Bathymetric plans for the post-excavation basins on Wielkie Bagno Maps: Z. Lipińska*

Data from the hydrological monitoring network was used to plan the details of restoration measures. Before designing the dams, experience from earlier similar projects implemented by Naturalists' Club, SNP and other organizations and institutions dealing with the conservation of peatlands in Northern Poland was gathered and analysed. After the draft of technical design was completed, and before implementation, several prototypes of dams with different technical details were developed to test the proposed constructions and select the best solution. After those tests, some technical adjustments of the technical design were introduced and eventually





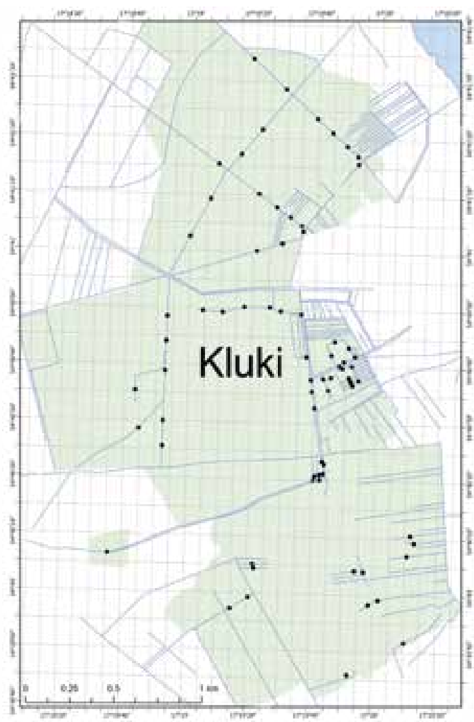


Figure 95.
Projected locations of the ditch blocking in Wielkie Bagno, Ciemińskie Błota and Kluki.
Maps: A. Olszewska.

347 dam locations were selected to block the water flow, to raise the water table and stabilise its fluctuations (Figure 95).

Restoring favourable water conditions in peat (i.e. conditions for preserving peat and preventing increased decomposition) must be gradual and stepwise to allow the vegetation to adapt in time to new water conditions and not to cause rapid changes, e.g. dying of trees across large areas. Therefore, areas where blocking of the ditches was planned, concentrate within the middle parts of the peatlands. To assess the impact of ditch blocking, a hydrological model was developed using the MODFLOW 2005 computational algorithm (Harbaugh 2005). Modelling of water flows showed that it is possible to obtain a certain increase in the water level in the central parts of the target areas. That may help to achieve a significant rise of water level at least in years with high precipitation (Figure 96A).

It was assessed that the spatial range of the rewetting will not go beyond the restoration area, as only blocking the outflow of rainwater was planned. In dry years, even blocking the ditches may not significantly change the situation, as it can be too dry to lever up the water level (Figure 96C). However, unless there is a remarkable reduction in rainfall, water retention from years and periods with high precipitation should at least partially reduce the desiccation and decomposition of peat.

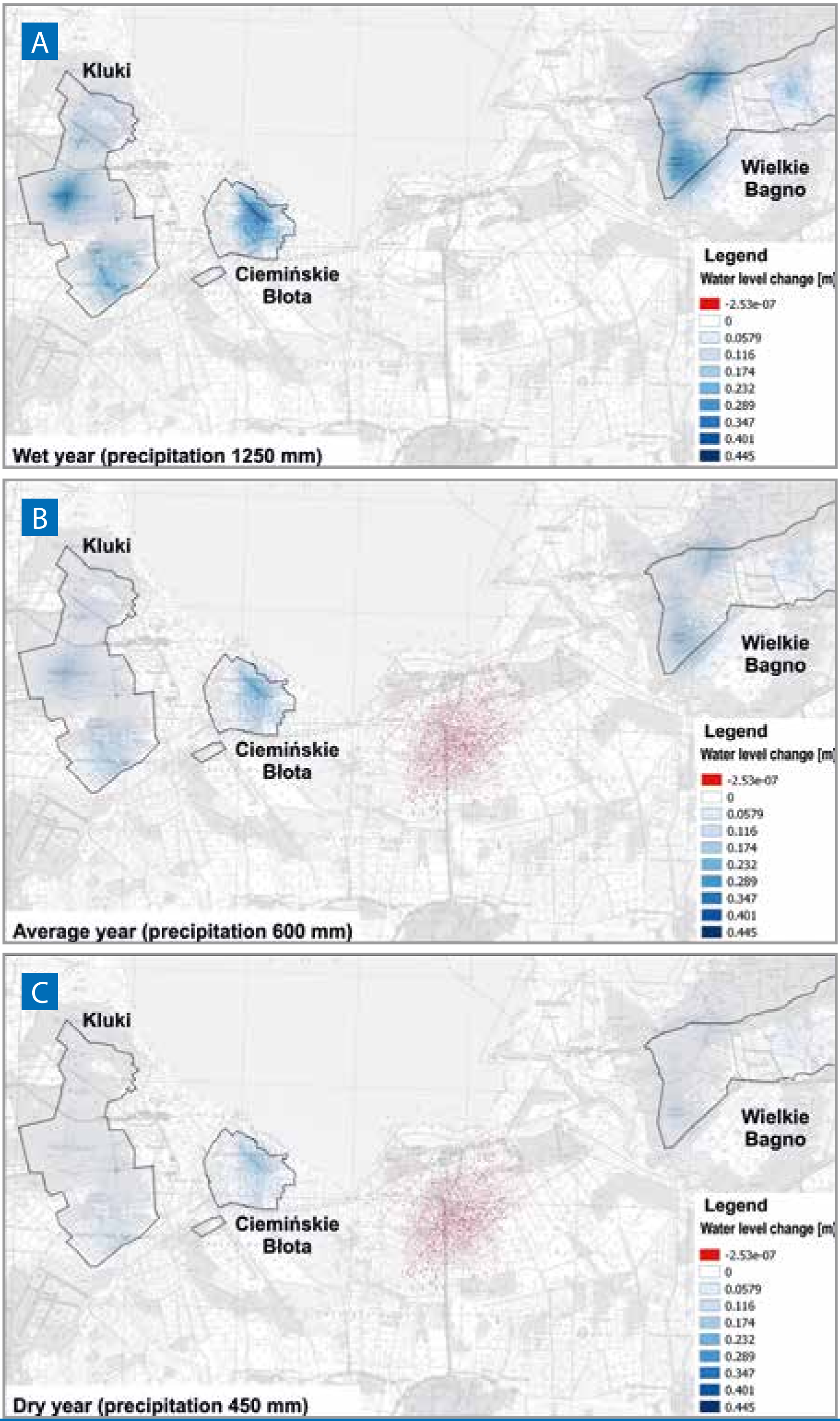


Figure 96. *Modelled changes in the groundwater level after the planned restoration measures in the LIFE Peat Restore peatlands in various years: A – wet, B – average, C – dry.*

While hydrological monitoring was being carried out and work on planning the details of the blocking of the ditches, the vegetation monitoring in permanent plots was started (Figure 97). The monitoring was carried out using the joint methodology (10 x 10 m plots with 1 x 1 m subplots) agreed among the project partners (see *Chapter 3.2*). In the restoration areas in Poland, in total, 38 monitoring plots were established. The sample plots were located in the patches where rewetting and removal of trees were planned and changes in vegetation expected. The vegetation sample plots were partly located near piezometers recording the water level (hydrological and chemical monitoring).

Figure 97.
One of the monitoring plots in Wielkie Bagno (above) and the subplot within in (left). Photos: K. Bociąg.

Preparatory work included also verification of areas where trees and shrubs were planned to be removed. The cost, tree biomass, height and density of the stand were estimated. Specific details of implementation were determined and the work plan was adjusted for each restoration area. On overdried patches of the *Erico-Sphagnetum medii* community, a clearcut was planned, as those are the most valuable elements of bog vegetation in SPN. Partial removal of trees was planned in the patches that had already passed into the forest phase, and the density of trees was so large that it hindered the development of the ground vegetation. It was decided to remove the trees as soon as possible, before blocking the ditches.

Additionally, from the beginning of the project, tests of floating islands as innovative methods of restoring peat-forming vegetation in areas flooded with water after peat exploitation were performed. Since 2017, in one of the post-excavating water basins in Wielkie Bagno, the prototypes of floating "islands" have been built and tested (Figure 98). Seven different construction types of "islands" were investigated throughout four years, each one for at least two years (Figures 98, 99).

Figure 98. *One of the first floating island prototypes after two months (August 2017) and after two years (August 2019) since launching. Photos: K. Bociąg.*

Figure 99. *Other prototypes after testing time. On the left – the island which lost anchoring and drifted to the shore (one year since launching in May 2020); on the right – the island which lost buoyancy after two years, May 2020. Photos: K. Bociąg.*

RESTORATION AND MONITORING RESULTS

Rewetting by blocking the ditches

After all preparatory work was done, in total 347 dams were built in the spring of 2021: 71 in Kluki, 73 in Ciemińskie Błota, and 203 in Wielkie Bagno. All dams were built according to the technical design.

Following the analysis of local conditions, experience from similar projects and construction of several prototype dams, it was decided to build combined wooden-soil dams (Figure 100).

Their external part consisted of walls made of oak wood boards and reinforced using wooden stakes inserted deep into the ground (Figures 100–103). The space between the walls was filled with burlap sacks filled with a mixture of peat and mineral material. The burlap sacks were used in order to make transportation easier and increase the durability of the structure. Each bag was only half-filled in order to make the construction of a wall easier and to make the bags close-fitting within the wall structure.

The bags were placed on top of one another resembling the manner in which bricks are used to build a wall – in rows of two to three (Figure 101). Depending on the size and depth of the ditches, dams were constructed using anywhere from 10 to nearly 100 bags. In the case of the largest dams, the two dam walls were linked using beams affixed at right angles. This was done to improve the

Figure 100. *Manually built dams in Wielkie Bagno (winter 2021). Photos: W. Spychała.*

durability of the wall. The dams were then covered with a thin layer of peat. The constructionson the large ditches have an overflow section at the top in order to make sure that at high water levels the water flow will be directed over these sections and not down the sides, which may damage the structure.

Given their location in the national park and lack of access roads, the dams were built of material transported using small tracked vehicles. In some locations, the material was moved manually. No heavy equipment was used, i.e. excavators or large tractors. In some cases, where the peat extraction area was large and featured water flows, a single-layer, wooden wall was built in place of the structures discussed above.

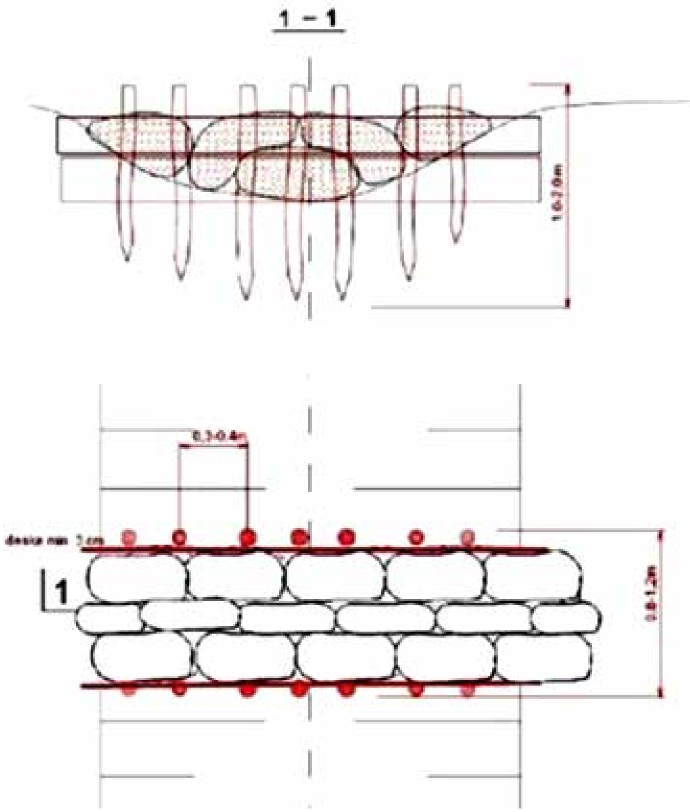


Figure 101. *Cross-sections of the peat dams with wooden walls. Drawing: Melbud S.C. Toruń.*

Figure 102. *Dam building, March 2021. Photo: W. Spychała.*

Figure 103. *Examples of completed dams, March 2021. Photos: W. Spychała.*

Tree removal

As mentioned in the previous subchapters, the tree removal was carried out in some selected areas with *Erico-Sphagnetum medii* community overgrown with trees, in several areas with a drained bog woodland with dense tree layers where it hindered the development of peat-forming ground vegetation. Additionally, the measure was implemented in three patches in post-harvested areas where the trees growing on the elevations (former ground level) between longitudinal peat cutting pits (current ground level) created shading on the peat-forming vegetation in those pits. In 2018 and 2019, i.e. before blocking the ditches in 2021, tree cutting in an area of ca. 65 ha were conducted (Figure 104). Trees were cut manually using chainsaws. The biomass was then removed from the restoration target area and stacked outside it in small piles for biodegradation. All that was also done manually or with help of a light, tracked vehicle. It was considered that further transportation of the biomass or leaving it in the ditches would disturb the ground and destroy the ground vegetation. The works were carried out in winter, on the frozen surface of the peat bog.

The tree removal from heavily drained bog areas allowed to improve the condition and even enlarge the open bog area, as well as initiated the recovery of peat-forming vegetation in post-harvested areas. Some fragments of orthophotos are presented in Figures 105 and 106 showing the vegetation pattern before and after restoration in Kluki and Wielkie Bagno. One year after the treatment, an increase in herb and dwarf shrub cover was observed in the vegetation monitoring plots. In some plots, the decline of *Sphagnum* cover was observed. However, at the time of this publication the observations covered too short period to interpret the long-term effect of the management.

Figure 104. *A drained bog on Wielkie Bagno before (November 2017) and soon after removal of trees (March 2018). Photos: K. Bociąg.*

Figure 105. *Results of tree removal in Kluki, restoration of two post-mining peatland areas with recovered moss dominated vegetation overgrown with trees (in 2019 and 2020). Map background: satellite images provided by Google Earth.*

Figure 106. *Results of tree removal in Wielkie Bagno, restoration of four drained overgrown peatland areas with Erico-Sphagnetum medii vegetation (in 2016 and 2020).*
Map background: satellite images provided by Google Earth.

Floating islands

On one of the post-excavating water basins (created as a result of flooding post-excavation site of peat mine in Krakulice) (Wielkie Bagno), after finalising the tests and choosing the most appropriate technical solutions, in total almost 200 floating islands with peat-forming vegetation were installed (Figures 107–111). They are constructed using wood and other natural materials.

The size of a floating island was ca. 2.3 x 2.3 metres. They were made of a wooden frame with double walls, inside which there was an expanded cork. From the bottom, the frame was fastened with a wooden structure, which forms the bottom of the island. Each island had four legs, each 30 cm high, and a chain with a wooden oak pole for anchoring at the bottom. The islands are connected with each other by chains equipped with wooden elements that act as bumpers (Figure 107).

The islands were installed in early spring 2021. The plan was to launch them from the shore and assemble on the water from a boat. Unexpectedly, at the time of the planned launching, the temperature dropped below 0°C and the basin was covered with thick ice. Eventually, the islands were slipped onto the ice and assembled (Figure 108). It proved to be a much easier and faster solution.

Each island was filled with bog peat. Two types of peat were used: loose peat and fibrous peat. The peat-filled islands were left for the peat to soak and settle down. After this period, the islands were planted with *Carex rostrata*, *Eriophorum angustifolium* and *Sphagnum cuspidatum*. *Calla palustris* was excluded from the plant composition on islands as it proved to not survive winter frosts.

It was expected that the floating islands on a post-excavating water basin will decrease the intensity of waving and will favour the development of peat-forming vegetation. On the islands, mire vegetation may develop. Birds may use the islands as resting or breeding places. Traces of birds visiting the islands (feathers, excrements) were observed even on prototypes. In spring 2021, SPN's employees observed nesting common stern *Sterna hirundo* on the islands.

