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Forest drainage in the Hunsrück-Hochwald National Park - an integrative approach

Abstract

The management of drained wetlands has become a key focus in the implementation of climate change adaptation measures in recent years, particularly in forested areas. Questions arise regarding appropriate methods to adequately plan and implement measures for dealing with drainage structures in forests. This study developed a methodology for analyzing the historical drainage of a forested area, specifically using the Hunsrück-Hochwald National Park as a case study. The park has undergone extensive wetland renaturation efforts, necessitating a profound understanding of the existing drainage ditch system. Three complementary methods were employed: historical analysis, LiDAR data investigations, and field surveys. The combined use of the three methods proved essential for accurately identifying and interpreting drainage structures in forested wetlands. Each method contributed unique strengths: historical analysis offered insights into the origin and intention of interventions, remote sensing enabled large-scale mapping, and field surveys ensured on-the-ground validation. Their integration not only reduced the risk of misinterpretation but also revealed the extent of past hydrological modifications and land use. This comprehensive approach provides a valuable foundation for climate-resilient conservation and water management strategies in forest landscapes.

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1 Introduction

Due to climate change, the likelihood of extreme weather events is significantly increasing, including more frequent occurrences of heavy rainfall and periods of low or no precipitation (Trenberth, 2008; IPCC, 2023). In Central Europe, this poses a challenge to a cultural landscape where water retention capacity has been intentionally or unintentionally diminished by human activities (Doležal et al., 2017). The consequences include an increasing occurrence of flood events or droughts with devastating effects on land use, cultural heritage, human lives, or ecosystems (Huang et al., 2015; Parasiewicz et al., 2019; Sesana et al., 2021). Forests contribute to this issue, because many of them are crisscrossed by drainage structures like, mostly open, systematically arranged drainage ditches (Doležal et al., 2017). By intentionally lowering the groundwater level, soil hydrological conditions were mostly altered to establish and enhance the growth of economically valuable tree species. As a result, the water retention capacity of drained forest areas has been significantly reduced. The hydrological impacts of such forest drainage affect the forests themselves. There are permanent changes in the ecosystem, such as alterations in soil composition, water availability, and vegetation (Lõhmus et al., 2015). However, the impacts of forest drainage extend far beyond the affected areas. Drained wetland areas and ditches release CO2 and CH4 (Peacock et al., 2021a, b). For Central Europe, García & García et al. (2023) demonstrated that dryer soils significantly contribute to atmospheric warming. On a landscape scale, forests are often situated in higher, more rainfall-prone areas. Therefore, a reduced water retention capacity has implications for entire catchment areas, even where no forests are present. Instead of contributing to climate change adaptation, drained forests may accelerate the effects of climate change.

In anticipation of the future repercussions of climate change, the necessity for a comprehensive enhancement of the water retention capacity across the entire cultural landscape has become increasingly evident (Similä et al., 2014; Sanz et al., 2017; Collentine & Futter, 2018; Eekhout & Vente, 2019). This is underscored by the heightened emphasis on the establishment of sponge cities or sponge landscapes (Oates et al., 2020; Peng et al., 2021). Achieving this goal demands a thorough understanding of the hydrological processes in the affected areas, encompassing both artificial and natural linear flow structures (Yan et al., 2020). Nevertheless, several studies indicate that a significant part of these structures has yet to be accurately mapped or documented. This is not an isolated occurrence and is applicable to a wide range of Central European cultural landscapes (Peacock et al., 2021a; Roelens et al., 2018; Ågren & Lidberg, 2019; Koschorreck et al., 2020; Flyckt et al., 2022).

In the context of hydrological restoration in forests, it often becomes apparent that there is insufficient knowledge about the existence and course of drainage networks. This lack of information can ultimately lead to inefficient implementation of hydrological restoration measures. Additionally, there is a significant lack of understanding regarding the historical dimension of drainage networks in the affected areas. However, this knowledge is of fundamental importance. It is crucial for understanding why the hydrological interventions were carried out in the first place and how long they have been in place. Furthermore, this historical insight can be leveraged for public outreach efforts accompanying the restoration measures. Historical knowledge can also be instrumental in identifying potential conflict areas early on, particularly in relation to stakeholders in heritage conservation or archaeology, and in developing strategies to address these conflicts proactively. Hence the aim of the study was to highlight the issue of forest drainage through drainage ditches, specifically addressing professional practice, which is increasingly confronted with planning challenges related to the management of drainage ditches. Therefore, this study addresses the following questions:

- What methods are essential for identifying intentional changes in the water retention capacity of forests with open ditches?
- What are the advantages and disadvantages of different data collection methods, such as historical analysis, field surveys, and remote sensing?
- Which data collection methods are suitable for both practical professional and scientific purposes?

In this study, various methods for answering the research question were tested using the example of the Hunsrück-Hochwald National Park, and the effectiveness of the measures was evaluated. The data collection for the study took place between 2015 and 2019, accompanying comprehensive renaturation measures in the area. The acquired knowledge was immediately utilized for the planning and execution of these interventions.

2 Materials and methods

2.1 Study area

The Hunsrück-Hochwald National Park (Figure 1), a mountainous, forested region covering 102 km² and located in the western German federal states of Rhineland-Palatinate (90%) and Saarland (10%), exemplifies efforts to enhance landscape-scale water retention capacity. Between 2015 and 2020, extensive measures were implemented to increase widespread water retention within the park (König et al., 2016). The park's elevation ranges from 809.3 meters above sea level at its highest point to 387.1 meters in the Idar Valley. It forms a watershed for the rivers Moselle, Nahe, and Saar. Annual precipitation varies between 800 and over 1300 mm, with higher elevations generally receiving more rainfall (Herrmann, 2017). Geologically, the formation of Taunus quartzite dominates the highlands, resulting in shallow, stony, nutrient-poor, and acidic soils. In lower-lying areas where Hunsrück slate predominates, we find deeper and more nutrient-rich soils. A distinctive feature of the park is the presence of numerous small-scale slope bogs, locally known as "Brücher", which can store significant amounts of water (König et al., 2016).

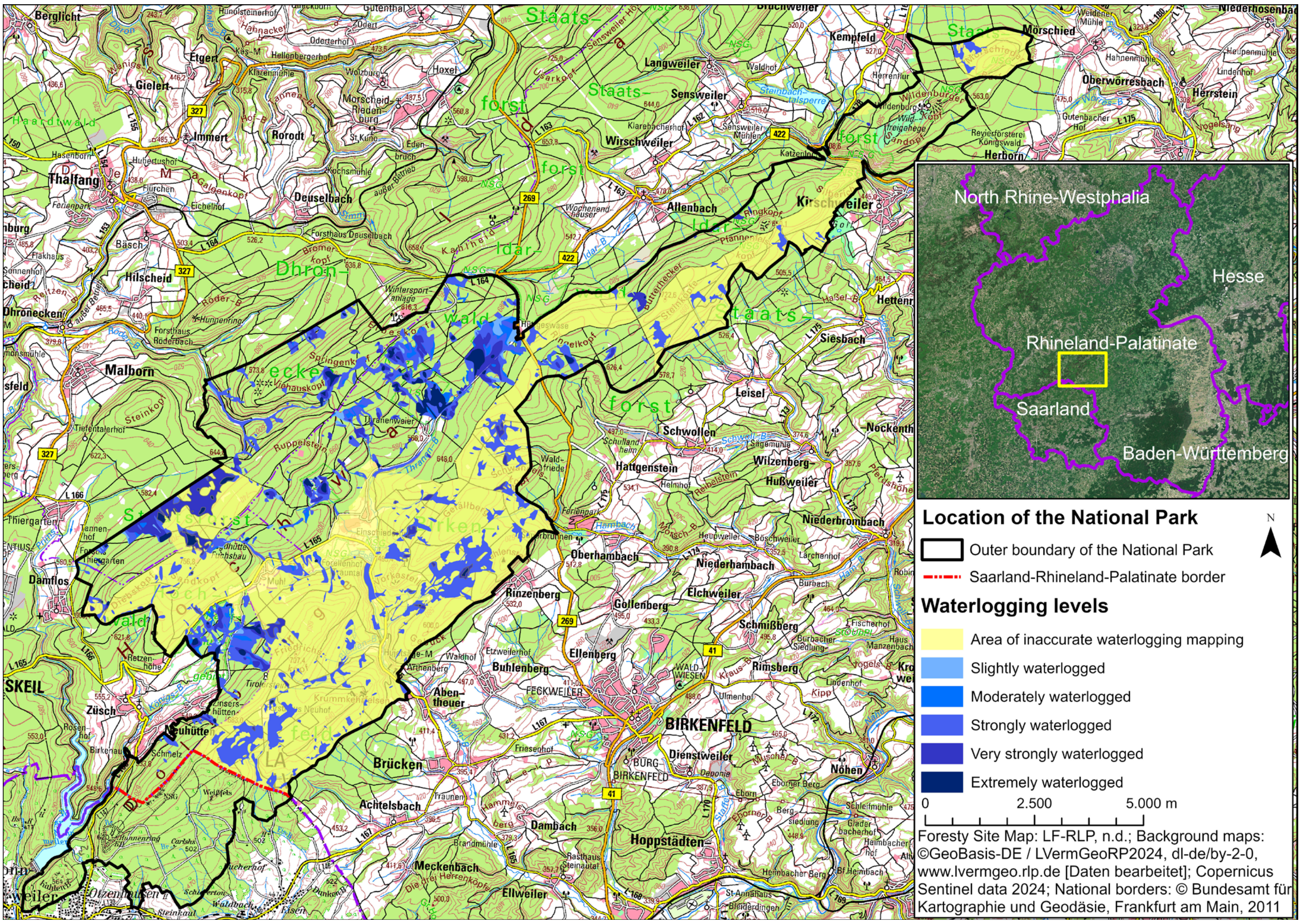

Figure 1. Location and waterlogging levels of the Hunsrück-Hochwald National Park.

