



# Comparing Ecohydrological Characteristics of European Kettle Holes and Prairie Potholes for Effective Conservation and Management

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## Abstract

The last glaciation period, known as the Wisconsin glaciation in North America and the Weichselian glaciation in North Central Europe (NCE), sculpted distinctive landscape features across these regions, including kettle holes in NCE and prairie potholes in the North America's Prairie Pothole Region (PPR). These depressions, formed by retreating glaciers, hold significant hydrological and ecological importance, and conservation interest. The primary aim of this review article is to compare the similarities and differences between kettle holes in NCE and prairie potholes in the PPR, particularly concerning their ecohydrological characteristics, which have not been thoroughly compared or documented. By clarifying these distinctions, we can gain a better understanding of their unique features. This, in turn, enables wetland scientists to propose tailored management strategies to policymakers and decision-makers for conservation efforts. Our review explores, in particular, kettle holes/prairie potholes' roles in water storage, nutrient cycling, and habitat provision. We also discuss the impact of anthropogenic activities, such as agricultural and land management practices, on the ecological integrity of these wetlands and propose strategies for their conservation and sustainable management. By elucidating the intricate interplay between geological history, hydrological processes, and ecological dynamics, this article provides valuable insights for researchers, policymakers, and conservation practitioners working towards the preservation of these globally significant wetland habitats. Our synthesis underscores the critical need for interdisciplinary research efforts and integrated management approaches to address the conservation challenges facing prairie potholes and kettle holes in the context of ongoing environmental changes and increasing human pressures.

**Keywords** North Central Europe · Prairie Pothole Region · Surface Hydrology · Groundwater Hydrology · Aquatic Plants · Wetland Ecosystems

## Introduction

The most recent glaciation commenced approximately 110,000 years ago and ended between 11,700 years ago (Severinghaus and Brook 1999) and even later in some regions such as the Prairie Pothole Region (PPR) ranging from 9000 to 13,000 years ago (Vasilas 2017), covering vast areas of the Northern Hemisphere. This period is called the Wisconsin glaciations in North America and the Weichselian glaciation in North Central Europe (NCE) (Severinghaus and Brook 1999).

The postglacial, till-dominated landscape of NCE and the PPR are dotted with depressions having a bowl-shaped bottom with gentle curvature (Hayashi and van der Kamp 2000). These depressions are called kettle holes (or kettles) in NCE and prairie potholes (or sloughs) in North America, i.e., the PPR.

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Among the numerous geomorphological features associated with glacial landscapes, such as drumlins, eskers, and moraines, kettle holes form when ice blocks, abandoned by a receding glacier, melt and create a depression in the terrain (Ala-aho et al. 2013; Bennett 2011; Evans 1997) (Fig. 1). These ice blocks, once detached, rest on the surface and may become partially or entirely covered. Upon subsequent melting, a void is left, resulting in a topographic pit. Commonly referred to as “kettle lakes”, simply “kettles”, or more broadly as “thermokarst lakes”, these landforms exhibit morphological variation depending on factors such as the amount of debris in the ice and the manner in which the ice is buried after glacier retreat (Fay 2002; Maizels 1977). Typically circular, kettles can exhibit raised rims or be level with the surrounding plains (Fig. 1). A specific subtype of kettles with elevated rims is aptly termed “crater” type kettle holes, underscoring the morphological resemblance between certain kettles and craters (Maizels 1992).

However, kettle hole is also used as a generic term in NCE to refer to depressions in the hummocky terrain of glaciated landscape without consideration of geological origin (e.g. Schweizer 2012). For instance, Kalettka and Rudat (2006) defined kettle holes as small, shallow, glacially created depressional wetlands that collect water from their catchments. The shallowness of kettle holes is ascribed to

the deposition of peat, gyttja, and gyttja mixed with silt and sand after the formation process (Karasiewicz 2019).

North American researchers use prairie pothole or prairie slough to avoid specific reference to the geological origin of a depression (e.g. supraglacial vs. subglacial), which is difficult, if not impossible to determine with confidence (Eyles and Lazorek 2014). To that regard, Kantrud et al. (1989a) postulated that prairie potholes were formed either by the scouring and shearing action of glaciers or by the collapse of ice blocks left behind and subsequently melted after glacial retreat. Flint (1955) noted that many prairie potholes in South Dakota originated when glacial drift materials obstructed ancient bedrock valleys. Additionally, some prairie potholes formed from sediments deposited by meltwater flowing from retreating glaciers (Kantrud et al., 1989a). The term “kettle hole” is used in NCE to indicate a depressional wetland, whereas “prairie pothole” or “prairie slough” is used in the PPR to indicate a topographic feature or a wetland with particular ecological and hydrological functions, although some researchers use “prairie wetland” or “prairie pothole wetland” to emphasize the ecohydrological functions (Winter 1989). In the following, “kettle hole” is used in its present usage in the literature of NCE, covering all depressional wetlands in the glaciated landscape of NCE. Although “prairie pothole” is used for the postglacial depressions of the PPR, the presence of *sensu stricto* kettle