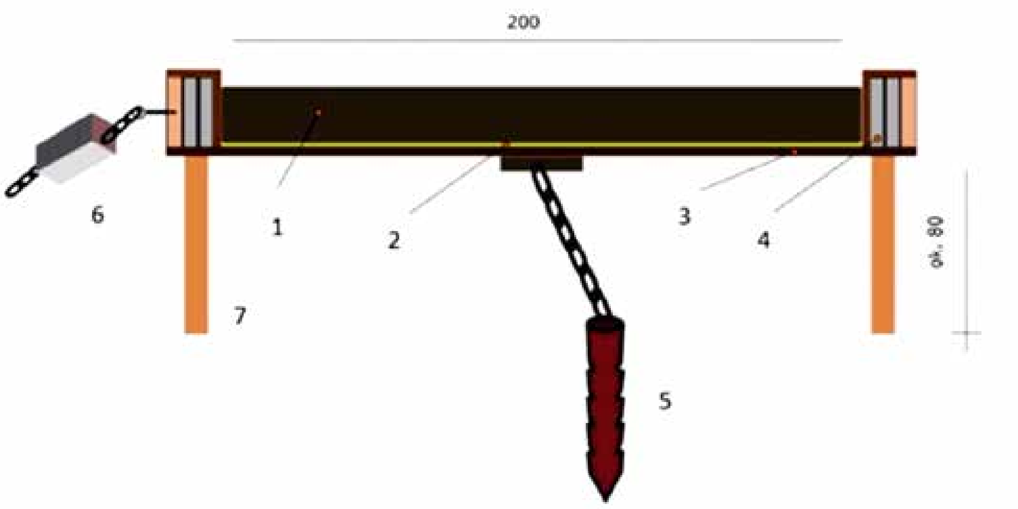


Figure 107. *The final construction of the floating island (cross-section): 1 – peat (ca. 15 cm); 2 – coconut mat; 3 – bottom; 4 – filling the sides with expanded cork mat; 5 – a stake driven into the bottom to anchor the island; 6 – bumper; 7 – leg. Drawing: M. Makowska.*

Figure 108. *Installation of floating islands, March 2021. Photos: W. Spychała.*

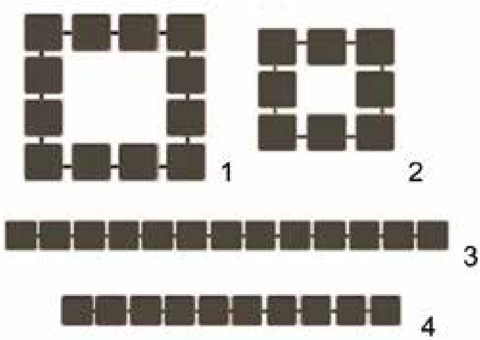


Figure 109. *Arrangement of the floating islands on the eastern part of the post-excavating water basin. Red square (on the left picture) – a set of 12 islands (No. 1 in the figure to the right); white square – a set of 8 islands (2), lines – sets of 13 (3) and 10 (4) islands.*

Figure 110. *Islands waiting on ice for the spring, March 2021. Photo: W. Spychała.*

Figure 111. *Floating islands, views from the drone, May 2021. Photos: A. Olszewska.*

Preliminary results

Hydrological monitoring provided valuable information about the hydrological conditions of the project areas. The collected data showed a seasonal rhythm of fluctuations in groundwater levels, depending on precipitation, air temperature and evaporation. In winter and at the beginning of spring, the water table was high and often stagnated at ground level (Figure 112). In summer, however, the water level dropped significantly, reaching the minimum in August or September. Then most of the drainage ditches dried up. The water resources in the summer season are influenced by the amount of spring retention rather than by high summer rainfall – the greater it is, the slower the water table falls and the faster it reacts to the amount of precipitation in summer.

Among the three studied sites (in the period from the beginning of November 2018 to the end of June 2021), the best water conditions in terms of peatland conservation were found in Ciemińskie Błota, where the average water level was 22 cm deep, although in summer and autumn it can be rather dry (Figure 113). The conditions in Kluki were worse due to the very deep drainage channel crossing the bog, and in Wielkie Bagno where the network of canals discharging the excess water beyond the border of the bog was very extensive (the average water level was below 30 cm).

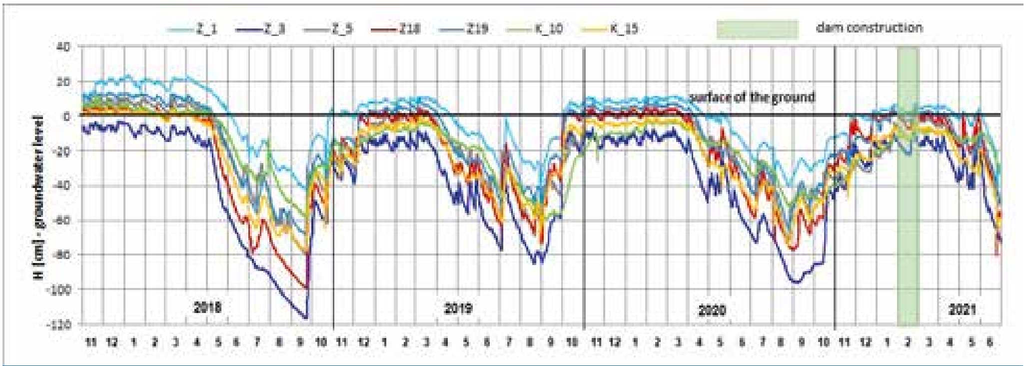


Figure 112. *Fluctuations of the groundwater table before and after the construction of dams in Wielkie Bagno and Kluki.*

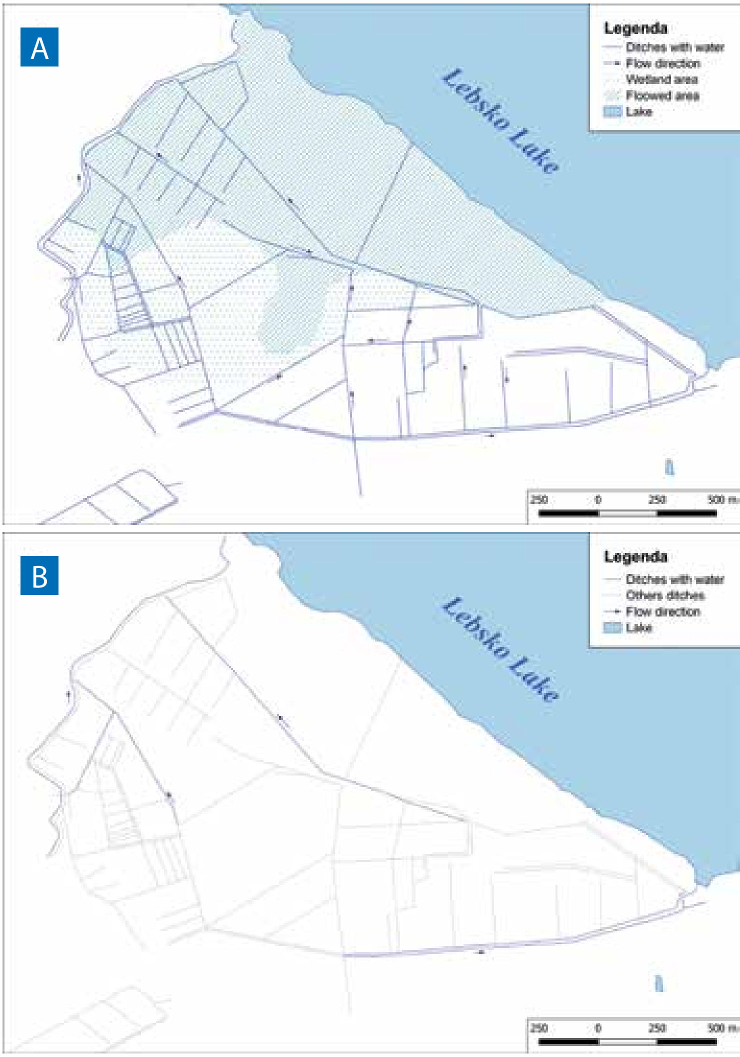


Figure 113. *Range of water surface retention in Ciemińskie Błota based on field mapping: A – in February 2020; B – in September 2020. Maps: M. Pawłowska.*

The dams were built in March and April 2021. A positive effect of water retention in the bogs was observed immediately after the construction of the dams, as most of them were built during the wet season. After building the dams, the water accumulated between the dams and stayed longer in the bog than before rewetting (Figure 114).

Figure 114. *Dams in Wielkie Bagno shortly after dam construction, May 2021. Photos: M. Pawłowska.*

The first field observations indicated that the dams function properly, as expected. The damming effect is well illustrated by the image from the drone before and after the dam construction (Figure 115). However, these were only the first results. In late spring and summer 2021, unfavorable weather (drought and high temperatures of the air) resulted in a significant drop of the groundwater table and did not give any chance for water to be retained by dams during the summer.

The results of hydrological observations in the post-excavating basin with floating islands (Wielkie Bagno) are presented in Figure 116. The reservoir is not deep, occupies an area of about 18 ha, and collects from 25 000 to 130 000 m^3 of water depending on the water level. During winters,

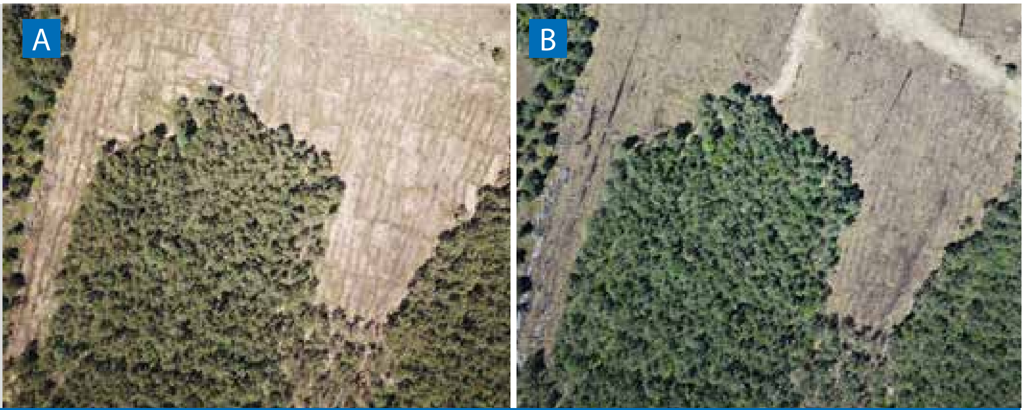


Figure 115. *A part of Wielkie Bagno: A – before construction of dams (June 2020), B – after construction of dams (May 2021). Photos: A. Olszewska.*

an ice cover forms on the surface of the reservoir, which reduces the supply and decreases the water level. This is clearly visible at the turn of January and February 2020, when the ice (without snow cover) formed and caused the drop of water level in the reservoir rapidly. The amplitudes of water level fluctuations in the reservoir reach a maximum of ca. 60 cm during the year and more or less correspond to changes in water retention in most of the bog. Such a range of water level fluctuations should therefore be taken into account in the design and construction of floating islands.

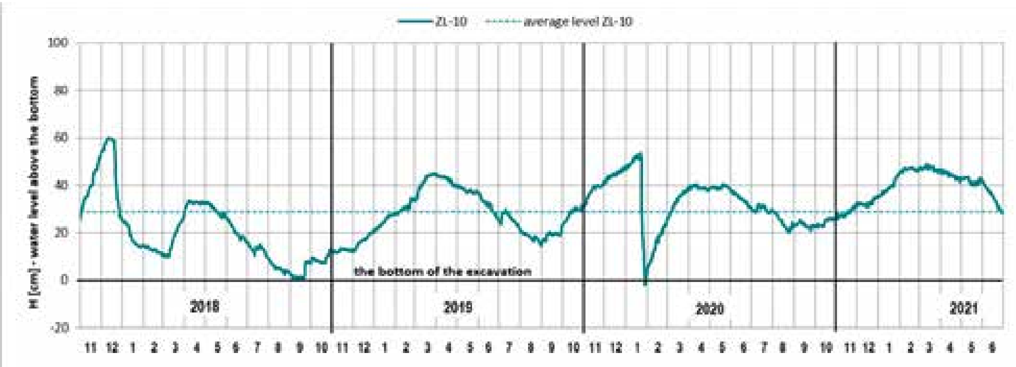


Figure 116. *Water level fluctuation of the post-excavation basin with floating islands in Wielkie Bagno from the end of 2017 to June 2021.*

The analysis of physical and chemical parameters of the surface water in channels, watercourses as well as groundwater in peatlands of SPN showed no apparent seasonality. Among the tested parameters, from the point of view of the functioning of peatlands, determining the variability of the water pH was of utmost importance, as the surface water pH results from water and calcium management and the dominant species in vegetation. All examined bogs were acidic and poor in calcium, on average about pH 5 (Figure 117). However, the pH value in surface water and groundwater varied from pH 2.9 to over 7.0. The highest values were mainly found in the transit channels that bring water from the surrounding areas. The lowest pH value was found mainly in the sites with *Sphagnum* peat deposits with poor peat decomposition, slow water mobility, and supplied by precipitation poor in nutrients (away from drainage ditches).

The water samples for all peatlands were characterized by low conductivity (<100 μS /cm), which indicates a low content of mineral substances. In this case, higher values were recorded in the drainage channels (ranging from 200 to 300 μS/cm), with a maximum in a deep channel crossing Kluki area, where the values even exceeded 600 μS/cm.

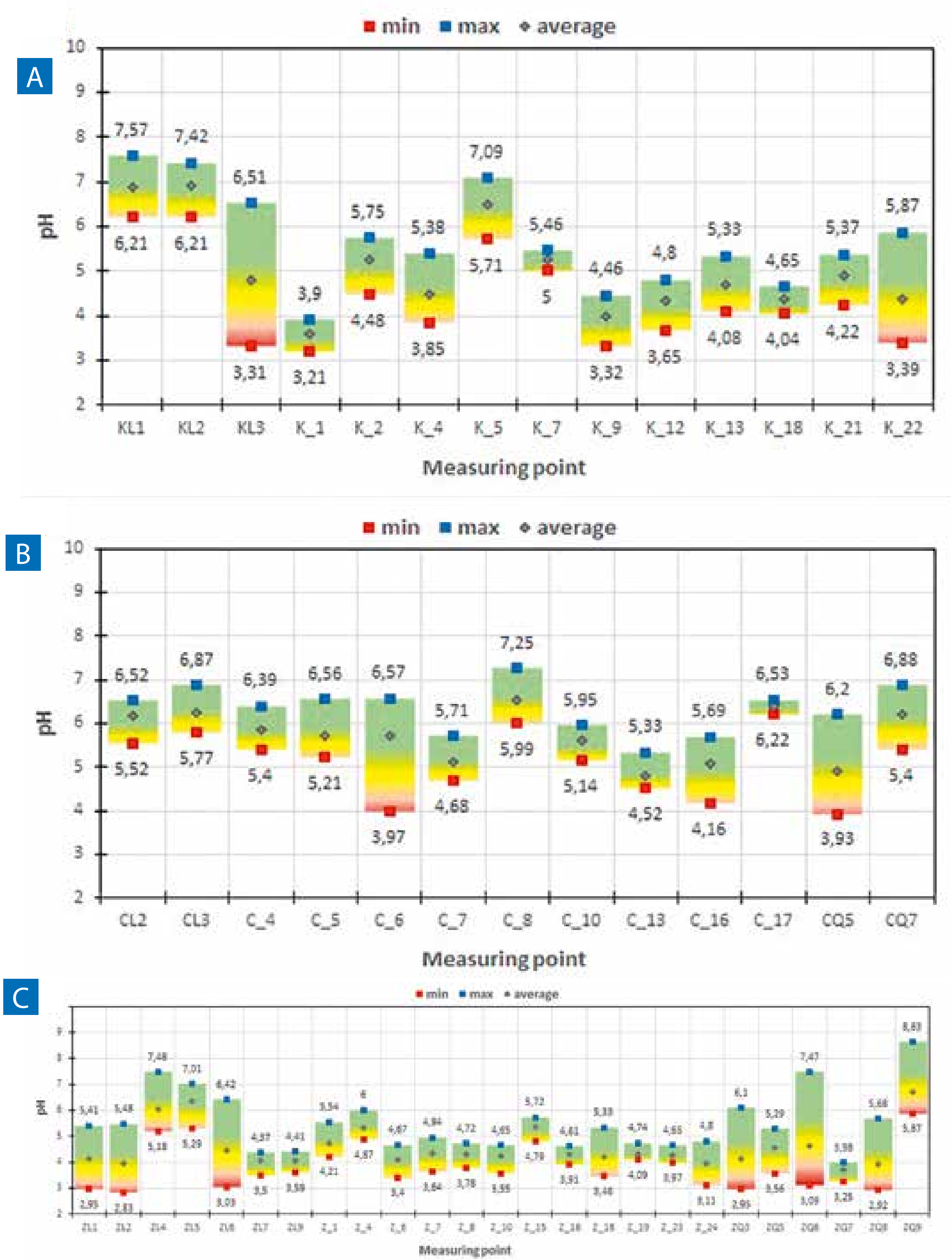


Figure 117. *pH variability in peatland waters: A – Kluki, B – Ciemińskie Błota, C – Wielkie Bagno.*

Laboratory surveys also included the determination of chlorides in order to assess the hydraulic relations of bogs and the neighboring areas, i.e. Łebsko Lake and Pustynka River and possible water exchange via transit channels. The local influence of the Łebsko Lake in Ciemińskie Błota through the channel leading to the lake was found, where the dominant hydrochemical type was the chloride-bicarbonate-sodium-calcium waters. High concentrations of nitrates (compared to the concentrations of total nitrogen and ammonia) may indicate the inflow of pollutants from the catchment area and the agricultural land surrounding the bogs. This mainly concerns the peripheral zones of Kluki and Wielkie Bagno.

CONSTRAINTS AND SOLUTIONS

Hydrological monitoring. In summer due to dense vegetation cover and in the spring due to flooding, there were difficulties to find the piezometers which, due to possible thefts, were well hidden (only metal lid protruding above the ground). As a solution, a metal detector was used to find them. These lids attracted wildlife animals. In many cases, they were bitten or removed by animals. Also, when the lids are lost the snails may enter the open piezometer pipes or the leaves block the pipe inlet, preventing the water level reader from being pulled out.

Dam building. Dams need to be durable, watertight and resistant to water erosion. In a national park, they must be made of natural materials. In the case of SPN, it was decided to build wood and earth dams. The materials used included hard oakwood and peat with an addition of mineral soil.