The potential natural vegetation of the national park would be acidophilous beech forest in the higher elevations, particularly Luzulo-Fagetum beech forests. In the lower parts oak-beech forests of the Luzulo-Fagetum type would develop. Additionally, the small-scale bogs host moisture-adapted species such as downy birch (*Betula pubescens*), occasionally mixed with rowan (*Sorbus aucuparia*), whitebeam (*Sorbus spp.*), peat mosses (*Sphagnum spp.*), cotton grass (*Eriophorum spp.*), and sundews (*Drosera spp.*). The persistent waterlogging leads to relatively open stands with a canopy cover of maximum 70%, often only reaching 30% (Scholtes, 2018). However, the actual vegetation differs significantly from the potential natural vegetation due to centuries of land use. While heavily modified beech forests cover approximately half of the forested area, many areas were afforested in the past with non-native conifers, particularly European spruce (*Picea abies*). These spruce stands are found both on former beech forest sites and in the bogs, where they have almost completely displaced the natural vegetation (Schultheiß, 2019).

The transformation of the bog areas in the Hunsrück-mountains required extensive hydrological interventions over the past 200 years, primarily through open drainage ditches (Schultheiß & Konold, 2022; Reiss et al., 2023). This extensive drainage system has led to a significant loss of water retaining functions. Consequently, their runoff reacts quickly and intensely to precipitation events: During heavy rainfall events, there is a rapid increase in runoff, and during periods of low precipitation, many watercourses completely dry up (Tempel, 2006; Zemke, 2021). It is hypothesized that, due to extensive draining in the past, the local forests contribute to the occurrence of floods both in the forested highlands and along major rivers (Tempel et al., 2015).

The conservation objectives of Hunsrück-Hochwald National Park can be summarized as follows: The primary aim is to enable largely undisturbed natural processes on 75% of the National Park area by 2045. Special attention is given to the wetland vegetation of small-scale slope bogs, which are considered a distinctive feature of the park. Due to significant hydrological modifications in these areas, a decision was made to deconstruct drainage structures before stopping human intervention. This approach aims to restore more natural hydrological conditions in these sensitive ecosystems. An EU-LIFE-project (LIFE Hochwald), which focused on the regeneration and protection of transition mires and bog woodlands within the park, exemplifies these conservation efforts. Between 2015 and 2020 the project involved removing non-native spruce plantations and implementing rewetting measures to support the re-establishment of original wetland vegetation by closing drainage ditches. Both the location and frequency of drainage ditches in Hunsrück-Hochwald National Park were largely unknown; for example, no map of drainage ditches existed. However, this was essential for efficiently planning the renaturalization measures.

Over the past 300 years, the area has experienced profound administrative transformations. In 1789, it was divided among six distinct German principalities, later came under French rule, in 1817 under Prussian and Oldenburg control, became part of the German Empire in 1871, and was ultimately integrated into modern Germany after 1945 (Figure 2).

2.2 Data analysis

An adequate answer to the research questions required a combination of historical analysis and comprehensive surveys of the current condition of the drainage system in the National Park. Therefore, an integrative approach to reconstruct the drainage system was used (Figure 3). The data collection for the study took place between 2015 and 2019, accompanying comprehensive renaturation measures in the area

2.2.1 Examination of the historical development

A profound historical analysis allows identifying the intentional interventions that were made to the hydrology in earlier times and whether there are more significant hydrological modifications aside from drainage ditches. It also gives information about the duration, historical evolution and motivations behind the drainage of the Hunsrück-Hochwald National Park. That’s why comprehensive landscape-generic studies were conducted using historical written sources, often located in archives (Seilter & Walz, 2014). Two types of records were prioritized: writ-

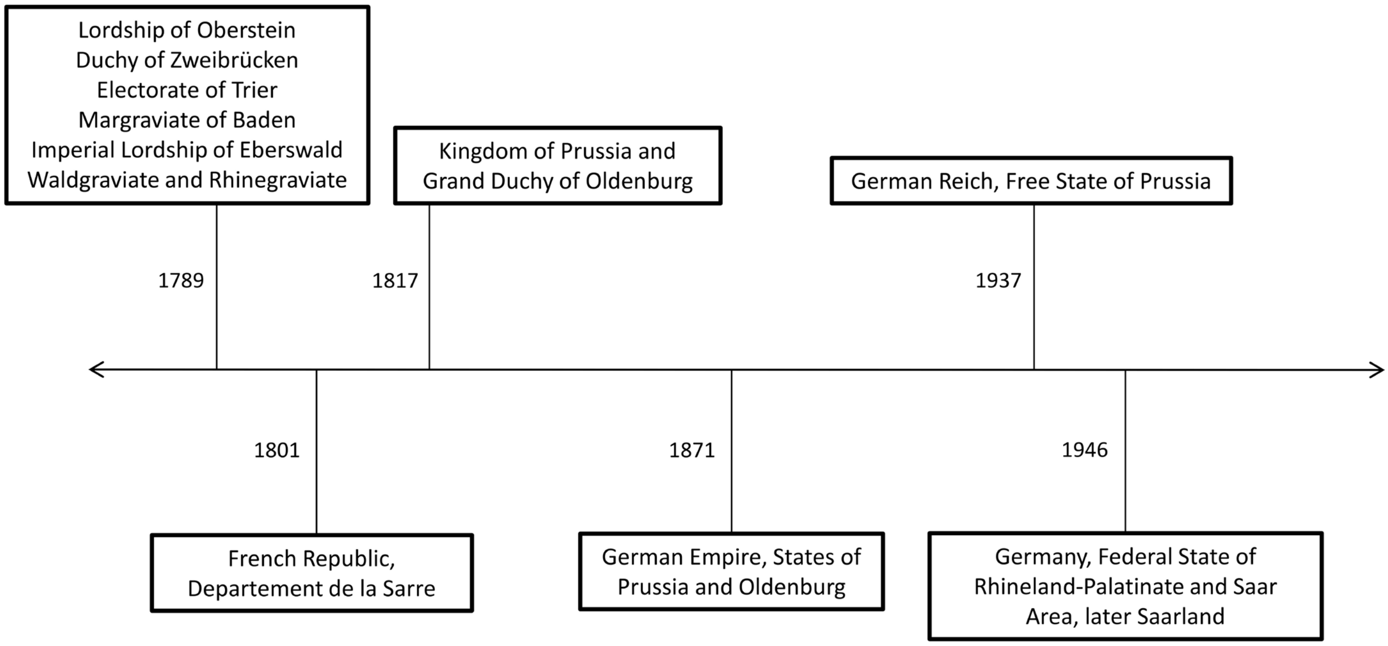

Figure 2. Rough timeline of the administrative rulers of the present-day Hunsrück-Hochwald National Park.

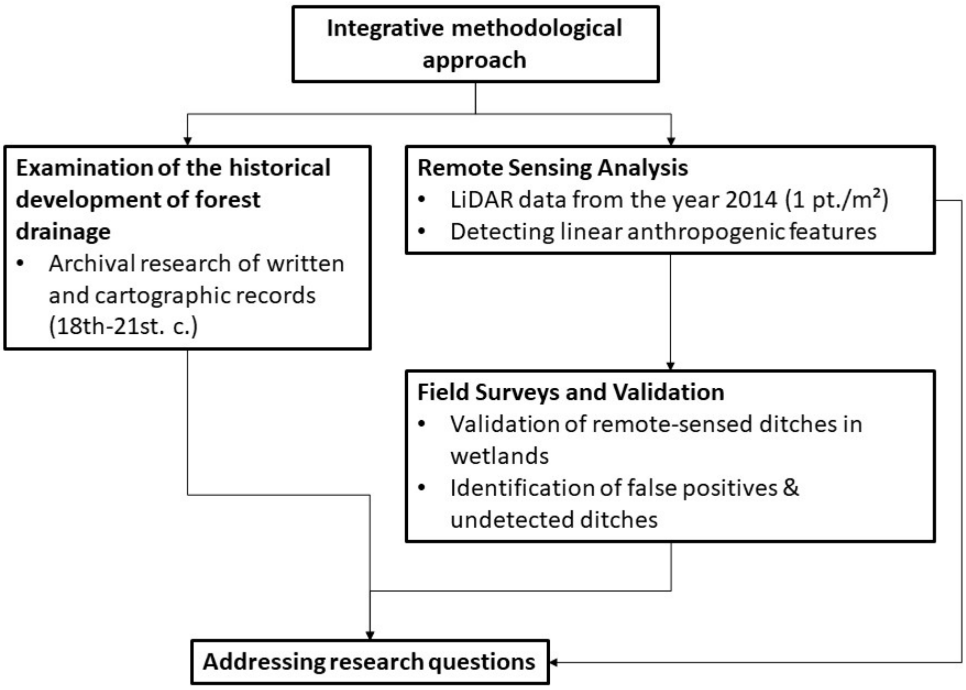

Figure 3. Methodological approach of the study.

ten sources and cartographic materials, as previous studies have shown that these can provide valuable insights into the historical development of forest drainage (Schultheiß & Konold, 2022). A preliminary investigation was carried out to identify potential locations where relevant records could be found, which included internet research and searches within online catalogs and consultations with local stakeholders and the state forestry administration for possible archival sources.

The search for records was relatively open and not restricted to documents with a direct forestry focus. In addition to written sources, historical cartographic materials, such as forestry maps from the mid-18th century and official topographic maps from the early 19th century, were also analyzed.

Relevant thematic information was located in organized collections across several archives, including the Prussian Privy State Archives in Berlin, the Archives Nationales in Paris, the State Archives in Speyer, and numerous local archives. Additionally, many records were stored in administrative offices, such as the Forestry Central Administration of Rhineland-Palatinate, though some were kept in unsorted conditions, such as in basements or storage rooms. The majority of pertinent records are currently preserved in the Rhineland-Palatinate State Main Archives in Koblenz, which houses a wealth of operational records from former and existing Hunsrück forestry offices (E. Bauer, personal communication, 2012). Historical sources, including forest management plans, forestry ordinances, historical accounts, and management plans from the second half of the 18th century onwards, were found in large numbers. Consequently, the analysis of historical records was primarily focused on this archive. A challenge was understanding the archival documents. A significant portion of the records was in French, while many of the German-language documents were written in Kurrent or Sütterlin script. However, it is important to note that the historical forestry or official topographical maps provided no direct information regarding specific drainage networks in the forest.

2.2.2 Forestry Site Mapping and Information on waterlogging levels

In this study, forestry site maps including waterlogging levels were utilized for two primary purposes. Firstly, they were employed to delineate wetland boundaries, providing valuable information on soil moisture regimes, which helped identify and demarcate wetland areas within the study region. Secondly, these maps were used to analyze the relationship between the occurrence of waterlogging and different degrees of soil saturation on the presence of drainage ditches. For the National Park, a digital forestry site mapping is available (Figure 1). This is based on forestry site mappings that took place from 1963 to 1975 and covers the Rhineland-Palatinate part of the protected area. It distinguishes between “non-waterlogged”, “slightly waterlogged”, “moderately waterlogged”, “strongly waterlogged”, “very strongly waterlogged”, and “extremely waterlogged” sites, with varying mapping accuracy (LF-RLP, n.d.). The waterlogging levels provide practical insights into how wet a site is and how long water stagnation lasts within a year. For example, a slightly waterlogged soil experiences water stagnation for a few days to weeks, a very strongly waterlogged soil for 6–11 months, and an extremely waterlogged soil remains waterlogged for more than 11 months per year. A large part of the map provides only an inaccurate waterlogging mapping depicting areas that are “strongly” to “extremely waterlogged” (45km², 42 % of the total area of the National Park). Especially the northern half of the National Park is completely mapped. For presentation reasons, non-waterlogged areas are hidden in maps depicted in this study. A dataset covering the entire area and all waterlogging levels in a digital waterlogging map does not currently exist (A. Kaus-Thiel, personal communication, 2018).

2.2.3 Analysis of ditches

Digital Elevation Models (DEMs) based on LiDAR raster data can be utilized for the detection of man-made structures, especially through hill shaded raster data. Simple visual interpretation allows the recognition of these structures and assign them to specific forms of use. In many cases, linear structures such as ditches, walls or paths can be visually captured easily and analyzed in their spatial extent (Kokalj & Hesse, 2017; Trotter et al., 2022; Flyckt et al., 2022). On-screen digitalization was suitable for this study because LiDAR raster data with a resolution of 1 point/m² referring to ground points and covering the entire area, were available. The scan depicts the area in the year 2014, when extensive closures of drainage ditches had not yet been carried out, which was advantageous for this analysis.

The remote sensing assessment of anthropogenic land use structures via visualization is prone to errors. This may be due to a lack of expertise of the analyst or inaccuracies in the DEM raw data, leading to limited interpretability (Kokalj & Hesse, 2017; Santamaría-Peña et al., 2021). To obtain an accurate picture of drainage systems, field surveys of drainage systems were conducted in the Hochwald forest based on the prior remote sensing analyses. The survey aimed to verify whether the remotely detected ditches were present, whether additional ditches existed, or whether structures mapped as ditches were, in fact, other elements, such as paths or embankments. The study should also determine whether the ditch structures are drainage ditches or other types of ditches, such as enclosures or trenches. Due to the large number of remotely mapped drainage ditches, the field surveys were spatially limited, focusing mainly on wetlands where nature conservation interventions were planned. They serve as examples of wetlands in the National Park that were drained with open ditches for silvicultural reasons and subsequently planted with spruce. The surveys also aimed to assess the condition of the drainage structures before planned closure or clearing activities, which could have resulted in significant alterations or obliteration of the affected drainage systems. Additionally, precise knowledge of the structure and course of the drainage systems was crucial for efficiently closing them during restoration activities. Hence, the general condition and spatial dimensions of the various ditches were recorded.

At the time of the field surveys, no portable device with GPS reception and GIS support was available, except for a handheld GPS-device. For the wetlands to be surveyed maps were first created that contained information on remotely detected ditches, wetland extents, and the DEM. GPS coordinates were recorded for prominent ditch structures or structures whose significance was unclear to verify them onsite. Based on these maps, the surveys were carried out, with the ditch systems being walked from the bottom to the top, as they typically branch out uphill in a fishbone-like pattern. All deviations from the remote sensing pre-mapping were recorded using the handheld GPS-device and a tape measure and were later corrected with GIS. This resulted in a ditch dataset that was initially created through remote sensing but was significantly refined for many ditch systems through on-site verification, making it much more accurate.

The authors already possessed extensive experience from previous studies on the remote sensing detection and subsequent ground-truthing of drainage systems in forests, which proved to be highly beneficial for this analysis (Schultheiß & Konold, 2022).

3 Results

3.1 The historical evolution of drainage ditches

3.1.1 The 18th century – Forest management is making its way into the Central European forests

The 18th century witnessed the intensive exploitation of Central European forests, propelled by the expansion of the iron industry and subsequent population growth. Charcoal production, timber harvesting, and grazing exerted considerable pressure on the forest. Towards the second half of the century, the forests in the Hunsrück region faced widespread, intense, and poorly regulated utilization, leading to thinning, dominance by clear-cut areas and coppice, and a scarcity of young growth and high-quality timber (Kling, 1790). Meadows and extensive small-scale slope bogs suffered from a lack of woody vegetation despite regeneration attempts, resulting in further thinning on overused and infertile soils (Arndt & Helbron, 1863).

This era marked the introduction of modern forestry practices in Central Europe. By the century's end, drainage emerged as an indispensable component of forest management (Laurop, 1796; Burgsdorf, 1796). The precise timing of initial drainage measures in the present-day National Park remains unclear.

3.1.2 French times – First attempts with drainage

The annexation of the Hunsrück region by France in 1801 marked a transformative period, initiating large-scale forest development with special attention to bogs. The challenging economic aspects of these areas, due to high soil moisture, prompted their integration into regular management (D'Egremont, 1808). The French Finance Ministry in Paris emphasized this integration in 1807, advocating the replacement of tree species considered uneconomically such as birch (*Betula pubescens*) or service tree (*Sorbus domestica*) with economically valuable beech (*Fagus sylvatica*) and oak (*Quercus robur*) (Massa & Suzanne, 1811; Baudrillart, 1821). Therefore, in the coming years, dozens of kilometers of drainage ditches were constructed.

3.1.3 Prussia and Oldenburg - Drainage becomes established

After 1815, the northern half of the National Park area belonged to Prussia and the southern part to the Grand Duchy of Oldenburg. Deteriorating economic conditions led to financial constraints and to the cessation of forestry activities including drainage (Arndt & Helbron, 1863). In the 1830s, drainage resurfaced in forestry practices to enhance silvicultural yield in wetlands by replacing mostly birch with spruce (*Picea abies*) (Arndt et al., 1860). The trend intensified in subsequent decades, involving the construction of new ditches and the seeding of almost all wetlands with spruce (Meyer, 1883). The 1870s and 1880s also saw the acquisition, drainage, and seeding with spruce of most of the forest meadows (Adam, 1883).

3.1.4 End of the 19th century - First doubts about drainage

Increasing drainage activities raised concerns among the local population and economy about the rising possibility of fluctuating water levels in the creeks and potential disruptions to water mills in the Idar Valley. Some forestry offices considered the 'public interest' in avoiding further drainage network expansion and wetland-to-spruce conversion (Meyer, 1883, p. 94). In the mid-1880s, the Prussian state initiated extensive melioration measures to improve rural living conditions. Watercourses were modified, and irrigation and drainage systems established in agricultural land, some of which received water from the forest drainage networks (Nestor, 1890; Kaiser, 1885).

By the end of the 19th century, the region faced profitability challenges due to poor infrastructure (Meyer, 1883). Local foresters aimed to improve the road network. This included the construction of new roads through high-altitude particularly wet spring areas of the wetlands, equipped with deep side ditches connected to drainage networks (Kaiser, 1902; Rheinen et al. 1926). These measures sought to comprehensively drain the underlying wetlands. They ceased with World War I in 1914, with subsequent discontinuation of almost all forestry activities.