The priority of the national park was to organize work in a manner that is least disruptive to plant life and the bog surface. This precludes the use of heavy equipment, which also refers to the transportation of materials. Peat may not be extracted on site – it must be shipped in from outside the park. This is the reason why all the materials used were transported using small, tracked vehicles. In some cases, material was hand-delivered to a given site. In the dam building, no large mechanical vehicles were used, such as excavators and tractors.

Both peat and mineral material were packed in jute sacks in order to make them easier to transport and make the material more durable when building a structure. Sacks were only half-filled to make them easier to carry by hand. The use of half-filled sacks also made it easier to pack them more tightly between dam walls.

In order to assure proper packing and consequently watertightness, sacks were placed in-between wooden walls in the manner of laying bricks in two to three rows. This method helped assure structural durability and the ability to prevent water leaks. Wooden poles were also inserted deep into the floor on the outside of the walls in order to help further reinforce them.

The dams also feature a low-head section in their middle part in order to help prevent washing away the dam sides at high water levels.

Tree removal. Due to the lack of severe winter (no frost) it was impossible to remove cut trees using regular forestry equipment. Therefore, light specialised equipment on wide caterpillar tracks was used.

Despite the best efforts, vegetation did suffer some temporary damage during the restoration process, and this is a problem for the national park, especially across the most valuable parts of the peatland. In such cases, human and equipment movement is partly restricted. For this reason, SNP decided not to place biomass in ditches that often were located at significant distances. Further transport was also not accepted. The biomass used was carried out of the cleared areas and placed in small piles for biodegradation.

Floating islands. When constructing floating islands, it is necessary to make sure that they are adequately durable in order to survive the winter season, which may include ice cover. It is further necessary to make sure they can remain afloat, which may become a problem when they absorb too much water. Each island must also be permanently anchored. SNP also attempts to use as few manmade materials as possible, i.e. plastic and Styrofoam were not accepted. In this case, the main building material used was wood. The islands' floatability was enhanced by expanded cork. This is a natural material that is durable, does not absorb water to a meaningful extent, and is not easily biodegradable. It was placed inside of a wooden structure in order to reduce the risk of mechanical damage. The wooden structure is equipped with wooden legs, which means that in the event of the loss of floatability, the island will not sink, but will settle above the bottom of the basin, which increases the likelihood of vegetation survival. Ropes made of natural materials and steel lines during the tests did not prove to be adequate, so in order to anchor the islands, a short chain affixed below each island was used. The chain was fixed to an oakwood pole in the bottom of the basin. The bottom of each island is not solid allowing vegetation constant access to water. The bottom is created using a coconut mat.

Among the herbaceous plants introduced on each floating island, *Carex rostrata* was found to be the best adapted species. *Calla palustris* flourished on the islands in the summer, but it was less likely to survive during the winter. Some vegetation was damaged by birds. Another plant species that thrives on these islands is *Sphagnum cuspidatum*. Leaving the islands to natural succession is not a good idea, as during the prototypes' tests it was observed that they become covered mainly with *Juncus* spp. and *Molinia caerulea*, undesirable species if they become dominant.

Floating islands are often used by birds for resting and nesting. In this case, this may lead to vegetation damage. There are methods to disturb the birds, however, in a national park the use of such methods is not permitted. The use of these islands by birds may thus be treated as an added environmental value, although this may damage the vegetation and decrease the success of peat-forming vegetation establishment.


Photo: M. Pakalne

4.2.3. Amalva peatland, Lithuania

Photo: Ž. Sinkevičius

Location: Southern Lithuania
WGS84 coordinates: 54.496516, 23.548799. https://ieej.lv/peatrestore
Altitude: 87.0 m a.s.l.

Protection status:
Area in Žuvintas Biosphere Reserve
Natura 2000 site (LTALYB003, LTALY0005)
Ramsar site No. 628

Total area of the Žuvintas Biosphere Reserve: 3 638 ha

Restoration area: 215 ha

EU importance habitat types in the restoration area:
Degraded raised bogs still capable of natural regeneration (7120)

Implementation: Lithuanian Fund for Nature (planning, expertise, coordination, nature management supervision, monitoring); State Forest Enterprise (clearing of trees and shrubs); Žuvintas Biosphere Reserve Directorate (supervision of actions related to nature management); JTC "Inžinerinis projektavimas" (technical design); JSC "Alytaus melioracija" (subcontractor for dam building)

Land manager: State Forest Enterprise

DESCRIPTION OF AMALVA PEATLAND

Amalva mire complex is located in Southern Lithuania and belongs to Žuvintas Biosphere Reserve. Draining of the area began as early as the beginning of the 20th century and continued during the Soviet period in the second half of the 20th century for peat extraction and agricultural purposes. As a result, considerable areas of fen and transitional mires were lost.

Restoration measures were implemented in 215 ha of degraded peatland in the southern (the most damaged) part of the Amalva mire complex. In the middle of the 20th century, the area was drained by a dense network of open (wide collective ditches and narrow drains) and closed (ceramic and plastic subsurface pipes) drainage (Figures 118, 119). The natural vegetation cover was completely destroyed. However, the planned economic activities were not efficient, thus the site was abandoned for the last four decades. Currently, only one protected habitat of European importance, Degraded raised bogs still capable of natural regeneration (7120), occurs in 30 ha of area (Figure 120). The rest of the peatland is severely damaged and does not meet the requirements for the habitats of European importance.

Figure 118. *The blocked collective ditch in Amalva, March 2021. Photo: J. Sendžikaitė.*

Figure 119. *Ceramic and plastic pipes installed to establish a subsurface drainage system were found in Amalva. It is a legacy of the Soviet reclamation school from the late 1980s. Photo: N. Zableckis.*

Figure 120. *After a vast drainage campaign in Soviet time, the formerly open Amalva raised bog gradually became replaced by forest. Photos: Ž. Sinkevičius.*

WHY WAS THE RESTORATION NEEDED?

Due to the drainage functioning for decades, the water levels in the area were extremely low, in some locations reaching 1.3 m below the peat surface. As a result, the natural habitats in the southern part of Amalva peatland were lost, and the typical open raised bog was replaced by forest and shrubbery. Before LIFE Peat Restore actions, only some fragments of degraded raised bog habitats were found in the central part of the peatland.

The first attempts to restore natural hydrological conditions of the Amalva mire complex (felling of trees to restore biodiversity) were implemented by a Lithuanian non-governmental organisation "Nature Heritage Fund" during the projects WETLIFE (LIFE07NAT/LT/530, 2009–2013) and WETLIFE2 (LIFE13NAT/LT/84, 2014–2018) (Figure 121). However, these actions did not include the whole degraded peatland area, and the southern part of the Amalva peatland remained unrestored. As this area urgently needed restoration, it was included in the LIFE Peat Restore project.

Figure 121. *A recovering peatland ecosystem in WETLIFE and WETLIFE'2 project area after implementation of restoration actions (damming of ditches and repeated special purpose clearings of trees) in the neighbourhood of LIFE Peat Restore site in the Amalva mire, October 2018. Photo: J. Sendžikaitė.*

Rewetting scenario. Within the LIFE Peat Restore project, the ditch blocking and clearing of trees and shrubs were planned in the southern part of Amalva peatland to improve the hydrological conditions and conservation status of the habitat, and to minimize GHG emissions from the heavily drained peatland. After the implementation of these actions, it is expected to minimize the increased decomposition of the upper peat layer and reduce GHG emissions from the degraded peatland. At the same time, the improved hydrological conditions will encourage vegetation shifts towards bog plant communities dominated by *Sphagnum* lawns in the central part of the restoration area and moist forests at the edges.

Non-intervention scenario. Without rewetting, further degradation of peatland would continue. Thus, the remains of bog habitats in the central part of the area would be gradually replaced by drained forests and shrubberies.

Estimated GHG reduction after rewetting: according to the GEST scenarios, after restoration GWP emissions from the Amalva area should be reduced from 5775 to 1503 t CO_2-eq/yr.

TARGET VEGETATION AND SPECIES

In Amalva, after the long time being drained and destruction of the natural vegetation, any species typical to raised bog vegetation are considered target species. In the case of successful restoration of hydrological conditions, gradual vegetation succession toward formation habitat similar to active raised bog is expected, i.e. vegetation with a *Sphagnum* lawn and other typical species of bogs and bog woodlands. On the edges of the area, moist oligotrophic and mesotrophic forests are expected to establish.

A target raised bog vegetation (depending on micro-structures) in open and semi-open habitats is characterized by dense moss cover with dominant *Sphagnum* species (*S. magellanicum*, *S. rubellum*, *S. fuscum*, *S. capillifolium*, *S. fallax*), solitary patches of *Aulacomnium palustre* and *Polytrichum strictum*, as well as growing dwarf forms of *Pinus sylvestris* and other typical vascular plants (e.g. *Rhynchospora alba*, *Eriophorum vaginatum*, *Vaccinium oxycoccos*, *Empetrum nigrum*, *Andromeda polifolia*, *Drosera rotundifolia*, *D. anglica* or *D.* x *obovata*). *Sphagnum cuspidatum*, *Utricularia minor*, *Carex rostrata*, *Calla palustris* grow in gradually overgrowing blocked ditches. In bog woodland, the tree layer is dominated by *Pinus sylvestris* and *Betula* pubescens, while *Ledum palustre*, *Vaccinium uliginosum*, *V. palustris*, *V. vitis-idaea* and other dwarf shrubs are present in the undergrowth. In the target vegetation, the moss carpet is dominated *Sphagnum* mosses (*S. magelanicum*, *S. angustifolium*, *S. capillifolium*, *S. falax*), with *Aulacomnium palustre*, *Pleurozium schreberi*, *Polytrichum* spp. and some other bryophytes present in the plant community (Figure 122).

Restoration may also have a positive effect on the population status of rare and protected bird species such as black grouse *Tetrao tetrix*, common crane *Grus grus*, great grey shrike *Lanius excubitor* and some waders.

Figure 122. *Some of the target plant species in raised bogs under restoration after heavily draining: A – Sphagnum mosses; B – Eriophorum vaginatum; C – Vaccinium oxycoccos; D – Drosera rotundifolia; E – Ledum palustre; F – Vaccinium uliginosum. Photos: J. Sendžikaitė.*

PREPARATORY WORK

A management plan for the Amalva mire was prepared and approved in 2017 before the LIFE Peat Restore project started implementing restoration actions in Amalva. The technical design for the restoration of the hydrological regime of the project site (simplified version presented in Figure 123) was prepared by the initiative of the Lithuanian Fund for Nature within the project LIFE Peat Restore (in 2018). Due to changes in the schedule of planned actions, the management plan was amended and approved in 2019.

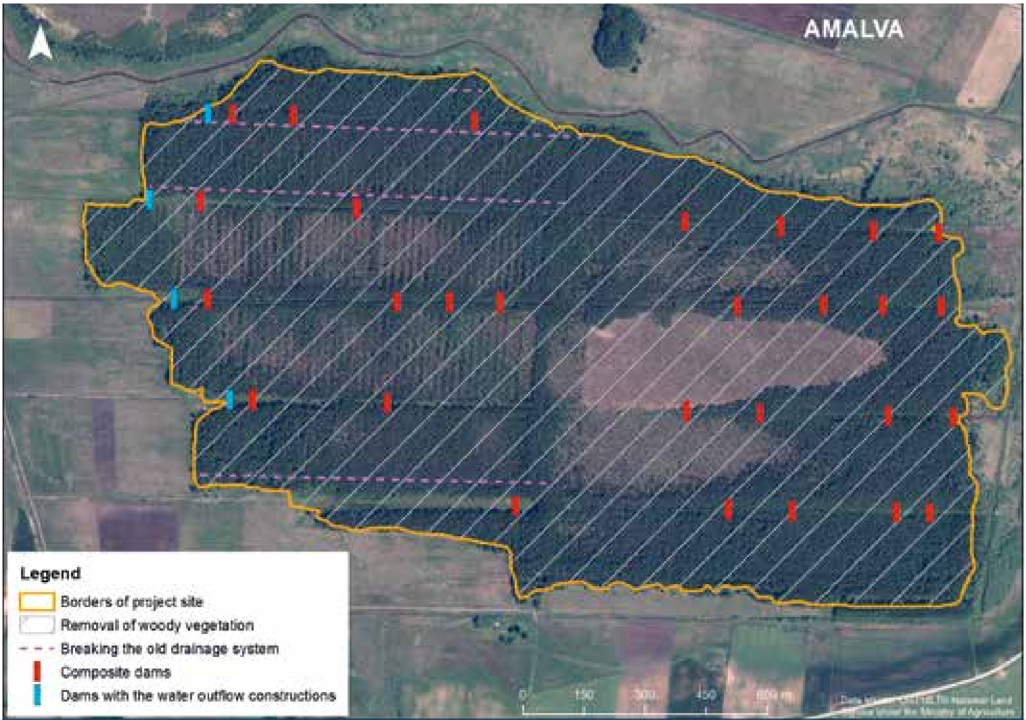


Figure 123. *Localisation of breaking the subsurface drainage systems and composite dams in the Amalva peatland. Map: JTC "Inžinerinis projektavimas", K. Jarmalavičienė, L. Jarašius.*

Since the heavily drained Amalva area was overgrown with forest, it was considered that it would not be enough to block or fill the ditches, as this may not allow reaching the aim and restoring the peatland functions. As required by the national legislation in Lithuania, any forest management actions in protected areas need forest management plans. That also referred to the Amalva case. Thus, the forestry management plan of Kazlų Rūda regional division of the State Forest Enterprise was adjusted in 2018 by planning the foreseen removal of trees.

To acquire more information about the area for restoration purposes, a survey of vegetation (vegetation mapping) and peat properties was performed. The monitoring system consisted of seven water level measurement wells and five vegetation monitoring plots located in the transect perpendicular to the main drainage ditch. Eight peat samples for understanding the physical and chemical properties (pH, C:N ratio) were taken. The peat depths were measured once, during the first monitoring year (2017). Hydrological and vegetation monitoring sites were established in 2017.

RESTORATION AND MONITORING RESULTS

To improve the hydroecological conditions of the degraded peatland, in addition to rewetting, trees and shrubs were removed in the whole Amalva project area (215 ha) in 2019–2020 (Figure 124). Removal of trees and shrubs was the first step followed by rewetting. Special purpose clearing, e.g. removal of all trees and shrubs was considered the most appropriate method.

Special purpose clearing in 200 ha performed by the State Forestry Enterprise, the manager of state-owned forest lands, while 15 ha of non-forest land overgrown by shrubs and young trees (classified as the habitat type Degraded raised bogs still capable of natural regeneration (7120)) in the central part of the area was managed by a subcontractor.

Figure 124. *Tree clearing in the Amalva area, November 2020. Photo: Ž. Sinkevičius.*

The special purpose clearings aimed at supporting biodiversity and climate mitigation in the Amalva peatland was among the largest forest cuttings in Lithuania so far done for peatland restoration. Approximately 20 000 m^3 of timber was cut, the majority of it was removed and sold by the State Forestry Enterprise (common practice), while the LIFE project purchased several hundred cubic metres of logging waste (branches, trunks) to fill it in the ditches to level the surface. The clearing and wood removal was performed by machinery, except for the central part of the peatland where forest clearing was done manually due to the vulnerability of the peat soil and ground vegetation. The rest of the area was dry (deeply drained), therefore machinery could access the area (Figure 125).

Figure 125. *Removal of woody vegetation from the Amalva area: A – by light minitractor with a small trailer, March 2019; B and C – by heavy machinery (forwarders); D – timber yard on a roadside near the project area. Photos: Ž. Sinkevičius (A–C), N. Zableckis (D).*

As the next step after tree removal, rewetting measures were implemented. Actions to restore the hydrological regime were performed by a local contracted company JSC "Alytaus melioracija", which is experienced in such works in Lithuania. Actions were performed in winter of 2020/2021. Wide-track excavators were used for building 28 composite dams on wide collective ditches. These dams were 4–10 m wide and made of plastic pile sheets and peat (Figure 126). Plastic pile sheets were mainly constructed manually using a hammer and later to make this construction solid and waterproof, excavators filled the ditch with compressed peat from both sides. In addition, four special dams supported by water outflow construction were built on the edges of collective ditches (Figure 127–129).

Amalva peatland was drained both by open ditches and drain pipes laid under the peat surface. Thus, it was very important to block not only the open ditches but also to dig out or break the remaining plastic and ceramic pipes (Figure 119). In order to locate these pipes, old drainage schemes were analysed. As soon as the pipes were located, the excavators dug out or broke the pipes and formed a small embankment instead.

All management actions were performed outside the bird breeding season, i.e. during the period from the end of summer until the end of winter. Therefore, the restoration work took two years.

Figure 126. *Installation of the plastic pile sheets dam. February 2021. Photo: Ž. Sinkevičius.*

Figure 127.
Blocked collective ditch in the Amalva peatland, February 2021. Photo: Z. Sinkevičius.

Figure 128.
Dam with water outflow construction in Amalva peatland, March 2021. Photo: J. Sendžikaitė.

Figure 130.
Rise of water level in the ditches in the Amalva peatland was observed immediately after blocking the ditches, March 2021. Photo: J. Sendžikaitė.