3.1.5 1920s-1945 - Times of crisis and further doubts

In the mid-1920s, drainage regained significance with the aim to promote spruce cultivation again (Clepeau, 1924). In the Hochwald forest, negative experiences with spruce, such as a high susceptibility to calamities (e.g. windthrow risks or infestation by pests) and cultivation costs, led to the commissioning of an expert report by Erdmann (1925). He recommended, for economic and ecological reasons, an immediate cessation of new drainage ditch construction in wetlands, the extensive removal of spruce from the Hochwald forest. Local foresters supported these recommendations. Disregarding local concerns, the highest forestry authority continued promoting spruce cultivation, resulting in new ditches and the cleaning of existing ones from 1926 onwards (Rheinen, 1926).

The planned drainage roads conceived before World War I proved impractical due to high soil moisture. For roads that had not yet been built, no further implementation took place (Wegener et al., 1926). Many of the already completed roads were taken out of use due to prohibitive maintenance costs (Meyer, 1930). The onset of World War II significantly impacted forest management, with a cessation of drainage ditch construction and maintenance in 1942 (Rheinen, 1942).

3.1.6 The post-war period - Drainage reaches new heights

From the late 1940s, a shift occurred in water management with an increasing number of springs tapped for drinking water supply and diverted through pipes. On many affected areas significant drying effects on the trees were observed, particularly in areas where tree species adapted to soil moisture conditions (Ude, 1956). The post-war years saw a swift resumption of spruce promotion, accompanied by extensive drainage activities prioritized for economic gain. In addition, efforts were made to create irrigation ditches for water transfer from wetlands to forest areas under threat of drought (Anonymous, 1955).

In the subsequent decades, systematic drainage of wetlands significantly increased the density of drainage systems; during this period, the dimensions of individual ditches grew noticeably. In the 1960s the intensified drainage effect had adverse consequences for many areas: they became excessively dry, reducing their economic usability— even the growth of spruce encountered issues. Additionally, it was recognized by the highest forestry authority that the risk of flooding had increased (Anonymous, 1963).

3.1.7 The 1970s and 1980s - Active drainage disappears

In the 1980s and 1990s, many forests in western Germany experienced severe damage from strong storm events. Particularly, the non-native spruce, which had been primarily thriving on drained wetlands, was uprooted. This led to a reevaluation of forestry practices, abandoning the spruce-centered approach in favour of ecological suitability (Schneider, 1990). Consequently, the establishment and maintenance of extensive drainage systems gradually lost importance and were eventually discontinued (Schultheiß & Konold, 2022).

3.1.8 2010-2020 - Restoration of wetlands

Between 2010 and 2020, several projects were implemented in the National Park area that focused on restoring wetlands to reinstate their role as a carbon sink and habitats typical of wetlands. The measures mostly involved removing the coniferous forest from wetlands using a soil-friendly cable crane and subsequently closing drainage ditches. Two methods were used: on very waterlogged wetlands the ditches to be closed were first cleaned and then wooden sheet piles were inserted (mostly made of Douglas fir). The gaps were filled with wood chips and sawdust (Rohland, 2017). On less waterlogged wetlands, mineral seals were placed in the drainage systems using a mini excavator, which are intended to create a dam effect. In some wetlands, additional measures were implemented on roads to reduce their drainage effect.

3.2 The typology of ditches in the Hunsrück-Hochwald National Park

3.2.1 Type and style of the ditches

Since the French era, predominantly open earth ditches were built for drainage in the present-day Hunsrück-Hochwald National Park. For stability reasons, the ditches have always had sloped embankments. The characterization of the drainage system was based on the encountered soil moisture. In general, the rule was: the higher the soil moisture or the slope inclination, the greater the density of the ditch network. In French times, the drainage ditches were laid out in systems that consisted of larger main and smaller side ditches (Merling et al., 1809; Massa, 1810). The basic structure remained largely unchanged in the centuries to come, even though from the second half of the 19th century, there was a significant increase in the density and dimension of drainage ditches.

3.2.2 Total length and spatial density of drainages ditches

In total 410 km of drainage ditches were mapped in the National Park, although the actual length of existing drainage ditches is likely slightly higher. This results in a ditch density of at least 4 km/km² for the entire National Park (102 km²). 45 kilometers of this were determined through field inspections.

As illustrated in Figure 4, all wetland areas are today intersected by drainage ditches, except for a few small sections in the Hohltriefbach Valley. This includes only ditches that drain the forest area.

It is evident that the location of the ditches depends significantly on hydrological properties of the soils. The occurrence of ditches correlates so closely with soil moisture that in transition areas from waterlogged to dry areas, ditches are only present where the soil is moist. On “dry” and “slightly waterlogged” areas, there are very few drainage ditches, mostly serving as connecting ditches between drainage systems that drain moister areas within wetlands or between drainage systems of different wetlands. In many cases, these areas are free or almost free of ditches. This effect is evident even on small, dry to slightly waterlogged islands within larger wetlands. For “moderately waterlogged” areas the same applies mostly.

Of the mapped 410 km drainage ditches, 375 km are located in “heavily” to “extremely waterlogged” areas (15.74 km²), the ditch network density on such sites is 23.82 km/km². On “heavily waterlogged” ar-

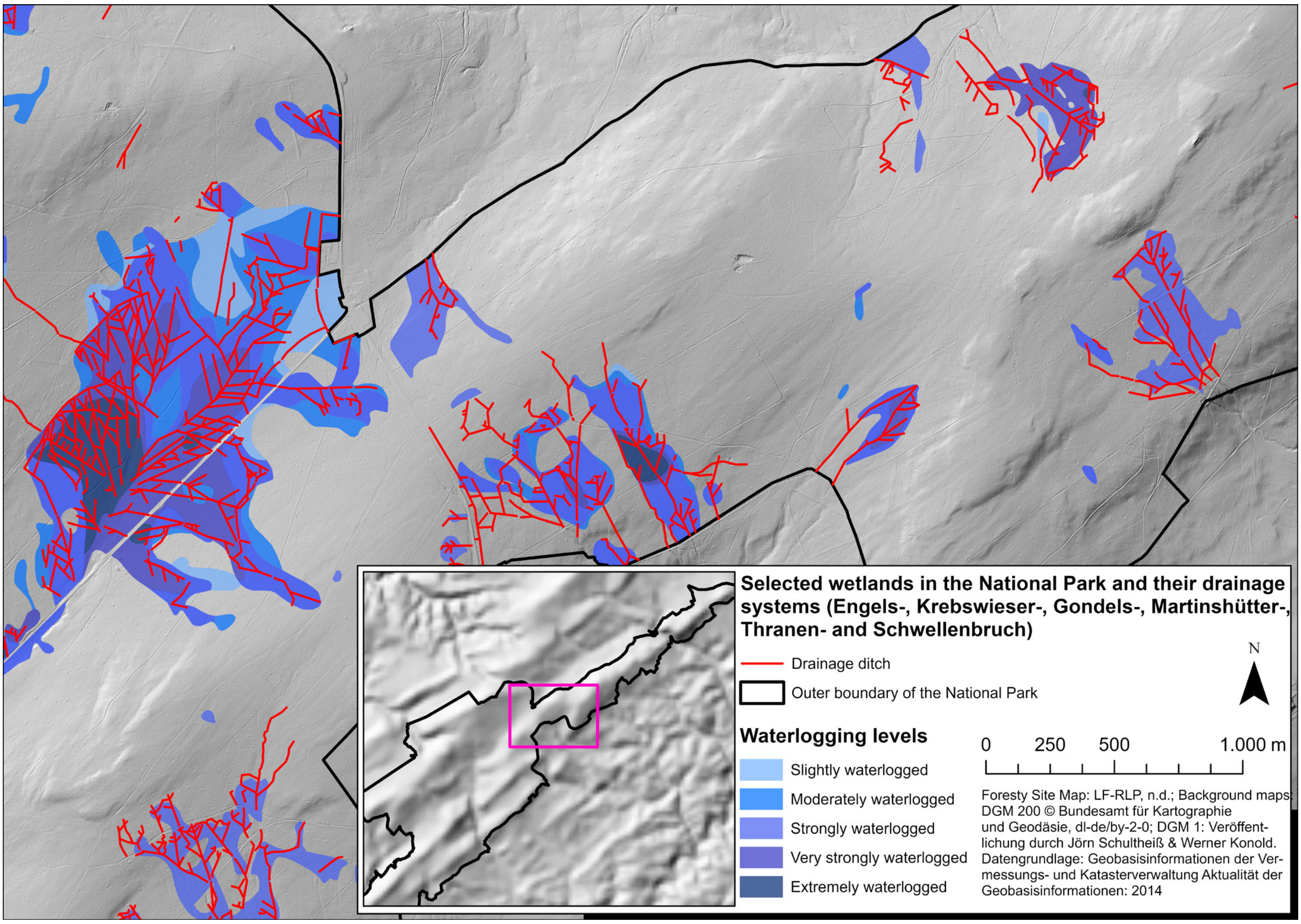

Figure 4. The drainage system of the Hunsrück-Hochwald National Park, illustrated here in the wetlands of Engels-, Krebswieser-, Gondels-, Martinshütter-, Thranen-, and Schwellenbruch.

Table 1. Length of drainage ditches, spatial extent, and ditch density of heavily waterlogged to extremely waterlogged sites in the Hunsrück-Hochwald National Park

Soil water regime	Ditch length (km)	Area (km²)	Ditch density (km/km²)
Heavily waterlogged	253	12.13	20.86
Very heavily waterlogged	87	2.75	31.64
Extremely waterlogged	35	0.86	40.70

eas drainage network density lies by 20.86 km/km², on “very heavily waterlogged” areas by 31.64 km/km², and on “extremely waterlogged” areas by 40.70 km/km² (Table 1).

3.2.3 The structure of the drainage network

The structure of the drainage network mostly reflects the layout established during the French era, consisting of main ditches from which branch offside ditches. The main ditches traverse the wetland areas downhill, mostly at the lowest points of the relief, exhibiting a steep slope accordingly. The side ditches originate at a gentler slope and extend into the area, facilitating the comprehensive drainage of the wetlands. It is noteworthy that in many cases, smaller wetland areas are also drained with differentiated drainage systems. These are connected to larger drainage systems located below by a long ditch that extends uphill from the larger system and fans out in the area to be drained. The drainage systems of bogs located topographically higher are often not directly connected to a stream. They are interconnected to lower wetlands because the upper ones drain into the drainage systems of the lower ones.

The existing drainage systems almost always discharge directly into one of the many natural watercourses. In some cases, the LiDAR-scan indicates that the respective stream was modified through

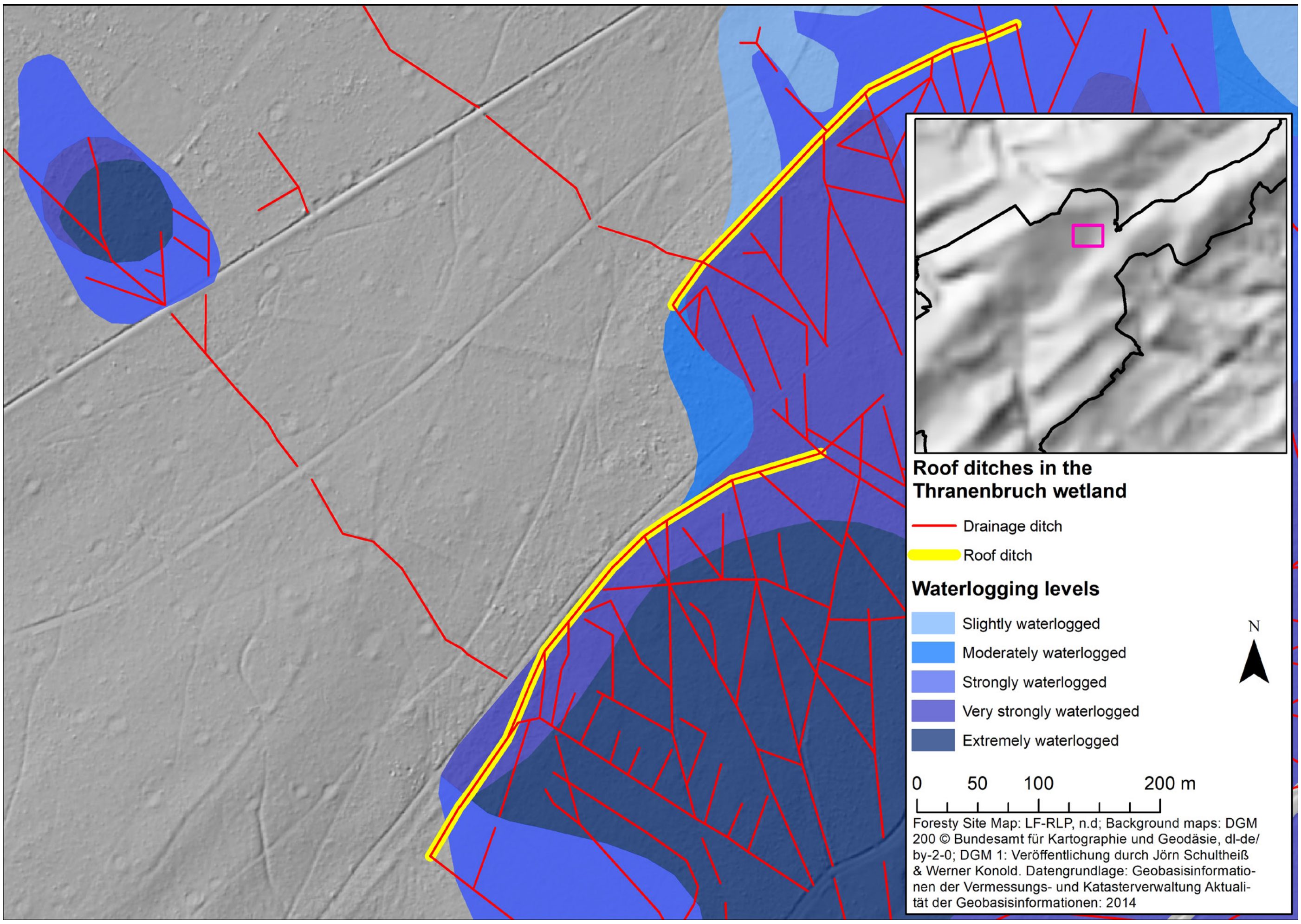

Figure 5. Roof ditches in the Thranenbruch wetland. The map excerpt also displays the drainage of a small wetland through a sophisticated ditch system, connected to the Thranenbruch wetland ditch system via a long ditch.

straightening and deepening measures. Presumably, these are watercourses that, after connecting a drainage system, were not adequately dimensioned for the expected water volume (Dengler, 1863). Such measures also often involved straightening some particularly meandering sections of watercourses.

Some natural streams were artificially extended by ditches to drain their own source areas. A notable instance is the Traunbach creek, extended several hundred meters in a northeast direction at the hamlet Hüttgeswasen. This extension forms a separate and highly differentiated drainage system. Additionally, certain streams have smaller wetlands in proximity, and relatively short drainage ditches extend into them from the stream.

3.2.4 Roof ditches

In the course of the remote sensing investigation, ditches were identified that deviate from the "classic" drainage ditch structure of main and side ditches. Some ditch systems are equipped with so-called "roof ditches". They are already mentioned by Gerhard (1922) and are intended to prevent water from flowing from above onto the drained wetland. Therefore, these roof ditches are located in the upper part of the ditch systems, run parallel to the slope through the wetland and drain into the extensive drainage system. Roof ditches are mainly found in spatially larger wetland areas with "high waterlogged" levels (Figure 5).

3.2.5 Enclosure ditches

Some drainage structures analyzed through LiDAR do not seem to have drainage as their sole purpose. Their main function was likely the early demarcation of property and land use boundaries, with drainage as a secondary consideration (Schultheiß, 2019). For instance, the Langbruch wetland is encircled by

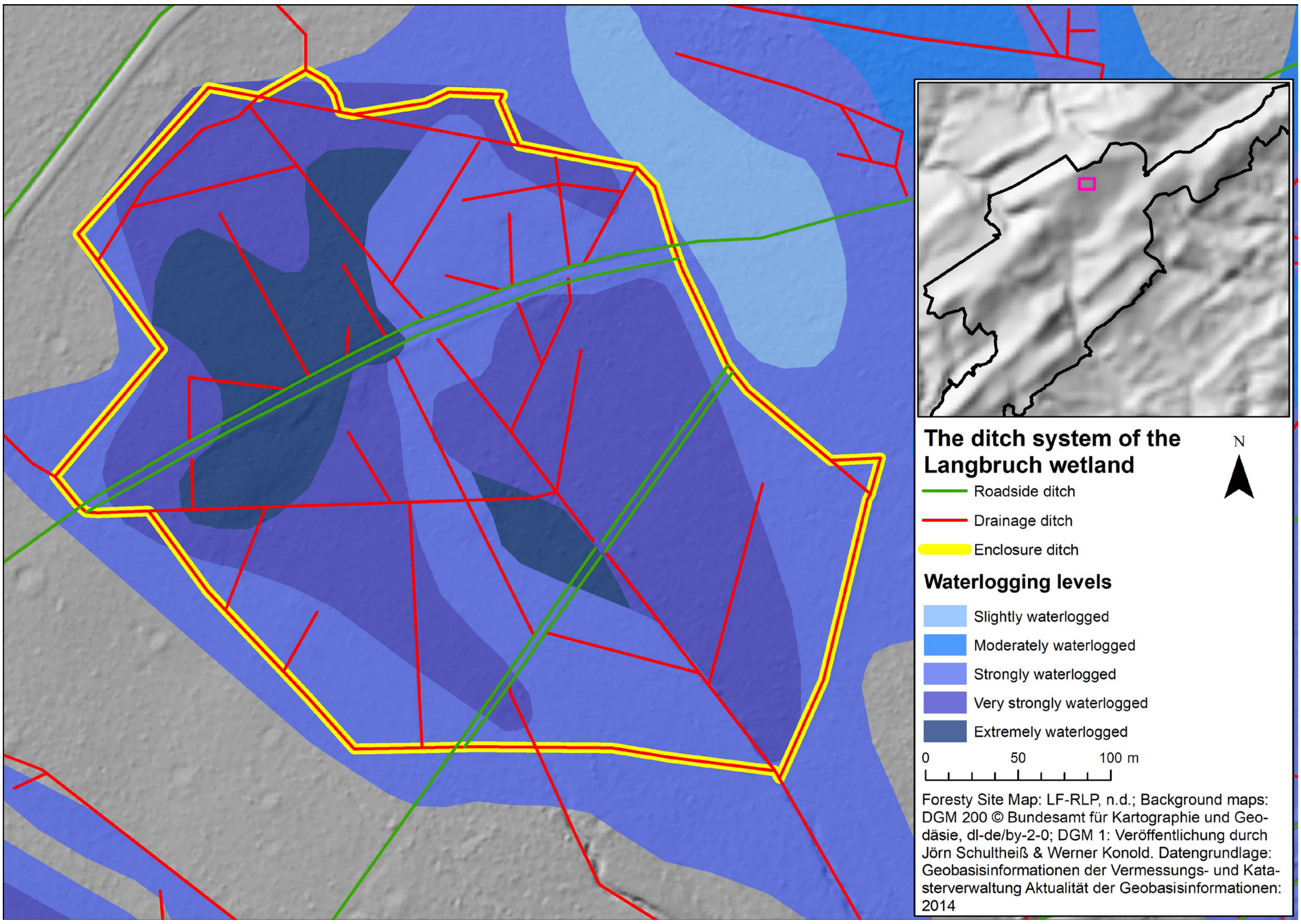

Figure 6. The ditch system of the Langbruch wetland. Some drainage ditches likely served as enclosing ditches.