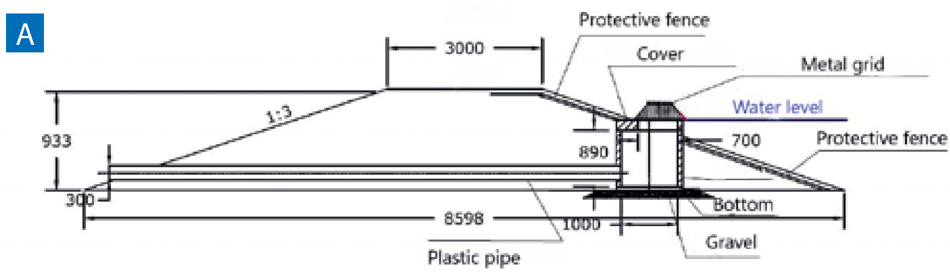


Figure 129. *Dam with the water outflow construction. Cross section of the dam (A) and view of a fenced concrete well for water outflow on the top of the dam (B). The dam is made of plastic pile sheets, peat, concrete well, plastic tube, protective metal fence and grid. Using this kind of construction will prevent plugging the outflow pipe with the litter (leaves and branches) and protect from undesirable activity of beavers. Scheme: JTC "Inžinerinis projektavimas". Photo: N. Zableckis.*

Figure 131. *Water level dynamics in Amalva peatland, in 2019–2021. Red line indicates the time of dam construction, i.e. finishing the rewetting actions.*

The results of hydrological monitoring show that the restoration has a positive effect on the hydrological conditions, as the water level increased very soon after the dam construction and raised above the peat surface during the following spring (Figures 130-131). However, to assess the restoration effect in the longer term more time is required.

Remarkable changes in vegetation cover (mainly in the tree layer) were determined after the implementation of large scale forest clearing. Due to this reason, the coverage of the tree layer decreased from 15–45% (in 2018) to 0–40% (in 2020) in the monitoring plots (10 × 10 m). A decrease in shrub cover was observed in all vegetation plots, while the cover of dwarf shrubs remained stable (Figure 132). Although the vegetation changes at subplot level (1 × 1 m) were not that noticeable as in the large plots, in some cases decline in the cover of dwarf shrubs (*Calluna vulgaris* and *Ledum palustre*) was recorded; it was caused by the vegetation damage while felling the trees and transporting timber out of the area.

Figure 132. *Changes in one of the permanent vegetation monitoring plots (10 × 10 m) in Amalva, the habitat type of EU importance "Degraded raised bogs still capable of natural regeneration", August 2018. A – before restoration; B – after restoration in 2020. Photos: Ž. Sinkevičius.*

CONSTRAINTS AND SOLUTIONS

In Lithuania, restoration of bogs had been practised for more than a decade. First of all, the planning procedures must be carried out, the planning documents prepared and agreed with the relevant stakeholders. However, this process may involve some unexpected aspects. Therefore, proper preparation including information dissemination and involvement of the local communities and stakeholders is highly important.

The key lessons learned in Amalva:

- All stakeholders including the local people must be not only well and timely informed about the proposed restoration actions, but also actively involved in restoration planning and implementation.
- Forest clearing is always a topic for the debates during the preparation of site management plans for protected areas. Peatlands are often assigned as "forest land" in the Lithuanian Real Estate Cadaster. It means that all actions in the peatland restoration site must be aligned with the National Forestry Law and Forest Clearing Rules. Most commonly, any nature management action affecting forest stand, e.g. rewetting the site with or without the removal of trees, causes a conflict with the forestry practice, particularly the sanitary requirements in the case of dying trees as a potential source for spreading diseases, dead wood, loss of forest land in case of the removal of trees without re-planting new trees, economic loss of timber if forest remains uncleared in rewetted area, and others.
- In the case of Amalva, large-scale special purpose clearing (215 ha) was planned and implemented in a drained peatland colonised by trees. The key lessons: (1) implementation of this action requires large efforts and is very expensive; (2) special purpose clearings of forest by removing almost all trees, except for the bog forms of Scots pine is questionable from the ecological point of view. Planning a mosaic-type cutting and leaving part of the forest uncut in the rewetted area would increase the amount of dead wood, creating habitats for species that depend on the presence of dead wood. If the water level is successfully restored, trees may gradually die. In drier places, the recovery of open peatland habitats is hardly possible, therefore the trees should be left untouched as part of the mosaic.
- Hydrological restoration is always challenging since the blocking of drainage systems might cause extra troubles to locate all subsurface drainage pipes that must be broken. Such data of old drainage infrastructure are lost, outdated or not properly registered. Therefore, it is recommended to adjust the hydrotechnical design if new drain pipes are found during the construction of dams and plan a buffer amount of resources to pay for the subcontractor.

4.2.4. Pūsčia peatland, Lithuania

Photo: Ž. Sinkevičius

Location: Northeastern Lithuania
WGS84 coordinates: 55.6799235, 26.099693. https://ieej.lv/peatrestore
Altitude: 151–154 m a.s.l.

Protection status:
Pūsčia Telmological Reserve, Natura 2000 site (LTZAR0030), Gražutė Regional Park

The total area of the telmological reserve: 100.6 ha

Restoration area: 82 ha

EU importance habitat types in the restoration area: Degraded raised bogs still capable of natural regeneration (7120); Depressions on peat substrates of the *Rhynchosporion* (7150); Bog woodland (91D0); Transition mires and quaking bogs (7140)

Implementation:
Lithuanian Fund for Nature (planning, expertise, coordination, nature management supervision),
JTC "Inžinerinis projektavimas" (technical design),
JSC "Anykščių melioracija" (subcontractor for dam building)

Land manager: National Land Service under the Ministry of Agriculture

DESCRIPTION OF PŪSČIA PEATLAND

Until the mid-20th century, the Pūsčia peatland was one of the largest natural raised bogs in North-Eastern Lithuania. However, in the 1970s industrial peat mining began and lasted for 30 years. The dense network of ditches (total length of ca. 35 km) and subsurface drainage caused desiccation of the whole peatland area resulting in unfavourable hydrological conditions. The upper layer of the mire, including vegetation, was removed and the whole area was significantly altered. Before restoration, bare peat and scarce heath patches dominated (Figures 133, 135), while part of the territory, especially the marginal areas, was colonised by trees (Figure 134).

Earlier attempts of rewetting the Pūsčia peatland were implemented in 2000. Although it had only a marginal effect, namely only at the dammed margins of the peatland, fragments of the vegetation typical to raised bog established as a result of spontaneous revegetation. Thus, despite the long-term functioning of artificial drainage and industrial peat mining, the site maintained fragmented near-natural features and biodiversity (Figure 136).

Figure 133. *Pioneer plant communities on bare peat. Photo: Ž. Sinkevičius.*

WHY WAS THE RESTORATION NEEDED?

Three decades of industrial peat extraction and intensive drainage has severely altered the raised bog (Figures 134A). After cessation of peat extraction, piles of peat and tree stumps remained. Moreover, some of the draining pipes were left under the peat surface and thus continuously drained the area. This caused a significant decrease of water level: up to 1 m below the peat surface during the dry season. Before restoration, the site was dominated by vegetation characteristic to post-harvested peatlands with species-poor, degraded vegetation and a large proportion of bare, unvegetated peat surfaces (Figures 133, 134B–C, 135, 137, 138).

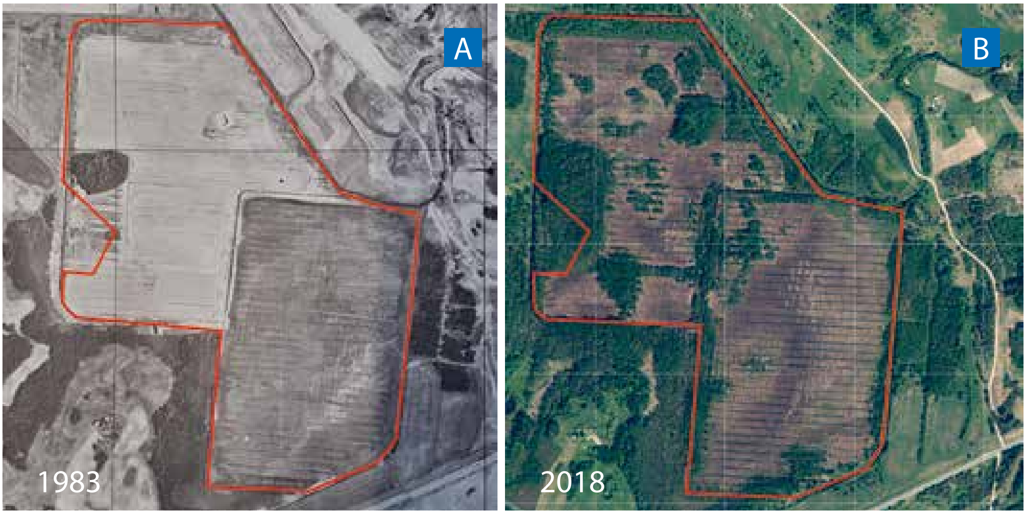


Figure 134.
Changes in the Pūsčia peatland:
A – the peat extraction area in 1983; natural vegetation cover was completely destroyed by peat extraction (a fragment of an orthophoto from 1983, source: Office of the Chief Archivist of Lithuania);
B – Pūsčia peatland before restoration measures implement by the LIFE Peat Restore project, in 2018 (source: www.geoportal.lt);
C – shortly after implementation of restoration measures, in 2020 (source: https://earth.google.com).

Figure 135. *In 2018, the area was mostly dominated by bare peat. Photo: L. Jarašius.*

Figure 136. *In 2018, spontaneous recovery of vegetation was observed on the margins of the peatland (followed by the first efforts of ditch blocking in 2000). Photo: J. Sendžikaitė.*

Figure 137. *Dry oligotrophic forest and shruberries in Pūsčia peatland, Augusts 2019. Photo: J. Sendžikaitė.*

Figure 138. *Old drainage system before rewetting in 2018. Photo: L. Jarašius.*

Rewetting scenario. After rewetting of the Pūsčia peatland, typical peat-forming raised bog and transitional mire plant communities dominated by *Sphagnum* lawns with dwarf forms of pines in the centre and moist forests on the edges are expected to establish (Figure 139).

Non-intervention scenario. Spontaneous revegetation without rewetting is nearly impossible or would take a very long time and might be unpredictable, as the area was severely damaged by drainage and peat extraction. If no restoration measures would be taken, wind and water erosion would continue to maintain bare, dry peat surfaces with only fragmentary recovery of peat-forming vegetation (Figures 136, 140).

Estimated GHG reduction after rewetting: according to the GEST scenario modelling, after restoration GWP emissions should be reduced from 968 to 527 t CO_2-eq/yr.

Figure 139. *Bog woodland at the southern margin of Pūsčia, in 2017. Photo: J. Sendžikaitė.*

Figure 140. *Rhynchosporion albae community in the eastern part of Pūsčia, rewetted in 2000. Photo: J. Sendžikaitė.*

TARGET VEGETATION AND SPECIES

Raised bog plant communities are the target vegetation in the Pūsčia area. As indicated by the preliminary monitoring results, the restoration measures have improved the hydrological condition, thus bare peat and heath dominated vegetation may be gradually replaced by typical raised bog species: *Sphagnum* spp. (e.g. *S. magellanicum*, *S. rubellum*, *S. fuscum*, *S. capillifolium*, *S. fallax*), *Aulacomnium palustre, Rhynchospora alba, Eriophorum vaginatum*, *Vaccinium oxycoccos*, *Empetrum nigrum*, *Andromeda polifolia*, *Drosera* spp. (*D. rotundifolia*, *D. anglica*, *D.* x *obovata*), as well as dwarf forms of *Pinus sylvestris* (Figure 141). *Sphagnum cuspidatum*, *Utricularia minor*, *Carex rostrata*, *Calla palustris* may establish as pioneer species in the gradually overgrowing blocked ditches. Moreover, all the previously drained forested peatland habitats may gradually turn into moist or very moist woodlands. In bog woodlands, *Pinus sylvestris* and *Betula* pubescens may dominate with *Frangula alnus* in the shrub layer and *Ledum palustre*, *Vaccinium uliginosum*, *V. palustris* and some other

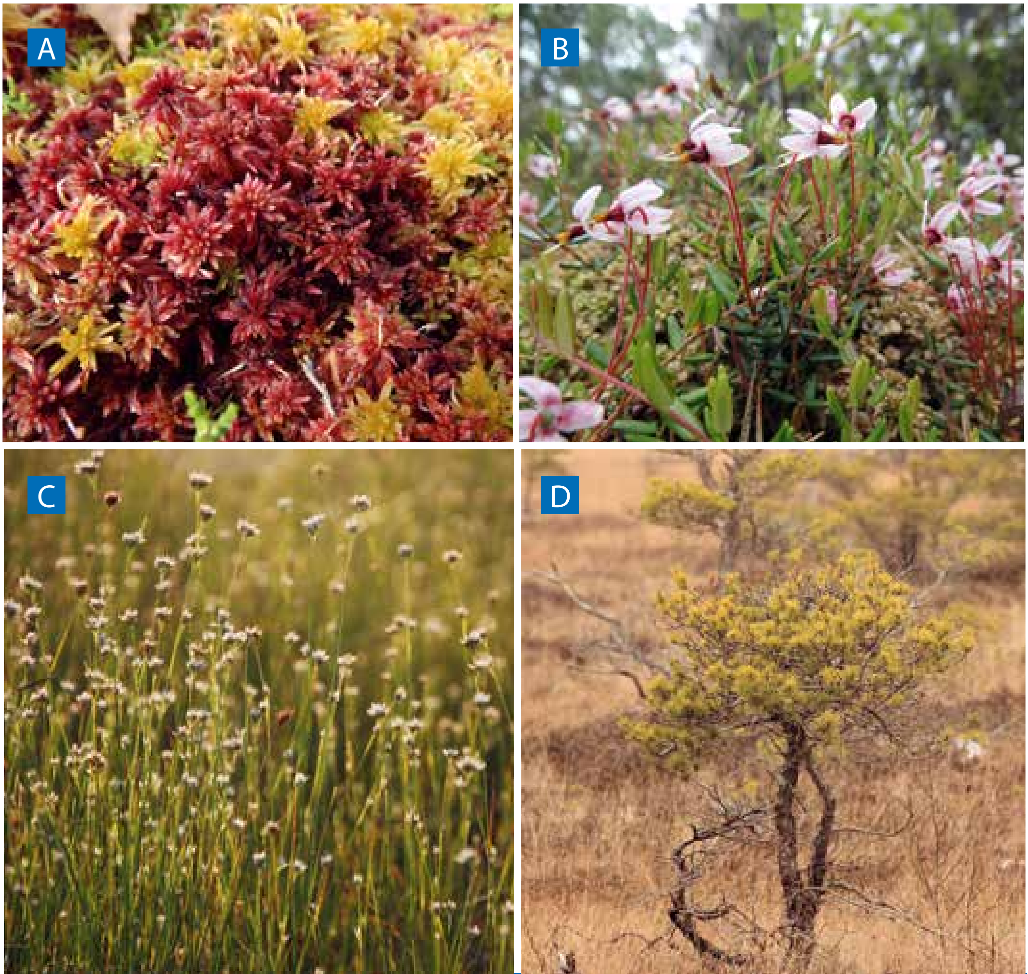


Figure 141. *Some of the target plant species in the Pūsčia peatland: A – Sphagnum rubellum (red) and S. fuscum (brown); B – flowering Vaccinium oxycoccos; C – Rhynchospora alba; D – a dwarf form of Pinus sylvestris, typical for intact raised bogs. Photos: J. Sendžikaitė (A, B), L. Šveistytė (C), Ž. Sinkevičius (D).*

raised bog species in the dwarf shrub layer. In the moss layer, *Sphagnum* species (*S. magelanicum*, *S. angustifolium*, *S. capillifolium*, *S. fallax*) may dominate, with patches of *Aulacomnium palustre*, *Pleurozium schreberi*, *Polytrichum* spp. and other species of raised bogs. Dam building will also have a positive effect on small fragments of transitional mires found in the northern part of the site, where small-sedge communities may establish.

Pūsčia peatland is also an important site for at least 16 rare and protected bird species, for example, black grouse *Tetrao tetrix*, common crane *Grus grus*, great grey shrike *Lanius excubitor* and amphibians such as fire-bellied toad *Bombina bombina*.

PREPARATORY WORK

Within the LIFE Peat Restore project, a management plan for Pūsčia Telmological Reserve was developed and approved in 2018. It foresees all the necessary measures to restore the peatland: preparation of technical design, dam construction (Figure 142), clearing of trees and tree shoots, monitoring of water level and vegetation aiming at restoring natural peatland habitats, improving conditions for protected species and climate mitigation.