a ditch precisely delineating the waterlogged areas (Figure 6). Similar indications are found for many former forest meadows that are now drained and populated with spruce (e.g. Helm, 1833). Comparing LiDAR scans with historical maps reveals that ditches exist precisely in the transition zone from former forest meadows to the forest. These ditches are only present where land-use boundaries were not marked by a natural stream, road, or path and only on meadows that were converted to spruce until the beginning of the 19th century (Figure 7). Today, these ditches are integrated into the drainage system and exhibit clear signs of drainage function during a field analysis.

3.2.6 Irrigation ditches

A map created by Kaiser (1885) illustrates the irrigation and drainage system for agricultural areas around the village of Thranenweier. The map reflects that water was directed from the northern adjacent, forest wetlands via drainage ditches and natural streams towards the dry areas in the south through irrigation ditches. Additionally, drainage ditches were present in the open land precisely where significant waterlogging occurred. In some sections, they were converted into irrigation ditches. A water basin served for partial regulation of the water system. The ditch system is still visible in today's LiDAR scan.

3.3 Field observations of drainage and irrigation structures

The on-site inspection of individual wetlands revealed that the drainage systems analyzed through remote sensing are mostly clearly visible in the field. The comparably steep main ditches are generally larger in dimension than the branching, less inclined side ditches. Despite the long period of no maintenance, the main ditches are usually in good condition. The free flow of water is often hindered by veg-

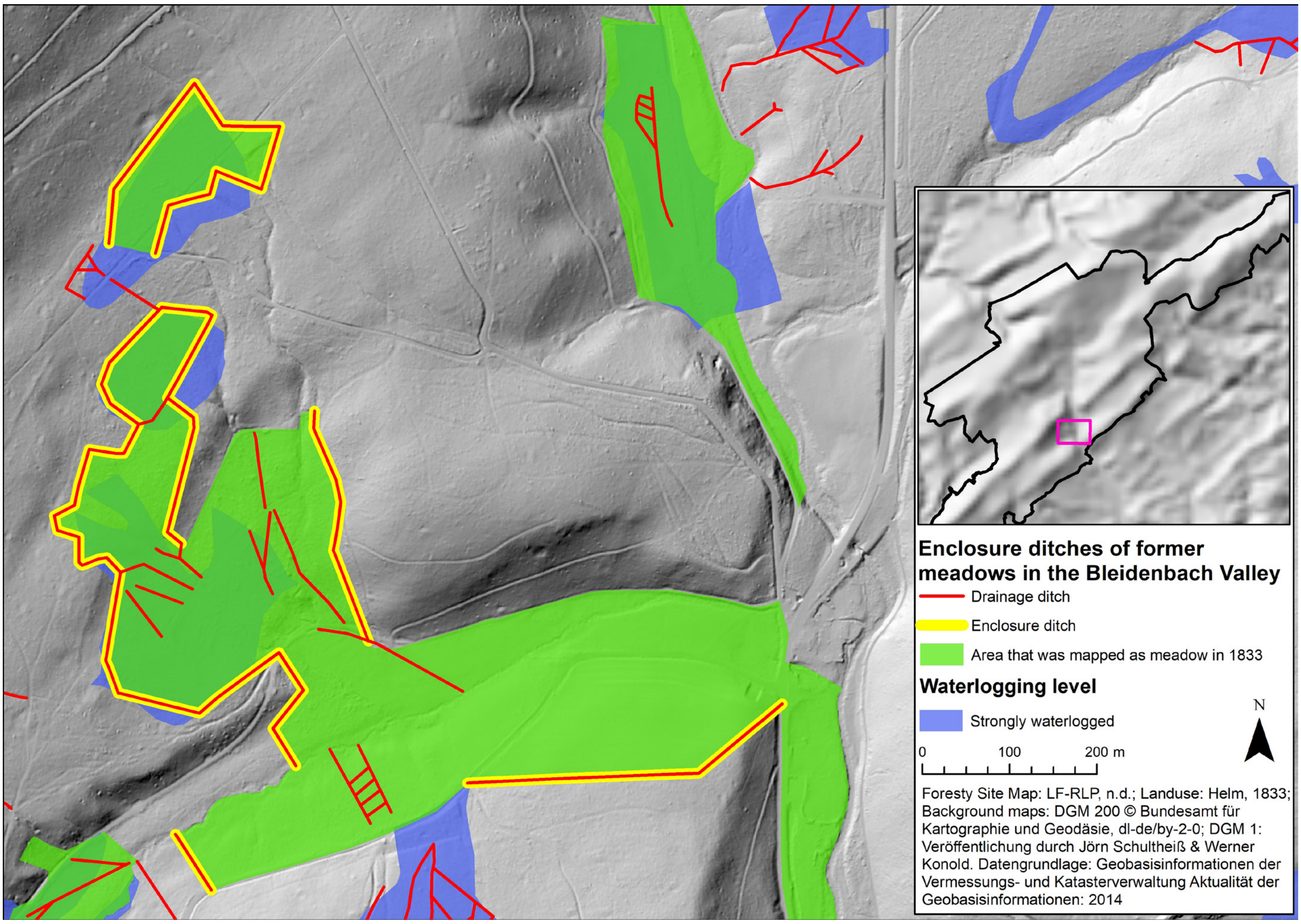

Figure 7. Former meadows in the Bleidenbach Valley mapped in by Helm in 1833 are now largely wooded. Many ditches not only served for drainage but also marked the former boundary between forest and open land use.

etation or fallen branches and logs (Figure 8a). A few main ditches have partly collapsed. However, many of them, especially when they have to carry a lot of water and have a higher slope, show clear signs of depth and width erosion as well as undercutting. Many side ditches are overgrown or sedimented (Figure 8b).

The roads built in the early 20th century for drainage purposes are almost all out of use today. Even now, they are clearly visible in the field as recognizable linear structures. Upon entering wet areas, they are heavily overgrown with moisture-indicating herbaceous vegetation. With an increase in the waterlogging stage, both the vegetation and the degree of wetness of the road body intensify. Noteworthy is their construction. They usually have two roadside ditches that are cut deep into the relief. This feature is almost nowhere else found in the National Park. Especially on steep slopes, these roadside ditches can be more than one meter deep. At the same time, the roads have a massive structure that likely served both road maintenance and additional drainage purposes.

Within a brief span of time, wetlands selected for restoration activities underwent a profound transformation. Previously drained and densely stocked with spruce, these wetlands developed into structurally rich areas. On very waterlogged wetlands, ditch closures with sheet piling, wood chips, and sawdust were implemented. There widespread waterlogging is clearly noticeable. Within a few years, diverse, wetland-adapted primary vegetation, including common reed (*Phragmites australis*), eagle fern (*Pteridium aquilinum*), and a significant increase in moss growth, developed in these areas. The closed drainage ditches are usually only faintly visible (Figures 8c & d). However, slight depressions and sedimentations still indicate that water regularly flows down

Figure 8. a) Main ditch in the Thranenbruch wetland before the spruces were removed and the entire ditch system was closed. The ditch is very clearly visible in the field, has a gentle slope, is filled with dead wood, and covered with moss; b) Heavily overgrown side ditch in the Langbruch wetland. Without the knowledge of the drainage system from the DEM, this structure would hardly be recognizable as a ditch in the field; c) Ditch closures in the Thranenbruch wetland using sawdust and Douglas fir sheet piling in 2018. Prior to this, all spruce trees in the area were harvested; d) The Ochsenbruch wetland in 2023, now characterized by moisture-indicating primary vegetation. Formerly dominated by spruce, which was removed after 2010. In 2015, drainage ditches were closed with sawdust and Douglas fir sheet piling.

in larger quantities on the filled main ditches during and after rainfall. Drainage systems with lower waterlogging levels were restored with mineral plugs. There a lower widespread waterlogging is evident in form of stagnating water in the ditches.

4 Discussion

4.1 The effectiveness of the methodological approach

The study demonstrates that a combination of historical analysis, DEM investigations, and field surveys provides a very precise representation of the drainage system in the Hunsrück-Hochwald National Park. The interaction between the three methods is particularly pronounced. Through historical analysis, it was not only possible to determine when forest drainage began and ended, but also to track its historical development. This revealed that drainage was viewed critically throughout. Furthermore, the historical analysis provided clear evidence that not all structures believed to have been designed for drainage reasons were actually intended for that purpose. This is especially apparent in the case of enclosing ditches, which primarily served to demarcate land or had administrative purposes. Additionally, the historical analysis revealed that certain pathways were deliberately constructed for drainage purposes, a fact that would not have been discernible without this method. The existence of irrigation ditches would also not have been discovered without the historical analysis.

4.2 Remote Sensing and DEM Analysis

The remote sensing investigation of the DEM offers extensive insights into the presence of drainage structures. Given the typical fishbone-like pattern of the drainage systems in the area, their presence could be accurately mapped without the need for extensive fieldwork, providing a comprehensive overview of the hydrological modifications within the study area. Field surveys, however, are essential to complete the investigations, as they are the only way to determine the actual condition of the drainage system. It is important to note that, without the knowledge gained from remote sensing, field investigations would be far less efficient. Smaller, gently sloping, or long-neglected drainage ditches would be difficult or impossible to locate in the field without precise location data from the DEM. At the same time, the study shows that without field surveys, drainage systems recorded solely using DEM data would present considerable inaccuracies, as structures could be misinterpreted as ditches or actual ditches could be overlooked.

It should be noted, however, that the low point density of the used DEM generated in 2014 resulted in a relatively coarse remote sensing analysis. With a higher-resolution DEM, a greater number of ditch structures would likely have been identified in the remote sensing analysis (Cățeanu & Ciubotaru, 2021). Thus, for an adequate evaluation of ditches, a point density of 2 points per meter is required (Rapinel et al., 2015). On the other hand, the use of 1 m DTMs also demonstrates a certain degree of practical applicability in planning. These DTMs are freely available for large parts of Germany and thus find the most widespread use in professional practice.

4.3 Challenges from renaturation measures

A methodological challenge is that many of the drainage ditches presented here have been significantly modified by the renaturation measures gradually implemented until 2019 (for example, by complete infilling). As a result, the collected data do not reflect the current ditch system but rather the historical one, which was primarily designed for drainage purposes. Although the ditches still exist, their visual detectability and hydrological effectiveness have been greatly altered (Zemke, 2021). This also makes it impossible to remotely reanalyze the pre-intervention ditch system using a higher-resolution DEM. Due to the extensive filling of the ditches and the intended adaptation to the surrounding terrain, alternative prospecting methods may become more suitable for future surveillance of the renaturated ditch networks. Particularly in sparsely wooded, renatured peatlands, filled ditches may remain visible through vegetation patterns, making them especially detectable in aerial imagery (Jucha et al., 2020).

In renaturation practice, there is often a heavy reliance on DEM analyses, supplemented by subsequent field surveys of the affected ditches. Our study demonstrates that this approach can quickly lead to misinterpretations. DEM analyses merely reflect the current state of the terrain surface without providing a broader contextual framework (Johnson & Ouimet, 2017). In cases such as that of Hunsrück-Hochwald National Park, where active interventions in the drainage systems are being planned, unintended errors in these interventions may rapidly occur if the context is not sufficiently expanded. Our study shows that the use of DEMs in landscape analyses provides significant added value only when combined with additional investigative methods. This has already been noted in other studies, including van der Schriek and Beex (2017).

4.4 Challenges of archival analysis

Archival data from hundreds of individual files were analysed and compiled into a cohesive picture, illustrating the historical development of drainage networks in the national park. This analysis allowed for the identification of when drainage efforts began, their peak period, and when they declined. Additionally, it provided valuable insights into the methods used, the underlying intentions, and the challenges faced. A significant difficulty in this research was the lack of historical records explicitly addressing forest drainage. Instead, information on this topic was scattered across various documents, such as forest management plans or financial records. Throughout the investigation, it became clear that drainage activities involved multiple disciplines, increasing the potential availability of relevant data. Not only did forestry administration influence the area's hydrology, but in the 19th century, extensive land improvement measures were undertaken in rural Prussia. These activities, originating mostly outside forestry, still had a significant impact on forest hydrology. By the 20th century, municipalities and private enterprises also played a growing role in modifying the hydrology of forests to secure drinking water for both municipal and private use.

The research revealed that a substantial amount of data potentially exists regarding the historical development of hydrological modifications in the study area, but it is dispersed across various locations. This dispersion is partly due to the fact that the region has belonged to different administrative entities in the past.

4.5 Field survey insights and limitations

The ditches were largely recognizable as well-defined, mostly straight depressions in the LiDAR image. It was found out that almost all structures classified as ditches through remote sensing were actually ditches. Especially on "very waterlogged" sites, many ditches would not have been detectable without knowledge of the LiDAR data. On the other hand, it was observed that in almost all visited areas side ditches that were not shown in the LiDAR could be identified. Their number was comparatively small. It was evident that the smaller or more sedimented a drainage ditch was, the less likely it was to be represented by the DEM. In general, the field survey expanded the mapping, particularly for smaller, heavily sedimented, or overgrown ditches. Therefore, a combination of remote sensing and on-site analysis is indispensable for a detailed survey of drainage systems.

Further difficulties arose in the classification of individual ditches. Many ditches traverse the lowest areas of the relief, where natural watercourses are flowing. Remote sensing investigations suggest that in the past natural watercourses were artificially deepened and straightened to optimize them for drainage. Therefore, they represent both natural watercourses and artificial ditches – they are semi-natural flow structures. This is especially true for structures in spring areas where the spatial dimensions of natural watercourses are still small. The classification of such structures as artificial ditches or natural watercourses was done on a case-by-case basis. In cases where significant modifications were evident in the field, these areas were also classified as ditches.

4.6 Methodological considerations and expertise required

A key challenge lies in the broad range of expertise required for the applied methodologies. Historical analysis demands knowledge of archival sources and an understanding of historical context, while remote sensing and field surveys require GIS expertise and the ability to recognize historical land-use structures in both the DEM and the field. Each method has distinct advantages and disadvantages in its application. As the study demonstrates, investigating the historical development of drainage in the area can provide precise information regarding the reasons, timeframes, and methods of drainage in forest areas. However, the time investment required to obtain this information is significant, due to the diversity of archival records and their wide spatial distribution. DEM analyses can be conducted quickly, but they carry the risk of misinterpretation when used alone. Field surveys are indispensable for accurately documenting the forest drainage system, though they demand significant time and manpower, particularly given the often challenging terrain.

Importantly, the study highlights that only by combining historical and remote analysis as well as field surveys can misinterpretations be significantly reduced, allowing for a precise understanding of the drainage system. The necessary effort is substantial, but it may be worthwhile for both scientific and practical reasons, such as in the renaturation of wetlands. In the Hunsrück-Hochwald National Park, this knowledge has contributed to more efficient planning and implementation of renaturation measures, providing an example of how nature conservation interventions can be more effectively implemented with a deeper understanding of hardly known anthropogenic influences.

Depending on the objective, it may be more appropriate to focus on specific methods. For instance, historical analyses are useful for understanding the full scope of human intervention in water management, which extends beyond drainage ditches. This can be particularly important when engaging with various stakeholder groups affected by changes to water systems, such as nature conservation, water supply management, cultural heritage preservation, or agriculture. Such information can also be highly valuable when communicating with the public. Remote sensing investigations may be advantageous when large-scale water retention measures are to be implemented without extensive planning. However, the integration of field surveys is essential, as they provide the only detailed picture of the drainage system in the affected forest area, which is crucial for accurate planning.

As highlighted by Roelens et al. (2018), Ågren & Lidberg (2019), Koschorreck et al. (2020), Peacock et al. (2021), and Flyckt et al. (2022) a significant portion of water flow paths has not been adequately documented, a fact that was also evident in the Hunsrück-Hochwald National Park. The study suggests that, particularly in regions characterized by wetlands where a comprehensive analysis of natural, semi-natural, and artificial watercourses has not yet been conducted, the number of such structures is likely to be significantly higher than previously assumed. The commonly held belief that Central European forests contribute positively to water retention capacity must be fundamentally reevaluated. This study underscores the significant and precise anthropogenic interventions undertaken in the past for water drainage, which remain effective and thus contribute to forests exacerbating the impacts of climate change.

4.7 Cultural-historical landscape understanding in protected areas

Through historical-generic studies like the one presented here, the long-term, culturally influenced character of a landscape can be captured. However, the methodological effort required for this is significant. This approach is of particular interest in protected areas such as national parks, where future anthropogenic influences are intended to be minimized as much as possible, thereby halting the active changes that have shaped the landscape for centuries and millennia.

The understanding that comprehensive landscape analyses are only possible through the combination of various investigative methods is not new and has been described, among others, by Affek et al. (2022). However, this study integrates the laborious examination of historical archival data. In particular, when combined with DEM data and field surveys, they enable a detailed analysis of the landscape shaping of a region.

The observation of ditches used to delineate usage or administrative boundaries has already been confirmed by other studies (including Affek, 2016). In our study, we found no evidence regarding the age of these ditches, and their basic structure does not differ from that of drainage ditches. They can only be identified as ditches marking usage or administrative boundaries based on their course and with reference to historical topographic maps.

4.8 Implications for future activities

The findings from this study are particularly relevant to hilly Central European regions that also include wetlands within forests. There may be significant knowledge gaps regarding the existence and courses of natural, semi-natural, and artificial watercourses in nearly all of these areas. The intensified efforts across Central Europe in recent years to increase landscape water retention demand a comprehensive understanding of hydrological processes to avoid misplanning or inefficient implementation. It is therefore imperative to document past interventions in the hydrology of cultural landscapes, spatially locate them, evaluate their environmental impacts, and develop adaptation strategies.