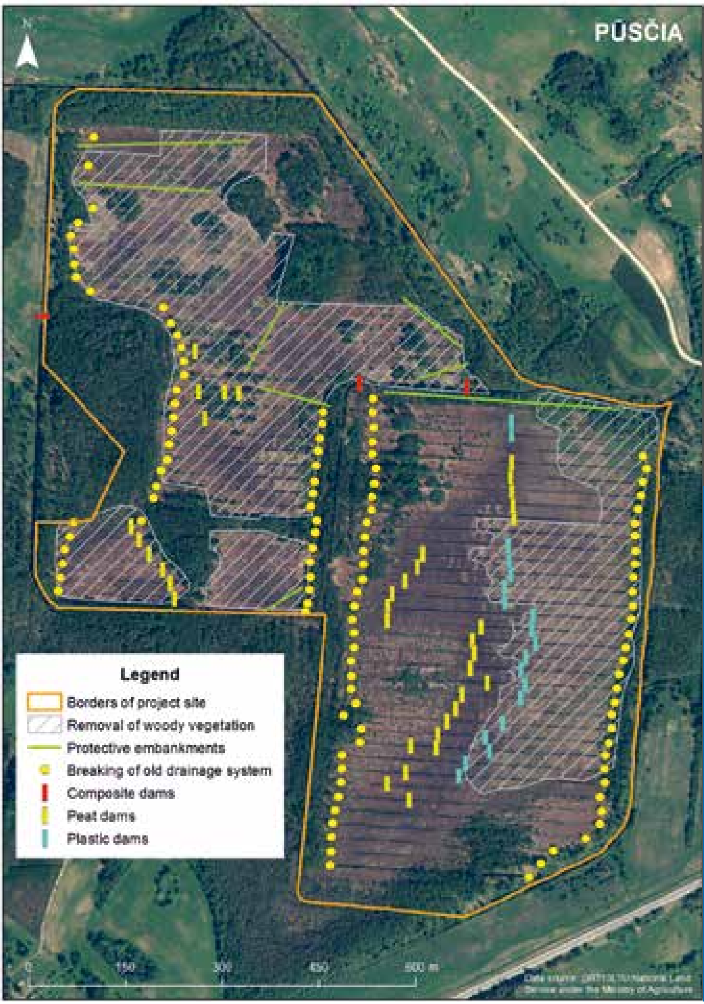


Figure 142. *Locations of dams in the Pūsčia peatland. Map: JTC "Inžinerinis projektavimas", K. Jarmalavičienė, L. Jarašius.*

Before approval of the site management plan, during the planning stage, vegetation monitoring plots and a hydrological monitoring system were already established (in 2017). Monitoring started two years before the implementation of restoration actions. The monitoring system consisted of six water level measurement wells and five vegetation monitoring plots located in a transect which is perpendicular to the main drainage ditch. Vegetation monitoring in permanent plots was carried out every year in August. The water table was automatically measured by loggers, the frequency of water level measurement every three hours. Additionally, 28 peat samples for analysis of the physical and chemical properties were taken (pH, C:N ratio) and peat depth was measured once, during the first monitoring year.

RESTORATION AND MONITORING RESULTS

The management actions in the Pūsčia peatland were implemented from January to March in 2019 restoring the hydrological regime in 81 ha and removing trees and shrubs in 32 hectares.

In 2018 and 2019, special purpose clearings were performed in areas which were not included into the forest land. Tree clearing was performed manually, the timber, mainly young pines and birches and branches were laid into the ditches (Figure 143) to create favorable conditions for the establishment of *Sphagnum* mosses. This was later supplemented by blocking the ditches by dams. The "islands" with bigger trees scattered through the center of the bog were left uncut (Figure 144).

Figure 143. *Timber and logging debris were laid down in the ditches. Voluntary field work camp "Restoration of Pūsčia peatland 2018", dedicated to the celebration of the 100th Anniversary of the Restoration of Lithuania's Independence", 11–12 February 2018. Photos: J. Sendžikaitė.*

Figure 144. *Rewetting effect in the Pūsčia peatland. The "islands" with bigger trees scattered across the bog were left uncut (June 2021). Photo: Ž. Sinkevičius.*

In order to restore favourable hydrological conditions, in 2019, 65 peat dams, 35 plastic pile sheet dams and three composite dams (made from plastic pile sheets and peat) were installed and the old subsurface drainage pipes (more than 100) were broken (Figures 145–149). To break the old drainage pipes the same principle as in the Amalva site was followed.

Figure 145. *Installation of a peat dam in the Pūsčia area. Photo: Ž. Sinkevičius.*

Figure 145. *Installation of a peat dam in the Pūsčia area. Photo: Ž. Sinkevičius.*

Figure 147. *Plastic pile sheet dam. Photo: J. Sendžikaitė.*

Figure 148. *Old asbestos pipes were broken in order to restore water level in the Pūsčia peatland. Photo: J. Sendžikaitė.*

The building of dams was performed by the contracted regional company JSC "Anykščių melioracija". Ditches (0.5–2.0 m width, 1.0–1.6 m depth) were dammed using the local peat in the areas accessible with heavy machinery. For this purpose, an excavator (12 t weight) with widened tracks (up to 80 cm) was used. Before building dams, the place for damming was prepared by removing stumps, vegetation and the top layer of the highly decomposed peat and set aside. The cleaned place was filled in by peat; if possible, it is advised to use wet peat taken from deeper peat layers, as it has a higher water accumulation capability. Peat must be compressed by the excavator bucket while filling up the ditch, thus the built dam will be less permeable. Later, the small (30–40 cm) embankment on the top of the dam was built in order to avoid the outflow of surface water (Zableckis et al. 2017). The schemes of peat dam installation are provided in Figure 150. Plastic pile sheets were installed manually and later reinforced by metal plates (Figures 146, 147).

Figure 149. *The rise of water level was particularly obvious during the spring flood season, March 2019. Photo: Ž. Sinkevičius.*

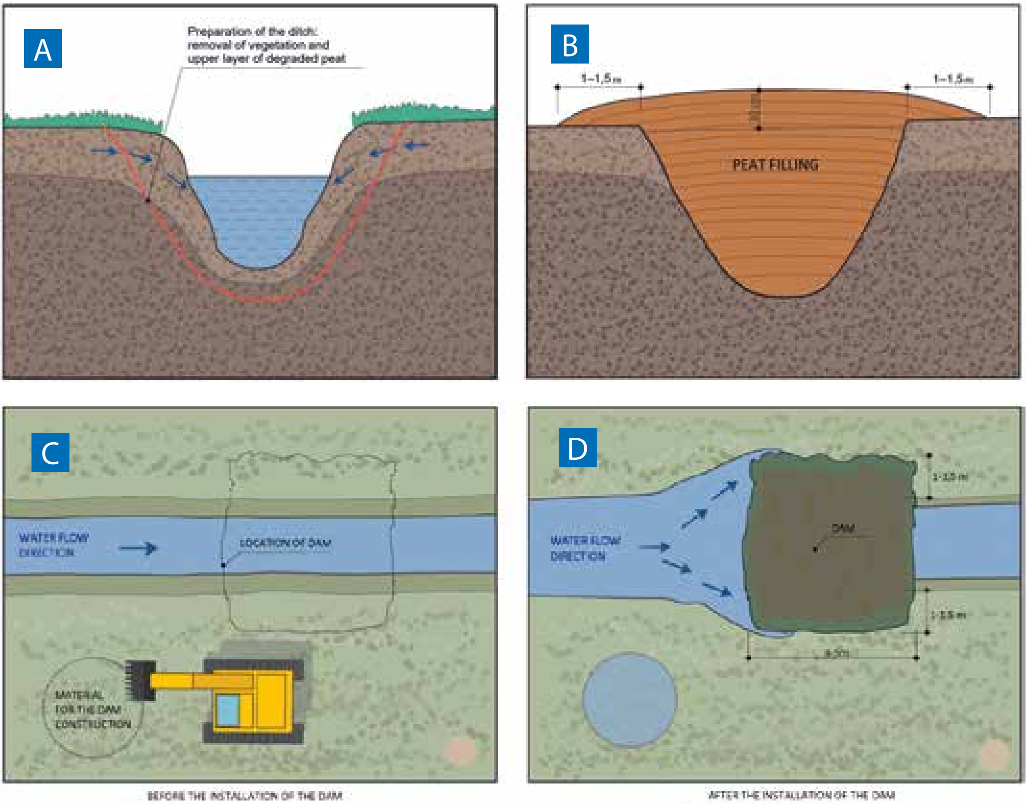


Figure 150. *Scheme of peat dam building. Cross-section of the ditch before (A) and after (B) the installation of the dam. View from above of the ditch before (C) and after (D) the installation of the dam. Source: Zableckis et al. (2017).*

Industrial peat extraction and drainage have caused damage to the bog surface and created significant elevation differences. In addition to dams, eight protective peat embankments reinforced with plastic pile sheets (total length 774 m) were installed. These constructions help to accumulate water in the depressions (Figure 151).

Figure 151. *Protective peat embankments reinforced with plastic pile sheets. Construction process (A) and the installed embankment (B), February 2019. Photos: Ž. Sinkevičius.*

Comparison of vegetation monitoring data obtained in 2018 (before rewetting), 2019 and 2020 (after rewetting) does not show any significant changes in vegetation cover in the monitoring plots after implementation of restoration measures in the Pūsčia peatland (Figure 152). Regeneration of typical peatland vegetation in post-harvested, abandoned peatlands requires more time, especially on bare peat.

Figure 152. *Vegetation dynamics in the permanent monitoring plots (10 × 10 m) on GESTs "Bare peat (moist) (PU-3, PU-4)" and "Wet meadow and forbs (PU-5)" in the Pūsčia peatland, August 2018–2020. Photos: J. Sendžikaitė.*

Management actions have caused a positive effect on water level in Pūsčia. Comparison of 2018 (before rewetting) and 2019–2021 (after rewetting) data shows that after implementation of restoration measures the average water level was 8–23 cm higher in all measurement points (Figures 153, 154). Moreover, in the period from October to December 2019 and 2020 the water level remained very close or above the peat surface in measurement points P4 and P5. However, some parts of the area were wetter than the heavily drained areas, as some restoration measures were implemented in Pūsčia already in 2000.

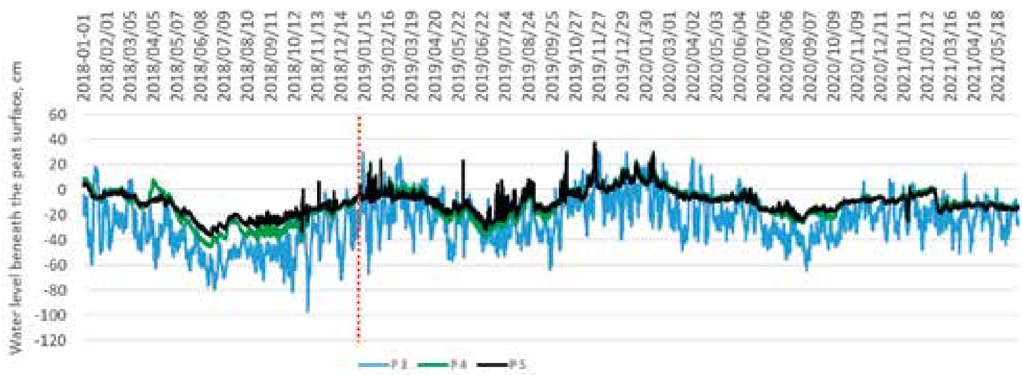


Figure 153. *Water level dynamics in the Pūsčia peatland, in 2018–2021. The red line indicates the period of dam construction.*

Figure 154. *Temporary open water areas that appeared after rewetting are very attractive for various bird species, June 2020. Photo: L. Jarašius.*

Figure 155. *The benefits of rewetting are obvious: a drainage ditch full of water, Pūsčia peatland, June 2021. Photo: J. Sendžikaitė*

CONSTRAINTS AND SOLUTIONS

In the Pūsčia peatland, 30 years of peat extraction and intensive drainage (both open ditches and subsurface pipes) had created a typical post-industrial raised bog landscape that was severely damaged. After the cessation of peat extraction, some piles of peat and tree stumps were left on the site. Artificial elevations were created in the place of the remaining raw peat piles which eventually overgrown with trees and shrubs. Without abolishing the drainage system, re-creating a natural or near-natural hydrological regime favourable for paludification is impossible. Moreover, some of the subsurface drainage pipes were difficult to locate. Thus, preparation of the technical design and restoration action was very challenging. In areas where the peat surface was particularly damaged and uneven, embankments were installed to retain the water. Earlier experience (e.g. Pakalne (ed.) 2008; Pakalne, Strazdiņa (eds.) 2013; Zableckis 2017) shows that peat dams are very reliable constructions for blocking and retaining the water. Still, in Pūsčia, in some cases plastic pile sheets were used either as reinforcement of dams and embankments or as alternatives for peat dams in places, which are hard to access with machinery.

In the Pūsčia peatland, special purpose clearings were performed only in areas that were most promising for restoration success. Trees were not cut at higher elevations, where the effect of restoration may be less noticeable and in the areas where the vegetation was already similar to bog woodland. It was considered that some forest stands will improve the habitat heterogeneity of the restored peatland.

Hydrological monitoring results show a positive effect of dam installation; however, by the middle of 2021, rather sharp water level fluctuations were still evident in the water level measurement points dominated by bare peat. It is expected that these fluctuations may decrease as soon as the bare peat will be replaced by *Sphagnum* dominated peat-forming vegetation. It is likely that the surface temperature on bare peat during the summer days may be very high, which has an unfavourable effect on the recovery of mire vegetation.


Photo: M. Pakalne

4.2.5. Sachara peatland, Lithuania

Photo: Ž. Sinkevičius

Location: Northeastern Lithuania
WGS84 coordinates: 55.943567, 25.493511. https://ieej.lv/peatrestore
Altitude: 113–116 m a.s.l.

Protection status: Sacharos pelkė Natura 2000 site (code LTROK0021)

The total area of the Natura 2000 site: 82 ha

Restoration area: 82 ha

EU importance habitat types in the restoration area:
Degraded raised bogs still capable of natural regeneration (7120), Bog woodland (91D0), Transition mires and quaking bogs (7140).

Implementation:
Lithuanian Fund for Nature (planning, expertise, coordination, nature management supervision);
State Forestry Enterprise (clearing of trees and shrubs);
JTC "Inžinerinis projektavimas" (technical design);
JSC "Anykščių melioracija" (implementation of technical design)

Land manager: State Forestry Enterprise

DESCRIPTION OF SACHARA PEATLAND

The Sachara peatland (82 ha) is a valuable wildlife area in Rokiškis district (Northeastern Lithuania) that is slowly recovering after industrial peat extraction. After cessation of peat extraction, the area was abandoned in 1981. Over several decades, the peatland ecosystem started to recover, although spontaneous regeneration in the whole area was disturbed by a dense network of functioning drainage ditches. Despite a long-term peat extraction and drainage, the peatland maintained some natural values (Figure 156), including three types of habitats of EU importance: Degraded raised bogs still capable of natural regeneration (7120), Bog woodland (91D0*), and Transitional mires and quaking bogs (7140).

Figure 156. *Spontaneous revegetation of old peat-cutting areas can be noticed in some parts of the Sachara peatland. Photo: J. Sendžikaitė.*

WHY WAS THE RESTORATION NEEDED?

Before restoration, despite the diversity of habitats and the gradual recovery of peat-forming vegetation, the Sachara peatland was severely damaged. The total length of open drainage ditches was 37 km, bare peat covered almost 9 hectares. Moreover, a network of functioning drainage pipes was left under the peat surface and contributed to draining the area. This has caused a significant water level decrease – up to 1 m below the peat surface during the dry season.

Rewetting scenario. Restoration actions will ensure more stable hydrological conditions and vegetation shift towards typical raised bog communities dominated by *Sphagnum* lawns with dwarf forms of pines in the central part of the area and transitional mires and moist oligotrophic forests at the edges of peatland.

Non-intervention scenario. Spontaneous revegetation without rewetting measures may not lead to successful recovery of the mire ecosystem because the site is severely damaged by peat extraction and drainage. Wind and water erosion favours bare peat fields if restoration measures are not taken. At the same time, trees will continue to grow the edges of the peatland and may gradually colonise the whole area.

Estimated GHG reduction after rewetting: according to the GEST scenario modelling, after the implementation of restoration GWP emissions should be reduced from 844 to 250 t CO_2-eq/yr.

TARGET VEGETATION AND SPECIES

Typical raised bog plant communities are the target vegetation in the Sachara peatland. Restoration measures may improve the hydrological conditions in the whole area, thus bare peat and dry heath habitats (with birches *Betula* spp. and Scots pine *Pinus sylvestris*) may be gradually replaced by typical active raised bog vegetation with the dominance of *Sphagnum* spp. (*S. magellanicum*, *S. rubellum*, *S. fuscum*, *S. capillifolium*, *S. fallax*), *Rhynchospora alba, Eriophorum vaginatum*, *Vaccinium oxycoccos*, *Empetrum nigrum*, *Andromeda polifolia*, *Drosera* spp. (*D. rotundifolia*, *D. anglica* or *D.* x *obovata*), as well as dwarf forms of *Pinus sylvestris* (Figures 141, 157). Moist bog woodland is expected to develop at the edges of the area. Some patches of the forest surrounding the area are assigned as habitat of the European importance Bog woodland (91D0*) dominated by *Pinus sylvestris, Betula pendula*, *Ledum palustre*, *Chamaedaphne calyculata* (Figure 157), *Vaccinium uliginosum, Andromeda polifolia, Huperzia selago*, as well as *Sphagnum* spp. (*S. angustifolium, S. palustre, S. magellanicum, S. capillifolium, S. fallax*), *Aulacomnium palustre*, *Pleurozium schreberi*.

In some wetter parts of the area, spontaneous revegetation had already taken place. These small areas are usually represented by transitional mire vegetation with *Eriophorum angustifolium, Carex lasiocarpa, C. rostrata* (Figure 157), *Sphagnum cuspidatum, S. fallax*. However, the condition of these habitats is still not favourable, and the implemented restoration actions may improve it. The Sachara area is also important for some animal species such as black grouse *Tetrao tetrix*, European nightjar *Caprimulgus europaeus* and common viper *Vipera berus*.