In most forest and open landscapes, significant insights could be gained using the relatively simple methodological approaches presented in this study.

5 Conclusions

This study emphasizes the effectiveness of integrating historical analysis, DEM investigations, and field surveys to accurately depict the drainage system in the Hunsrück-Hochwald National Park. A combination of remote sensing (DEM analysis), historical analysis, and field surveys is necessary to obtain an accurate understanding of the drainage system and to minimize misinterpretations. Historical analysis provides precise information on the origins and purpose of drainage systems but is time intensive. DEM analysis is fast but prone to misinterpretation. Field surveys are essential for accurate documentation but require significant time and labor. The combination of all three methods provides the greatest benefit for both research and practice. However, depending on the objective, specific methods may be prioritized, such as historical analysis for stakeholder communication or remote sensing for large-scale interventions.

The combined use of these methodologies not only mitigated misinterpretations but also yielded valuable insights into historical land use and hydrological modifications. Although each method has distinct strengths and challenges, the collaborative approach enhances understanding of anthropogenic influences on water systems, particularly in the context of climate change. Overall, this study advocates for a comprehensive examination of hydrological processes to inform more effective nature conservation and water management strategies.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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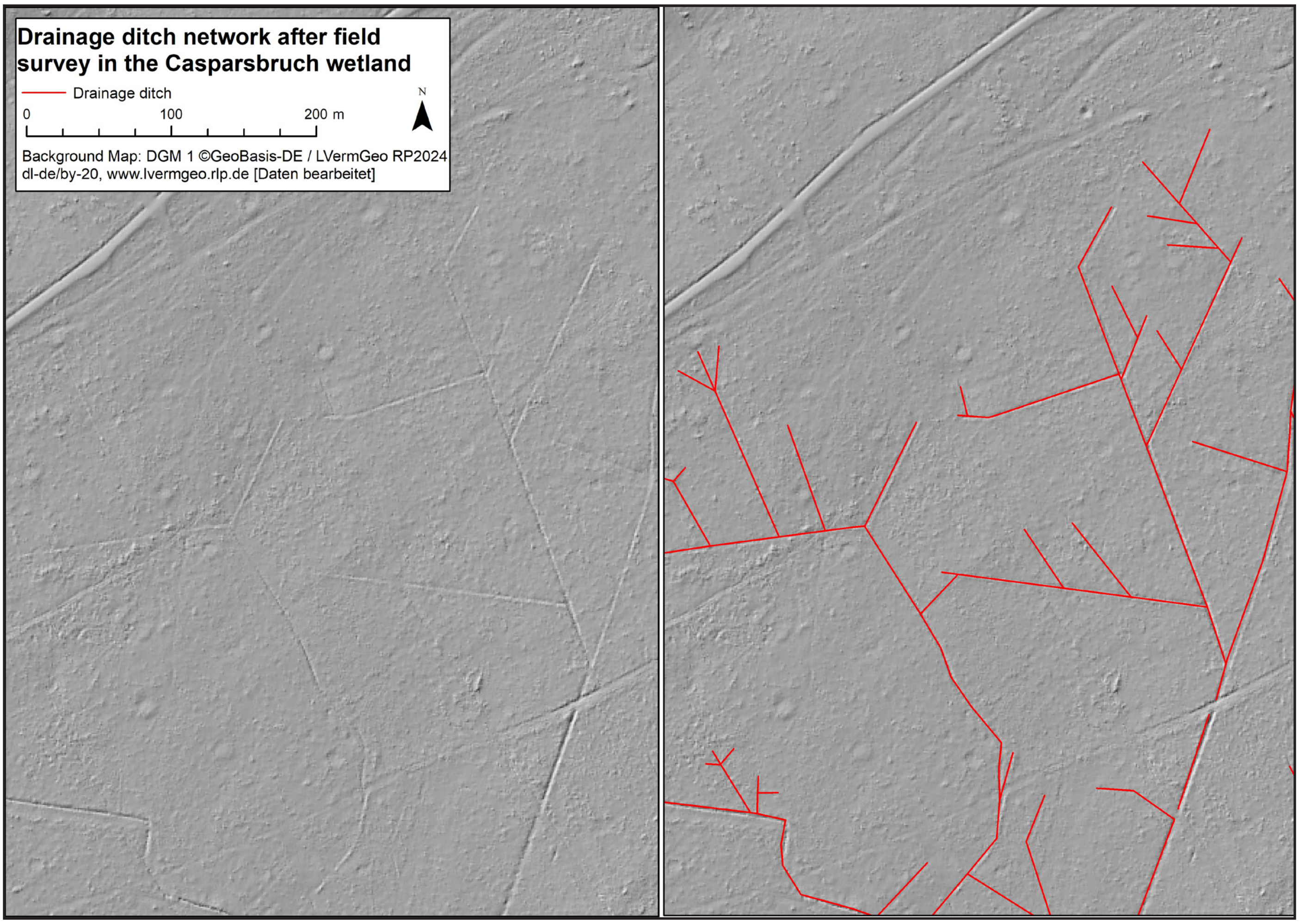
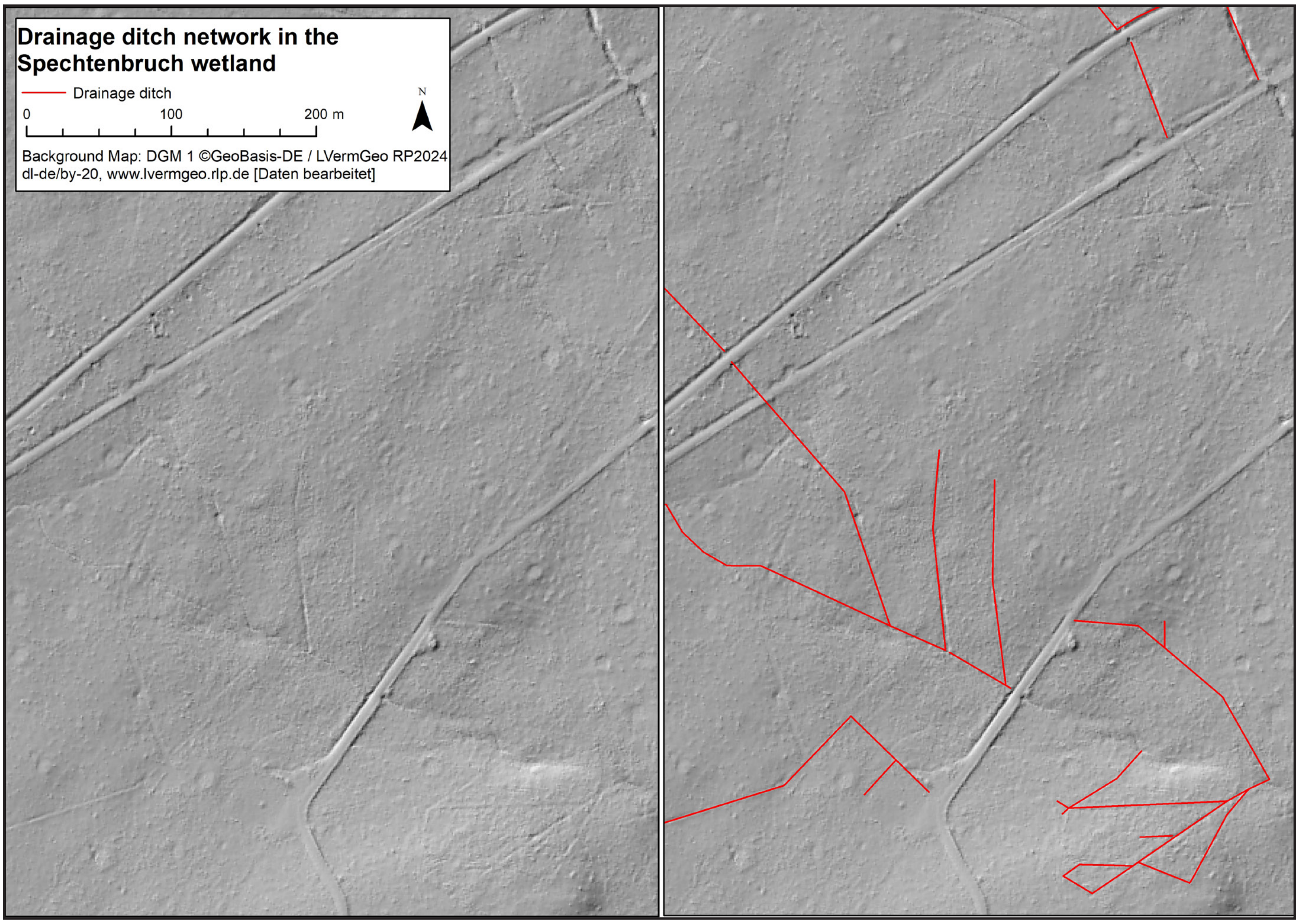
Supplementary material

Measuring of a ditch using a tape measure.



Structures that suggest drainage ditches in the DEM (left) and after the analyzation of DEM-data and the field survey (right) in the Casparsbruch wetland. Without the integration of field surveys, many of the smaller ditches would not have been identified.



Structures in the DEM in the Spechtenbruch wetland show ditches running along the contour line into the Riedfloß stream, which was also partly artificially modified. Based on remote sensing and field investigations, a portion of the Riedfloß was classified as a ditch due to its significant artificial modification, while a lower-lying section was not.