Figure 157. *Some target plant species in the Sachara peatland: A – Vaccinium oxycoccos; B – Drosera rotundifolia; C – Chamaedaphne calyculata; D – Carex rostrata. Photos: J. Sendžikaitė.*

PREPARATORY WORK

To implement the restoration activities, a whole set of planning procedures was performed:

- The Sachara peatland was included in the list of nationally and internationally protected sites, as part of Nature 2000 network, in 2018. The designation of a protected area is the only way in Lithuania to enable forest clearing for the restoration of biodiversity;
- A site management plan was prepared and approved in 2018;
- A technical design for restoration of the hydrological regime was prepared and approved in 2019 (Figure 158);
- The local forestry management plan of Rokiškis Regional Division of State Forest Enterprise was supplemented with measures needed for restoration of the Sachara peatland and approved in 2019. It enabled forest clearing for biodiversity conservation and special purpose forest clearings.

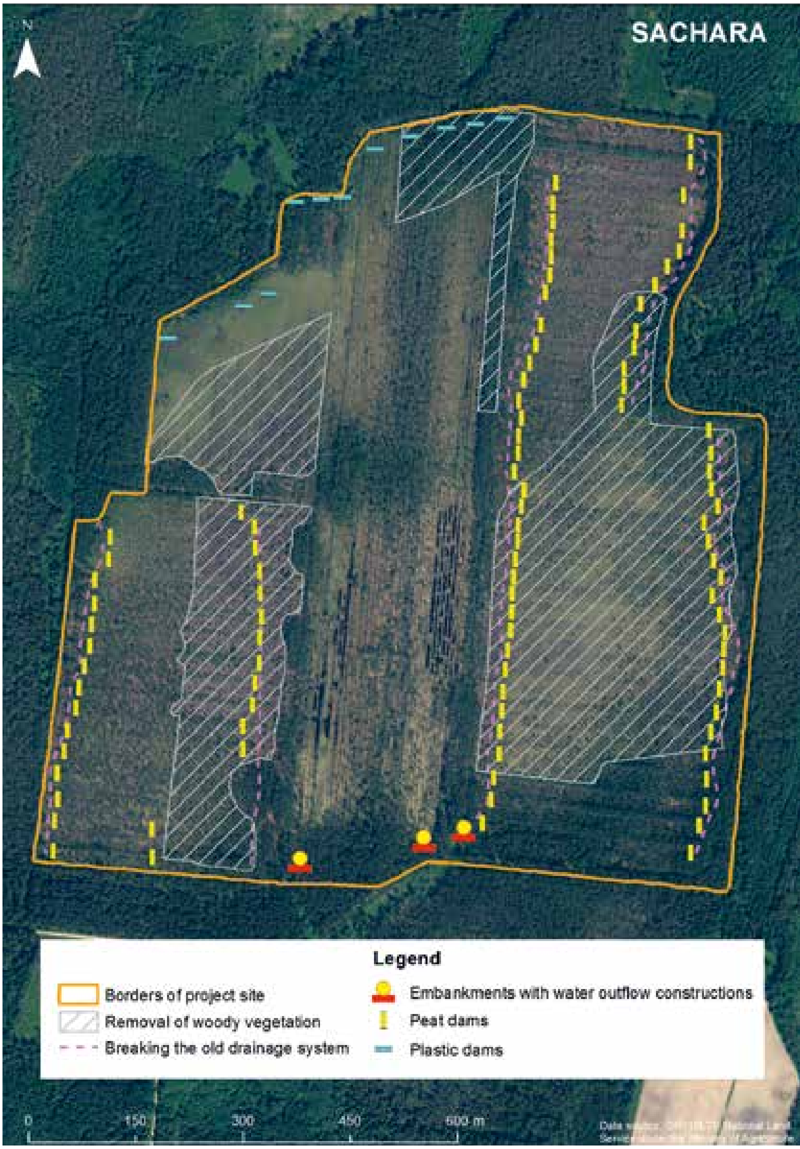


Figure 158. *Location of dams in the Sachara peatland. Map: JTC "Inžinerinis projektavimas", K. Jarmalavičienė, L. Jarašius.*

During the planning stage, vegetation monitoring plots and water level monitoring wells were established. The monitoring system consisted of five water level measurement wells and five vegetation monitoring plots located in a transect perpendicular to the main drainage ditch. The monitoring was started three years before restoration, in 2017. The vegetation monitoring in permanent plots was carried out before (August 2018) and after (August 2020) implementation of restoration actions. The water table was automatically measured by loggers, the frequency of water level measurement was three hours. Additionally, 12 peat samples for analysis of the physical and chemical properties were taken (pH, C:N ratio), and peat depth was measured once, during the first monitoring year.

RESTORATION AND MONITORING RESULTS

The forest covering 30 ha (mainly birches and pines with an admixture of spruce *Picea abies*, established after drainage) was cleared because it caused increased evapotranspiration and thus unfavourably affected the hydrological condition of the peatland (Figures 159, 160). In addition, the special purpose clearings were applied in 4 ha, i.e. in the areas where later the ditches were blocked by dams. Additionally, technological clearings for creation of special "corridors without trees" were performed to ensure accessibility for the machinery to reach dam building locations. In this way, almost 34 ha of forest were cleared. Part of the work (3 ha) was performed by the State Forestry Enterprise. In total 1648 m^3 of timber was cut, out of which 721 m^3 (457 m^3 by the State Forestry Enterprise, and 264 m^3 by the LIFE project subcontractor) were removed from the bog. 264 m^3 of timber were sold as an income for the project. The rest of the timber was laid into the drainage ditches to provide a substrate for the colonisation of *Sphagnum* mosses. The forest clearing was performed mainly manually; harvesters were used only in some drier places.

To improve the hydrological condition, three embankments with water outflow constructions and 100 dams of various types (peat dams, plastic pile sheet dams, mixed constructions made of peat and plastic pile sheets) were installed. In the areas accessible with heavy machinery, the ditches (0.5–2.0 m width, 1.0–1.6 m depth) were blocked using the local peat. At the same time, subsurface drainage pipes were broken at the edges of the restoration area (Figure 161). For this purpose, an excavator (12 tons weight) with widened (up to 80 cm) tracks was used. In particularly wet and

Figure 159. *Sachara petland before (left) and after (right) restoration. Photos: Ž. Sinkevičius.*

difficult to access places, plastic pile sheet dams were installed (Figure 162). The width of these dams varied from 4 to 16 metres. In addition, three special embankments supported by water outflow constructions were built at the edges of collective ditches (Figure 163). For the dam instalment and breaking the old drainage system, the same technique as in Pūsčia and Amalva was applied.

Figure 160. *Tree cutting was performed manually in a large part of the Sachara peatland, March 2020. Photo: Ž. Sinkevičius.*

Figure 161. *A peat dam located at the place where the old drainage pipe was broken, March 2020. Photo: L. Jarašius.*

Figure 162. *Plastic pile sheet dams were installed in particularly wet and difficult to access places, March 2020. Photo: J. Sendžikaitė.*

Figure 163. *Installation of water outflow embankment (A) with a water outflow construction (B) in Sachara peatland, March 2020. Photo: L. Jarašius.*

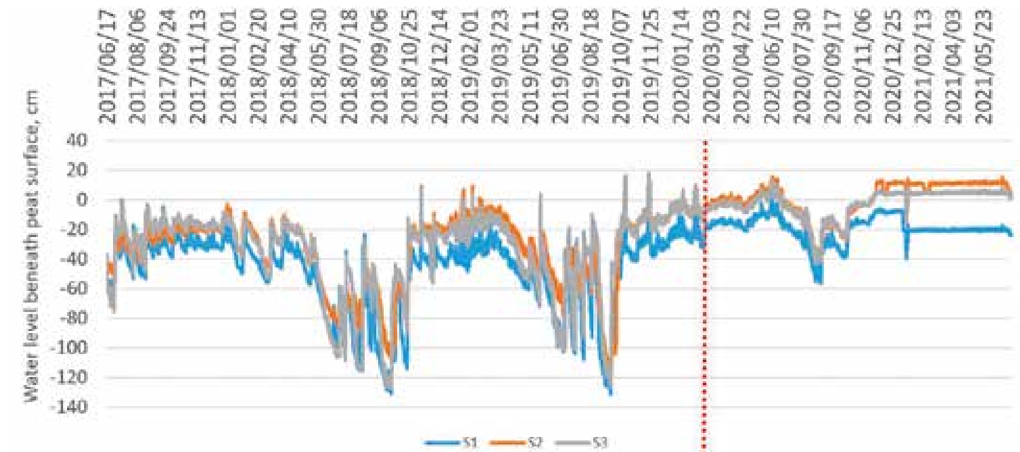


Figure 164. *Water level dynamics in Sachara peatland. The red line indicates the time of dam construction.*

Hydrological monitoring shows a positive effect of implemented restoration actions – installation of dams combined with tree removal. The average water level in 2020 (after rewetting) increased in all measurement points by 12–40 cm, compared to the period of 2018–2019 (before rewetting). Moreover, a decrease in water level fluctuations was noticed in all measurement points during 2020 (Figure 164). In some piezometers (S1, S2, S3), the difference between the maximum and minimum water levels (amplitude) decreased more than twice, which indicates the peatland's capacity to retain water even in the dry season. The highest water level was recorded in piezometer S2 characterized by the GEST "Moist forests and shrubberies" (Figures 165-167).

Figure 165. *The rise of water level was noticed soon after the implementation of restoration measures (March 2020) and even during the active vegetation period, July 2021. Photos: J. Sendžikaitė.*

Figure 166. *Hydrological monitoring shows positive effects of the restoration measures, July 2021. Photo: J. Sendžikaitė.*

Figure 167. *High water level was observed in the monitoring wells even in the middle of July 2021. Photo: J. Sendžikaitė.*

CONSTRAINTS AND SOLUTIONS

Several difficulties had to be overcome, and the solutions found:

- Most degraded peatlands in Lithuania occur on forest land, therefore any management actions in such an area must be aligned with the National Forestry Law. Removal of woody vegetation must strictly follow the national forest clearing regulations, therefore granting a legal protection status for the site, as in the case of Sachara, is the only possibility to obtain the necessary permissions for peatland restoration actions, e.g. enabling tree removal, which must be foreseen in the nature management plan and then accordingly set up in the forestry management plan.
- The biggest challenge was to locate the subsurface drainage pipes since the detailed plans of the old drainage system either are missing or are not documented at all. Before building the dams, it was very important to dismantle the old subsurface drainage system (ceramic pipes). The excavator should search the subsurface pipes beneath and break them. The same approach was used in Pūsčia and Amalva peatlands.

Photo: J. Sendžikaitė

4.2.6. Aukštumala peatland, Lithuania

Photo: E. Lukošius

Location: Western Lithuania
WGS84 coordinates: 55.3910816, 21.4314279. https://ieej.lv/peatrestore
Altitude: 1–3 m a.s.l.

Protection status: Nemunas Delta Regional Park, Natura 2000 site (LTSLUB001, LTSIU0013), Ramsar site No. 629

The total area of the regional park: 29 112 ha
Total area of Aukštumala peatland: 3 018 ha

Restoration area: 10 ha

EU importance habitat types in the restoration area: none

Implementation: Lithuanian Fund for Nature (planning, expertise),
JTC "J. Jonyno ecofirma" (technical design),
JSC "Klasmann-Deilmann Šilutė" (preparation of the field)

Land manager: State, rented by JSC "Klasmann-Deilmann Šilutė"

DESCRIPTION OF AUKŠTUMALA PEATLAND

Aukštumala raised bog (3018 ha) is located in Nemunas Delta Regional Park, in the Western Lithuania. Peat harvesting in Aukštumala peatbog started at the end of the 19th century when a peat litter factory was built in the north-eastern part of the bog. At the end of the 1960s, a dense drainage network was created, access roads, water pumping stations and protective dams were built, which altered two thirds of the peatland area, subsequently designated for industrial peat harvesting. The peat harvesting area covers 1670 ha, while 1285 ha of the former pristine peatland has been protected as a telmological reserve since 1996.

The LIFE Peat Restore project site (10 ha) is located at the nort-eastern margin of the peat harvesting fields still in operation (Figure 168). Peat harvesting in the LIFE Peat Restore project site was completed almost 20 years ago, as the peat deposits are almost depleted. The residual peat layer varied from 0.05 to 2.25 metres. Before restoration, the site had unfavourable hydrological conditions (deep drainage), increased decomposition of the upper peat layer and vegetation typical for heavily drained bogs. In addition, there was an increased risk of fire incidents during the dry seasons.

Figure 168. *The experimental field for the reintroduction of Sphagnum and other peat-forming vegetation in Aukštumala peatland, 2020. Photo: N. Zableckis.*

WHY WAS THE RESTORATION NEEDED?

The purpose of restoration in the Aukštumala site was to demonstrate a new attitude on how to start reclamation in post-harvested parts of peatland while mining is ongoing in other sections. Another reason to implement the restoration actions in Aukštumala was to establish and demonstrate a new reclamation and after-use practice, as since the early 1990s in none of the peat mining areas in Lithuania the peat extraction has ceased and thus new sustainable solutions are needed. In addition, Aukštumala mire is an outstanding peatland with a historical significance in peatland science, therefore it may serve as a lighthouse for other peat extraction companies in Lithuania.

The restoration and demonstration site at the eastern edge of the Aukštumala mire had been drained and peat harvested for a long time, since the 19th century. It was suffering from heavy drainage and peat extraction impact that could not be prevented without active intervention.

Rewetting scenario. Peat moss lawns dominated by *Sphagnum* species (e.g. *S. magellanicum*, *S. fuscum*, *S. rubellum*) are expected to grow in the experimental field that was specially prepared and designed for the establishment of raised bog vegetation.

Non-intervention scenario. In a case if no restoration measures were taken, bare peat surfaces would be gradually replaced by shrubs and reedbeds, the heavily drained peatland would continuously deteriorate and be a source of large GHG emissions in the long term.

Estimated GHG reduction after rewetting: based on the GEST scenario modelling, after restoration GWP emissions should be reduced from 74 to 33 t CO_2-eq/yr.

TARGET VEGETATION AND SPECIES

The aim of restoration in the post-harvested peatland was to establish near-natural bog vegetation, mainly dominated by *Sphagnum* species. The biomass of *Sphagnum* and other mires plant species grown in this way can be used as a donor material in the future to restore heavily damaged peatlands and/or to restore exploited peatlands. This may help to prevent potential damage of vegetation cover in natural or near-natural habitats. When the need arises, it is not only easy to collect the donor material by hand or by machinery in the experimental field, but also to properly prepare it for transportation to the target restoration areas. This is especially relevant for countries where it is problematic to collect the donor material for restoration of damaged peatlands.

Before restoration the Aukštumala site was mostly characterized by bare peat surfaces and reed beds spontaneously established after cessation of peat extraction. In addition, significant water level fluctuations (> 1 m) during the dry and wet periods were observed. Therefore, in order to mitigate the GHG emissions and encourage recovery of the lost ecosystem services it is crucial to restore a functioning peatland ecosystem. The residual 0.05 to 2.25 m thick peat layer was mixed containing both bog and fen peat, in some parts dominated by acidic bog peat. It is expected that the bare acidic, nutrient poor peat surfaces may be gradually replaced by typical raised bog species such as *Sphagnum* spp. (*S. magellanicum*, *S. fuscum*, *S. rubellum*, *S. capillifolium*, *S. fallax*) (Figure 169), *Aulacomnium palustre*, *Rhynchospora alba*, *Eriophorum vaginatum*, *Vaccinium oxycoccos*, *Empetrum nigrum*, *Andromeda polifolia*, *Drosera* spp.

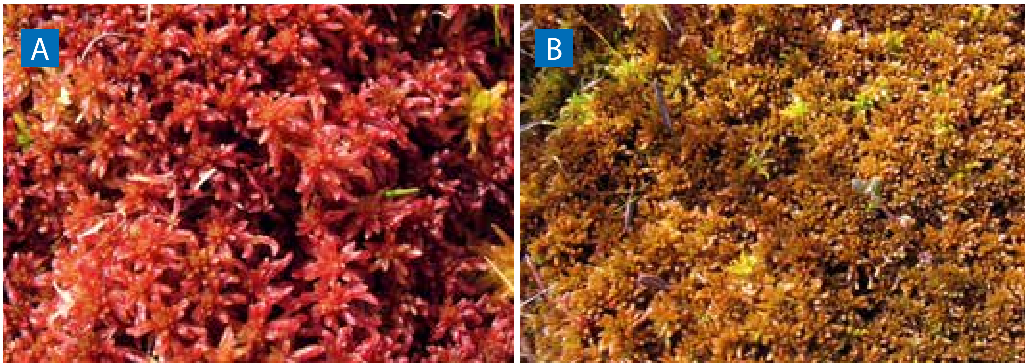


Figure 169. *The target Sphagnum species for the re-creation of vegetation cover in post-harvested peatlands: A – Sphagnum rubellum; B – Sphagnum fuscum. Photos: S. Sprainaitytė.*

PREPARATORY WORK

The first knowledge on the site was gathered before the LIFE Peat Restore project was launched, when the scientists from the Nature Research Centre (Vilnius) carried out the first small-scale *Sphagnum* reintroduction experiment in 2011 (Sendžikaitė et al. 2013; Jarašius 2015). However, due to unfavourable hydrological conditions at the experimental site (the depth of the water table varied between -45 and -82 cm during the growing season and more than 1 m during the year) and severe droughts, this experiment was not successful.

The technical design for the establishment of a new *Sphagnum* reintroduction experimental site was subcontracted by the initiative of the project LIFE Peat Restore. This included measurements of site elevation, analyses of peat and irrigation water properties, infiltration capacities and hydrological regime, as well as analyses of the possibilities to ensure adequate water levels in the peat fields for the reintroduction of *Sphagnum* and other mire species. The Lithuanian Geological Survey was informed about ongoing LIFE project actions, nevertheless the site was not excluded from the mining licence.

In order to gain more knowledge about growing of *Sphagnum*, the project team visited *Sphagnum* cultivation sites in Germany (Hankhousen Moor, managed by the University of Greifswald; Ruhler Moss, managed by company Klasmann-Deilmann), participated in seminars and consulted with experts from University of Greifswald and Greifswald Mire Centre (Germany) and scientists from the Nature Research Centre (Lithuania) who had conducted the first *Sphagnum* cultivation experiments in the Aukštumala bog in 2011.

To monitor the hydrological condition, 12 wells were installed to measure the water level, providing very accurate data on the hydrology of the experimental *Sphagnum* cultivation area.

Six peat samples for analysis of the physical and chemical properties were taken (pH, C:N ratio) and peat depth was measured once, during the first monitoring year. Chemical analysis of peat showed that the site was mostly characterized by acidic oligotrophic, i.e. very poor conditions, as the pH values varied from 3.11 to 4.62 (5.31 in exceptional cases), and C:N ratio varied from 24.8 to 31.4. These conditions were suitable for the establishment of *Sphagnum* dominated communities.

RESTORATION AND MONITORING RESULTS

The restoration actions were agreed with the peat extraction company operating in Aukštumala. The technical measures included reshaping of the site, installing irrigation systems (Figures 168, 170, 171A), setting water sources and supply, providing electric power, constructing the embankments, spreading diaspores of *Sphagnum* and other peat-forming vegetation, and maintenance of the field. The experimental area covering 2 ha was divided into two parts (1 ha in size each), irrigated by ditches installed at every 10 metres. Therefore, the area was levelled and the embankments installed (Figure 168).

For water supply, a water reservoir has been excavated to the south from the experimental field for storing rain and snowmelt water. In addition, an alternative source of water supply was provided from the collective ditch to the east from the restoration area. Due to the absence of electricity in the restoration area, a solar panel with accumulated electricity storage was installed to power the electric water pumps. They must ensure a constant optimal water level (close to the peat surface) in the fields where *Sphagnum* and other mire species were reintroduced.

Automatic electric pumps (maintained by solar panels) provide water from the reservoirs to *Sphagnum* fields to ensure constant optimal water level. Water is supplied via pipes; overflow for

Figure 170.
Preparation of the peat surface for spreading of donor vegetation in Aukštumala Peatland (Lithuania), August 2019.
Photos: J. Sendžikaitė.

excessive water is installed to the east from the experimental field. The surplus of water flows through the irrigation pipes. Generally, the diameter of the pipes depends on the size of the catchment area. In the Aukštumala restoration area, 300 mm pipes were used. The restoration area neighboursed with active peat extraction fields, therefore keeping a favourable water level during the whole year is the biggest challenge. Optimal water level depth during the vegetation season is the main factor to ensure survival and further development of donor fragments of raised bog plant cover in post-harvested peatlands.

Sphagnum reintroduction was performed by volunteers during a two-day work camp in September 2019. *Sphagnum* mosses and fragments of other peat forming plants (the volume of the donor material was ca. 120 m^3) were collected by hand from old peat excavation pits, as well as from damaged peat fields, where peat extraction will take place (Figure 171B). Spreading of donor material was performed both manually (Figure 171C) and using a slightly modified one-disc fertilizer spreader (Figure 171D). Attached to the mini-tractor and serviced by two people, it spread mosses corresponding to the spreading speed of 5–6 people. Due to high winds during the spreading, it was impossible to mulch *Sphagnum* by straw immediately in all the area. Therefore, *Sphagnum* and mulch were pressed by a wide-wheel tractor. Some days later, the whole experimental field was covered by straw (Figure 171E, 171F) for improving favourable microclimate (higher relative humidity, stabler temperatures) for reintroduced plants and irrigated by water from the water storage reservoir.

Figure 171. *Reintroduction of peat-forming vegetation on peat fields in Aukštumala peatland, Lithuania: A – levelling of peat surface (April 2019), B – collection of donor material; (C) manual and (D) mechanized application of the donor material; E – straw mulching; F – flooded field covered with straw mulch (September 2019). Photos: J. Sendžikaitė, L. Šveistytė, Klasmann-Deilmann Šilutė.*

Hydrological data obtained in the 2018–2020 show that after implementation of restoration actions (re-shaping experimental site, planting of donor material and irrigation) the water level fluctuations have decreased significantly. Thus, the hydrological conditions for peat-forming vegetation became more favourable. Nevertheless, during the dry vegetation period of 2020, the water level decreased indicating that the maintenance of hydrological conditions in the Aukštumala experimental field should be improved (Figure 172).

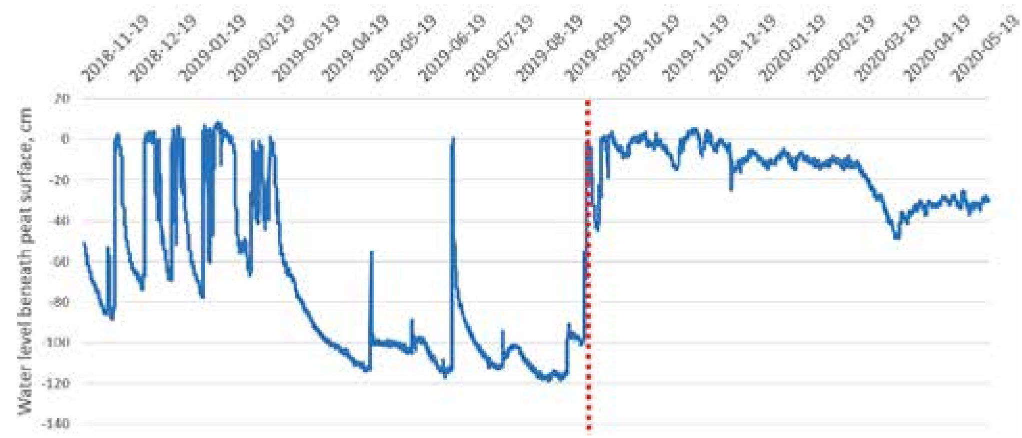


Figure 172. *Water level fluctuation in Aukštumala site from November 2018/11 to June 2021. Red vertical line indicates the time of flooding the experimental field after the reintroduction of peat-forming vegetation.*

CONSTRAINTS AND SOLUTIONS

The Aukštumala peatland is a typical mining site in the Baltic countries when peat extraction started from the lagg and continued towards the centre of the peatland. It means that when the extraction is finalised on the peatland margins, such areas have direct contact with the ongoing peat mining and drainage. These circumstances create complex problems for the restoration of such sites, mainly due to intensive drainage. In Aukštumala case, the site was the "hostage" of peat mining on one side and polder reclamation system on the other side, which caused difficulties to find a solution on how to accumulate water. In addition, an independent electricity source was needed to run water pumps to ensure constant water supply. Large efforts were invested in reshaping the site, installing a water reservoir and irrigation system, providing electric power and maintenance of the field.

The reintroduction of peat-forming vegetation is a promising approach for restoring post-harvested peatlands. At the same time, it is a costly and time-consuming technique, which requires a lot of studies and preparatory work: precise planning and site preparation, assurance of water supply, assessment of the surrounding sites, especially if the restoration site is located close to active peat extraction fields. Therefore, before deciding to reintroduce peat-forming vegetation it is crucial to carry out comprehensive studies on the site hydrology, peat properties and peat layer depth. Also, a pre-assessment of the need for further regular maintenance has to be performed. It should also be taken into consideration that a relatively stable water level must be ensured before the reintroduction of peat-forming vegetation. The need for a functioning irrigation system has been proven during the dry vegetation seasons of 2019, 2020 and 2021. Experience from other countries shows that reintroduction of peat-forming vegetation in post-harvested peatlands is possible, however, optimal hydrological regime and further maintenance must be ensured.

Conclusions

1. The LIFE Peat Restore project actions helped to restore at least 5300 ha of peatlands in five European countries (Estonia, Latvia, Lithuania, Poland, Germany). The LIFE Peat Restore GHG assessment based on the GEST approach shows that rewetting and other actions aimed at improving the peatland functions will reduce the global warming potential by 9889 t CO_2 -eq/yr.

2. The experience of the LIFE Peat Restore project re-confirms the well-known fact that restoring deteriorated peatland ecosystems is a challenging task. It is far more complicated to restore a degraded peatland than preserving it as a functioning natural system that provides multiple ecosystem services including a significant contribution to sequestration of GHGs.

3. The project areas included different peatland types and degrees of degradation. The solutions and approaches to achieve the best result are site-dependent. Although, due to the severe degradation in the past, it was not always possible to completely prevent the drainage and peat extraction effects, the preliminary monitoring results suggest that the restoration measures may lead to considerable improvements in all restoration areas. However, full recovery of functioning peatland ecosystems may take decades. In some cases, blocking of ditches has brought immediate and very promising results. Thus, the LIFE Peat Restore actions were contributing to reducing the GHG emissions, mitigation of climate change and conservation of biodiversity. To confirm the success of the project actions, the monitoring in all areas should be continued.

4. Thorough pre-restoration inventories, as a basis for the development of site management plans and technical designs, are highly important to achieve the desired results. This included proper understanding of the peatland functioning in each individual case, the interactions at landscape level and providing alternative solutions.

5. The project included both well-known techniques that have already proved their efficiency (e.g. peat dams, plastic sheet piling dams, composite dams and similar constructions), less-tested (e.g. reintroduction peat-forming vegetation on bare peat, large scale tree removal, placement of small size timber and branches into ditches, long peat dikes) and innovative solutions (designing and installing floating artificial islands with peat-forming vegetation in post-harvested water basins). The lessons learned, although some of them site-specific, including the preparation and planning stage, techniques and solutions for various challenges may be applicable in other peatland restoration projects elsewhere.

6. Restoration techniques used in the project were aimed at preventing the negative impact of artificial drainage. However, post-harvested and heavily damaged peatlands undergo a long-term succession period before the establishment of favourable conditions for water retention, peat formation, carbon sequestration and providing other ecosystem services. Changing climate

may cause higher temperatures, less precipitation that will further disturb recovery of the (near) natural hydrological regime and ecological conditions, especially in raised bogs, which depend upon precipitation. Also, it has an effect on the desired reduction of greenhouse gases.

7. Parallel to planning the peatland restoration measures, it is highly important to involve the stakeholders (local communities, authorities), as lack of information or misunderstandings may lead to significant delays in the implementation. Sometimes it may even cause serious risks for the implementation or full implementation (e.g. wide scale tree removal before rewetting in Lithuania). The public involvement and dissemination of information must always be done timely, with a time reserve.

8. It is highly important to understand all potential legal and administrative constraints and solutions already at the planning stage. Regular communication with the relevant authorities and landowners or managers is among the key issues in successful peatland restoration.

Photo: M. Pakalne

Recommendations

1. Peatland restoration projects always require time, as not only administrative and technical solutions have to be found, but also the restoration success in a natural system, which usually reacts with a time lag, needs to be observed. For baseline surveys, set up of monitoring systems, technical planning, approval and tendering procedures and the restoration actions sufficient time buffers must be devoted, especially for monitoring the effects of the restoration. On many unforeseen incidents must be reacted: (a) legal and public administrative obstacles (e.g. detection of protected species requiring adapted restoration planning, acquiring landowner agreements or land purchase, archaeological findings during restoration causing delay, administrations not being familiar with the project aims and their justification); (b) finding specialised companies for technical implementation (e.g. greenhouse gas measurements, restoration actions) that are capable of giving realistic offers considering site requirements and meeting timelines; (c) weather conditions ("too wet" conditions, "too mild" or "too cold" winters challenging restoration techniques, "too dry" conditions threatening rewetting and restoration efforts). According to the LIFE Peat Restore experience, it is recommended to have longer project durations than five years to properly assess the restoration process, to summarise and share the experience and to plan the actions after the end of the LIFE project.

2. Prior to restoring the hydrological regime of the peatland, it is very important to carry out a comprehensive inventory and planning. Usually, such details are not available in the site management plans and must be specified in the following detailed planning work stage. According to the LIFE Peat Restore experience and earlier experience, hydrological modelling or digital terrain models are tools that help to determine the potential changes, the potential restoration effect and the most appropriate locations of dams or other constructions (several alternatives may be included in the model). Where the digital terrain models are not available, data obtained by LiDaR laser scanners can be used to create the model before rewetting, especially in large areas; in smaller areas also land-based levelling tools can be applied.

3. During the planning stage, nature conservation conflicts may arise and solutions must be found. That may be illustrated by the Estonian LIFE Peat Restore area where the conflict arose between fish protection and rewetting the peatland, as two of the ditches were designated as protected spawning streams for salmon and trout. Blocking such streams was prohibited, while restoring degraded peatlands was considered a national priority. This particular case shows that various stakeholders, including nature conservation experts, do not always communicate with each other sufficiently. Therefore, it is highly important to timely seek information from different institutions about their plans regarding the site selected for restoration.

4. In peatland restoration projects, it is highly important to involve a qualified, experienced personnel in all relevant fields during the site surveys, restoration planning and designing the actions. It is often not enough with having an approved site management plan, as they are often

too general (e.g. in Estonia). To include all necessary details of a specific project, the restoration objectives, specific restoration areas and actions must be planned either within a special restoration plan, or during the preparation of the technical design, as it was practised also by the LIFE Peat Restore project teams.

5. The planning stage must be always well integrated with the monitoring of restoration success. In peatland restoration projects, monitoring of water levels and vegetation as a primary indicator of ecosystem changes are priorities. However, in many cases, monitoring of other parameters (e.g. water and soil chemistry) and biodiversity elements are highly important. To get more information about the hydrology of the site it is recommended to establish a hydrological monitoring network that provides valuable data on the water level before restoration and its dynamics after rewetting. Monitoring of water level and vegetation must be comprehensive and planned in a way that the data can be later inter-correlated, i.e. the changes in water level resulting from rewetting can be interpreted taking into account the vegetation shift.

6. Depending on the peatland site, the degree of human impact and degradation severity, the first results can be observed immediately after restoration. This may also last longer, especially in heavily degraded post-harvested peatland where it is particularly difficult to rise and maintain the water level, i.e. stabilise the water level fluctuations. Short-term changes indicate the trend of how the peatland may change after restoration, but long-term changes are very valuable to observe and assess the ecosystem recovery. Therefore, it is highly recommended to continue the monitoring after the end of the restoration project, also in order to intervene in case the restoration success is threatened.

7. The location of dams on the drainage ditches should be chosen not only considering the slope inclination or water flow direction in peatlands, but also pragmatically assessing the accessibility options and possibilities to transport materials for dam construction. Dam width, height and stability should be planned in a manner to prevent damage of the dams by the water flowing along the ditch or around it. Based on these studies and plans, the technical design or technical documentation is developed providing all the necessary information about location and type of dams or other constructions.

8. Different management approaches for peatland restoration may be applied for the forest stands established on drained peatlands. In some areas, the trees may be removed, while in some areas they may be left to fall down and decay as the water level rises. It is always a tradeoff of ecological necessity and economic feasibility, therefore no general recommendation can be given on peatland forest management. However, other aspects than GHG emission must be considered when selecting the management strategy, particularly the emotional aspect of the local community or the general public. Also, the economical perspective, especially in hardly accessible sites, when the timber harvesting is not profitable and doubtful from the ecological point of view, may not be of minor importance.

9. Awareness is rising, especially in the nearest surroundings of the restoration sites, and early stakeholder involvement is of utmost importance for successful project implementation. Timely

involvement of stakeholders and local communities may later prevent significant risks and delays in implementation.

10. Rewetting of all drained peatlands is not a CAN but a MUST, as we have to meet the goal of the Paris Agreement, carbon neutrality by 2050. Restoring peatlands significantly contributes to mitigating global warming. For achieving this, there is an urgent need for rapid action on a wide scale. There is no more time for more considerations, more research and more discussion on the need and importance to do so. In case of any further delay, climate change may diminish or destroy the restoration potential, thus making the overall goal impossible to achieve.


Photo: M. Pakalne

References

Adhikari A., Shah R., Baral S., Khanal R. 2011. Terminologies used in climate change. Kathmandu, Nepal, IUCN.

Ābelīte G. (ed.) 2019. Dabas lieguma "Baltezera purvs" dabas aizsardzības plāns. Latvijas Universitāte, Rīga.

Beike A. K., Spagnuolo V., Lüth V., Steinhart F., Gómez J.-R., Krebs M., Adamo P., Asensio, A. I. R., Ferndández J. A., Giordano S., Decker E. L., Reski R. 2014. Clonal in vitro propagation of peat mosses (*Sphagnum* L.) as novel green resources for basic and applied research. Plant Cell, Tissue and Organ Culture 11 (3), 1037–1049.

Beyer C., Höper H. 2015. Greenhouse gas exchange of rewetted bog peat extraction sites and a *Sphagnum* cultivation site in northwest Germany, Biogeosciences 12, 2101–2117, https://doi.org/10.5194/bg-12-2101-2015.

Blanka L. (ed.) 2011. Dabas parks "Engures ezers". Dabas aizsardzības plāns (2011–2025). Eiroprojekts, Rīga, 132 p.

Blievernicht A., Irrgang S., Zander M., Ulrichs C. 2013. *Sphagnum* biomass – the next generation of growing media. Peatlands International 1, 32–35.

Brust K., Krebs M., Wahren A., Gaudig G., Joosten H. 2018. The water balance of a Sphagnum farming site in north-west Germany. Mires and Peat, 20(10), 1–12, doi: 10.19189/ MaP.2017.OMB.301.

Bugnon J.-L., Rochefort L., Price J. S. 1997. Field experiment of *Sphagnum* reintroduction on a dry abandoned peatland in Eastern Canada. Wetlands 17(4), 513–517.

Caporn S. J. M., Rosenburgh A. E., Keightley A. T., Hinde S. L., Riggs J. L., Buckler M., Wright N. A. 2017. *Sphagnum* restoration on degraded blanket and raised bogs in the UK using micropropagated source material: a review of progress. Mires and Peat 20, 1–17.

Copernicus. Copernicus Open Access Hub. Web interface for open access to satellite Sentinel-1, Sentinel-2, Sentinel-3 and Sentinel-5P user products, https://scihub.copernicus.eu/

Couwenberg J., Augustin J., Michaelis D., Joosten H. 2008. Emission reductions from rewetting of peatlands. Towards a field guide for the assessment of greenhouse gas emissions from Central European peatlands. Duene Greifswald/RSPB Sandy, 28 p.

Couwenberg J., Thiele A., Tanneberger F., Augustin J., Bärisch S., Dubovik D., Liashchynskaya N., Michaelis D., Minke M., Skuratovich A., Joosten H. 2011. Assessing greenhouse gas emissions from peatlands using vegetation as a proxy. Hydrobiologia 674, 67–89.

Couwenberg J. 2011. Vegetation as a proxy for greenhouse gas fluxes – the GEST approach. In: Tanneberger F. & Wichtmann W. (eds.) Carbon credits from peatland rewetting, Schweizerbart, Stuttgart, 37–42.

Dēliņa A., Ģederts P. 2013. Hydrological Research in Melnais Lake Mire, Rožu Mire, Aklais Mire and Aizkraukle Mire and Forests. In: Pakalne M., Strazdiņa L. (eds.) Raised Bog Management for Biological Diversity Conservation in Latvia. Hansa Print Riga, Rīga, pp. 108–124.

Dunnicliff J. 1993. Geotechnical Instrumentation for Monitoring Field Performance. Wiley-Interscience, pp. 117.

EEA 2010. EU 2010 Biodiversity Baseline. European Environment Agency, https://www.eea.europa.eu/publications/eu-2010-biodiversity-baseline.

EEA 2017. European Environment Agency – Glossary, based on: IPCC Third Assessment Report, 2001, https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Carbon_dioxide_equivalent.

FAO 2020. Peatlands mapping and monitoring – Recommendations and technical overview. FAO, Rome, https://doi.org/10.4060/ca8200en.

Gaudig G., Fengler F., Krebs M., Prager A., Schulz J., Wichmann S. et al. 2014. *Sphagnum* farming in Germany – a review of progress. Mires and Peat 13 (8), 1–11.

Gaudig G., Krebs M., Prager A., Wichmann S., Barney M., Caporn S. J. M. et al. 2018. *Sphagnum* farming from species selection to the production of growing media: a review. Mires and Peat 20 (13), 1–30.

Harbaugh A. W. 2005. MODFLOW-2005 – the U. S. Geological Survey modular ground-water model – the Ground-Water Flow Process, U.S. Geological Survey Techniques and Methods 6-A16.

Hájek M., Horsák M., Hájková P., Dítě D. 2006. Habitat diversity of central European fens in relation to environmental gradients and an effort to standardise fen terminology in ecological studies. Perspectives in Plant Ecology Evolution and Systematics 8, 97–114.

Headley T. R., Tanner C. C. 2006. Application of floating wetlands for enhanced stormwater treatment: A review. NIWA Project: ARC06231. National Institute of Water & Atmospheric Research Ltd, Hamilton.

Hoshi Y. 2017. *Sphagnum* growth in floating cultures: Effect of planting design. Mires and Peat 20 (8), 1–10.

HUA (Humboldt University Peatland Archive). 1953–1972. Scientific Collections at Humboldt-University. Faculty of Life Sciences, Albrecht Daniel Thaer-Institute of Agricultural and Horticultural Sciences, Berlin.

Ilomets M. 2017. Estonia. In: H. Joosten, F. Tanneberger & A. Moen (Eds.) Mires and peatlands of Europe. Status, distribution and conservation. Schweizerbart Science Publishers, Stuttgart, pp. 360–371.

IUCN 2021. Peatlands and climate change. International Union for Conservation of Nature, https://www.iucn.org/resources/issues-briefs/peatlands-and-climate-change.

Jarašius L. 2015. Aukštapelkių augalų bendrijų ekologinio atkūrimo galimybės degradavusioje Aukštumalos pelkės dalyje ir išeksploatuotame durpyne. Daktaro disertacija. Vilniaus Universitetas, Vilnius.

Joabsson A., Christensen T. R., B. Walle´n B. 1999. Vascular plant controls on methane emissions from northern peatforming wetlands. Trends in Ecology and Evolution 14, 385–388.

Joosten H. 2021. Annexes to STRP24 Doc. 3.1.3 (C): Draft Ramsar Technical Report on Global Guidelines for Peatland Rewetting and Restoration. The Convention on Wetlands, 24th Meeting of the Scientific and Technical Review Panel Virtual meeting, 29 April 2021.

Joosten H., Tanneberger F., Moen A. (eds.) 2017. Mires and peatlands of Europe. Status, distribution and conservation. Schweizerbart Science Publishers, Stuttgart.

Joosten H., Clarke D. 2002. Wise use of mires and peatlands. Background and principles including a framework for decision-making. Saarrijärvi, http://www.imcg.net/media/download_gallery/books/wump_wise_use_of_mires_and_peatlands_book.pdf.

Karofeld E., Müür M., Vellak K. 2016. Factors affecting re-vegetation dynamics of experimentally restored extracted peatland in Estonia. Environmental Science and Pollution Research, 23, 13706–13717, doi: 10.1007/ s11356-015-5396-4.

Koska I., Succow M., Clausnitzer U., Timmermann T., Roth S. 2001. Vegetationskundliche Kennzeichnung von Mooren (topische Betrachtung). In Succow M., Joosten H. (eds), Landschaftsökologische Moorkunde. Schweizerbart, Stuttgart, pp. 112–184.

Kotowski W., Dembek W., Pawlikowski P. 2017. Poland. In: Joosten H., Tanneberger F., Moen A. (eds.) Mires and peatlands of Europe. Status, distribution and conservation. Schweizerbart Science Publishers, Stuttgart, pp. 549–571.

LIFE Peat Restore 2018. Kaļķainu zāļu purvu apsaimniekošanas plāns dabas parka "Engures ezers" teritorijai Orhideju takas apkārtnē. Latvijas Universitāte, Rīga.

Lindenmayer D. B., Likens G. E. 2010. The science and application of ecological monitoring. Biological Conservation 143, 1317–1328.

Lode E. 2020. Groundwater dynamics in LIFE Peat Restore project area located on the Läänemaa–Suursoo Mire Complex. The Second Report for the EU LIFE project LIFE15 CCM/DE/000138 https://drive.google.com/drive/folders/1lEtO2M-m71aORT1eRgy9VF1AdjRIx6pL?usp=sharing.

Lode E. 2021A. Groundwater dynamics in LIFE Peat Restore project area located on the Läänemaa–Suursoo Mire Complex. The Fifth Report for the LIFE Peat Restore EU LIFE project LIFE15 CCM/DE/000138. Prolongation of data sets up to the end of 2020. https://drive.google.com/drive/folders/1lEtO2M-m71aORT1eRgy9VF1AdjRIx6pL?usp=sharing.

Lode E. 2021B. Groundwater dynamics in LIFE Peat Restore project area located on the Läänemaa–Suursoo Mire Complex. The Sixth Report for the LIFE Peat Restore EU LIFE project LIFE15 CCM/DE/000138. Eco-hydrological modelling, https://drive.google.com/drive/folders/1lEtO2M-m71aORT1eRgy9VF1AdjRIx6pL?usp=sharing.

KESE 2020. Seireprogramm. Haudelindude kooslused (madalsood ja rabad). (Monitoring program. Breeding bird communities (fens and bogs). Estonian Environmental Agency), https://kese.envir.ee/kese/viewProgramNew.action?uid=473785.

McBride A., Diack I., Droy N., Hamill B., Jones P., Schutten J., Skinner A., Street M. (eds.). 2011. The fen management handbook. Scottish Natural Heritage, Perth.

Money R. P. 1995. Re-establishment of a *Sphagnum* dominated flora on cut-over lowland raised bogs. In: Wheeler B. D., Shaw S. C., Fojt W. E., Robertsons R. A. (eds.) Restoration of Temperate Wetlands, pp. 405–422.

Müller J. 2009. Forestry and water budget of the lowlands in northeast Germany — consequences for the choice of tree species and for forest management. Journal of water and land development, v. 13a,.-1 pp. 133-148. doi: 10.2478/v10025-010-0024-7

Nusbaums J. 2008. Preventing drainage influence in the raised bogs. In: Pakalne M. (ed.). Mire Conservation and Management in Especially Protected Nature Areas in Latvia. Jelgava Printing House, Rīga, pp. 118–131.

Pakalne M. 1994. Rare rich fen and lakeside communities of the Baltic Coast (Latvia, Coastal Lowland). Doctoral Thesis. University of Latvia, Riga, 146 p.

Pakalne M. (ed.) 2008. Mire conservation and management in especially protected nature areas in Latvia. Latvian Fund for Nature, Riga.

Pakalne M., Strazdiņa L. (eds.) 2013. Raised Bog Management for Biological Diversity Conservation in Latvia. Hansa Print Riga, Riga.

Pakalne M., Priede A. 2019. Calcareous fen succession in Engure Lake Nature Park in Latvia. In: 28th Meeting of the European Vegetation Survey (2019): Vegetation Diversity and Global Change. Book of Abstracts. Madrid.

Pētersons J., Pakalne M., Rudusāne A., Priede A., Grīnberga L., Lazdiņš A., Nusbaums J. 2019. Sphagnum reintroduction demo site. In: Priede A., Gancone A. (eds.) Sustainable and responsible after-use of peat extraction areas. Baltijas krasti, Riga, pp. 226–238.

Priede A. (ed.) 2017. Protected habitat management guidelines for Latvia. Vol. 4. Mires and springs. Nature Conservation Agency, Sigulda.

Pschenyckyj C., Riondato E., Wilson D., Flood K., O'Driscoll C., Renou-Wilson F. 2021. Optimising water quality returns from peatland management while delivering co-benefits for climate and biodiversity. Report produced for An Fóram Uisce.

Purre A.-H., Ilomets M. 2018. Relationships between bryophyte production and substrate properties in restored milled peatlands. Restoration Ecology 26 (5), 858–864.

Purre A.-H., Ilomets M., Truus L., Pajula R., Sepp K. 2020. The impact of manipulations of moss-layer-transfer technique on plant functional types biomass in revegetated milled peatlands. Restoration Ecology 28 (6), 1584–1595.

Purre A.-H., Truus L., Ilomets M. 2021. Decade of vegetation development on two revegetated milled peatlands with different trophic status. Mires and Peat 27 (02), 1–16.

Quinty F., Rochefort L. 1997. Plant reintroduction on a harvested peat bog. In: Trettin C. C., Jurgensen M. E., Grigal D. E., Gale M. R., Jeglum J. K. (eds.) Northern Forested Wetlands: Ecology and Management. New York, USA, pp. 133–146.

Quinty F., Rochefort L. 2003. Peatland Restoration Guide, second edition. Canadian Sphagnum Peat Moss Association and New Brunswick Department of Natural Resources and Energy. Québec,

Québec.

Roze D. 2015. Ekoloģisko faktoru ietekme uz Lēzela lipares *Liparis loeselii* (L.) Rich. populāciju dzīvotspēju Latvijā. Promocijas darbs. Daugavpils Universitāte, Daugavpils.

Rochefort L., Lode E. 2006. Restoration of degraded boreal peatlands. In: Wieder R. K., Vitt D. H. (eds.) Boreal Peatland Ecosystems. Ecological Studies 188, Springer-Verlag, Berlin, Heidelberg, 381–422.

Schaffers A. P., Sykora K. V. 2000. Reliability of Ellenberg indicator values for moisture, nitrogen and soil reaction: a comparison with field measurements. Journal of Vegetation Science 11, 225–244.

Schrader T. (ed.) 2016. Cultivation of *Sphagnum* in Northeast Friesland. Ideas, methods and experiences for *Sphagnum* farming. Wageningen University, http://kenniswerkplaatsnoordoostfryslan.nl/uploads/files/ACT-1636-Case-Business-Peat-moss-final-report-april-2016.pdf.

Schumann M., Joosten H. 2008. Global peatland restoration manual. Institute of Botany and Landscape Ecology, Greifswald University, Germany.

Sendžikaitė J., Pakalnis R., Jarašius L. 2013. Aukštapelkinių bendrijų atkūrimo bandymai išeksploatuotuose durpynuose (Experiment on restoration of raised bog vegetation cover in post-mined peatlands). In: Patrauklios kaimo aplinkos išsaugojimas ir formavimas: pelkės ir kitos šlapžemės (Nature Protection – Neighbours – Build and Conserve a Livable Environment in the Countryside: Bogs, Fens and other Wetlands.) Sargeliai, Kruenta, pp. 52–62, http://sargeliai.org/uploads/Publikacijos/konferencija_saukote_20120921_75dpi.pdf

Photo: M. Pakalne

Sentinel Playground. Web application for browsing of Sentinel-2 satellite imagery. https://apps.sentinel-hub.com/sentinel-playground.

Salm J.-O., Remm L., Haljasorg M.-L., Karofeld E., Kohv K., Kohv M., Kraut A., Krumm L., Meriste M., Oro L., Pungas-Kohv P., Sellis Sikk K. 2020. Soode taastamine: senised kogemused teguloo "soode kaitse ja taastamine" näitel (Handbook "Restoration of mires: experience to date of the protection and restoration of mires"). Eesti Sood, Tartu, https://issuu.com/elfond/docs/soode_taastamise_k_siraamat_20.06.20.

Similä M., Aapala K., Penttinen J. 2014. (eds.). Ecological restoration in drained peatlands – best practices from Finland. Metsähallitus, Syke, https://julkaisut.metsa.fi/julkaisut/show/1733.

Spalviņš A. et al. 2012. Regional hydrogeological model of Latvia for management of its groundwater resources. In: 5th International Scientific Conference "Applied Information and Communication Technologies". University of Agriculture, Latvia, Jelgava.

Succow M., Joosten H. (eds). 2001. Landschaftsökologische Moorkunde, 2. Aufl. Schweizbart Stuttgart.

Trepel M., Pfadenhauer J., Zeitz J., Jeschke L. 2017. Germany. In: H. Joosten, F. Tanneberger & A. Moen (Eds.) Mires and peatlands of Europe. Status, distribution and conservation. Schweizerbart Science Publishers, Stuttgart, pp. 413–425.

Tuittila E.-S., Vasander H., Laine L. 2003. Success of re-introduced *Sphagnum* in a cutaway peatland. Boreal Environment Research, 8, 245–250.

Van de Moortel A. M. K., Meers E., De Pauw N., Tack F. M. G. 2010. Effects of vegetation, season and temperature on the removal of pollutants in experimental floating treatment wetlands. Water, Air & Soil Pollution 212 (1–4), 1–4.

Whalen S. C. 2005. Biogeochemistry of methane exchange between natural wetlands and the atmosphere. Environmental Engineering Science 22, 73–94.

White S. A., Taylor M. D., Damrel D. Z. 2012. Floral colonization of free-water surface constructed wetland system in Grady County, Georgia. Castanea 77, 159–171.

Wichmann S., Prager A., Gaudig G. 2017. Establishing *Sphagnum* cultures on bog grassland, cut-over bogs, and floating mats: procedures, costs and area potential in Germany. Mires and Peat 20 (3), 1–19.

Wu H., Zhang J., Ngo H. H., Guo W., Hu Z., Liang S., Fan J., Liu H. 2015. A review on the sustainability of constructed wetlands for wastewater treatment: design and operation. Bioresource Technology 175, 594–601.

Xiuzhen L., Mander Ü., Ma Z., Jia Y. 2009. Water quality problems and potential for wetlands as treatment systems in the Yangtze River Delta, China. Wetlands 29 (4), 1125–1132.

Yeh N., Yeh P., Chang Y.-H. 2015. Artificial floating islands for environmental improvement. Renewable and Sustainable Energy Reviews 47, 616–622.

Zableckis N., Sinkevičius Ž., Jarašius L., Sendžikaitė J. 2017. Best practice on restoration of Aukštumala raised bog. LIFE Aukstumala LIFE12 NAT/LT/000965. Lithuanian Fund for Nature, Vilnius.