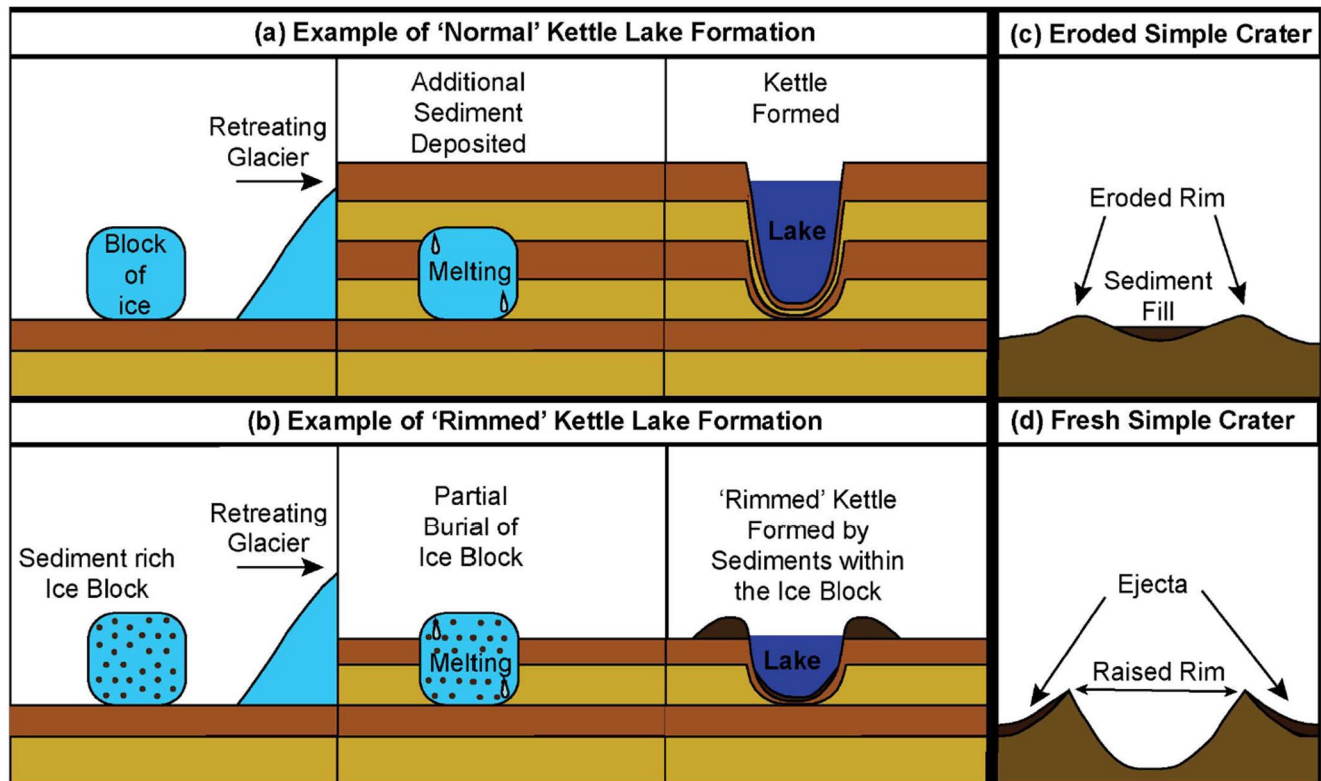


Fig. 1 Schematic of the formation mechanism for normal kettle hole and rimmed kettle hole, taken from Day et al. (2023)

holes in northern and southern Ontario, which are outside of the PPR, is also reported in the literature (e.g. Campbell et al. 1997; Day et al. 2023).

In North America, the PPR covers about 800,000  $km^2$  that extend across five U.S. states (Minnesota, Iowa, North and South Dakota, and Montana) and three Canadian provinces (Saskatchewan, Manitoba, and Alberta). The PPR has a high density of depressions and hosts millions of migrating waterfowl during breeding and nesting season (Hansen and Loesch 2017). The physiography of the PPR is characterized by (1) glacial sediments deposited during the Wisconsin glaciation and (2) cold and semi-arid climates, where mean annual precipitation is exceeded by potential evapotranspiration (Goldhaber et al. 2014). The dominant glacial sediments in the PPR is clay-rich till, which has generally low hydraulic conductivity except for the top most 5–10 m of the weathered zone, where the network of macropores and fractures increase the hydraulic conductivity by several orders of magnitude (Lennox et al. 1988; van der Kamp and Hayashi 1998). To that respect, based on the study of Winter and LaBaugh (2003), glacial tills generally exhibit relatively high hydraulic conductivity values ( $> 1$  m/year) in the intensely fractured near-surface zone, typically within 4–5 m of the surface, while the hydraulic conductivity values drop substantially ( $10^{-3}$  to  $10^{-2}$  m/year) in the deeper zones.

Kettle holes are typical postglacial landscape features of the young Pleistocene moraine areas, which occur widely across the agricultural and forested landscapes in NCE (Platen et al. 2016). The glaciated areas containing kettle holes cover approximately 200,000–300,000  $km^2$  across northeastern Germany, northern Poland, and parts of Denmark, Lithuania, and the Baltic states. Kettle holes are typically less than 0.01  $km^2$  in size and their dimension is a function of the extent of burial and the size of the dead ice block (Maizels 1977). Due to the relatively short period of landscape evolution in hummocky terrains, stream networks have not reached full development. As a result, the majority of kettle holes remain unconnected to any streams (Lischeid and Kalettka 2012). These post-glaciated depressions are distributed densely over an undulating terrain and are categorized as having permanent or temporary/seasonal ponds (Lischeid et al. 2018). The soil type in NCE varies from mainly loamy to sandy, in contrast to clay-rich soils of the PPR. Land use ranges from intensively used areas for agricultural production to small isolated patches of forests. Their perimeter is highly dynamic and fluctuates significantly with changes in hydroperiod (Kayler et al. 2018). Some specific properties of kettle holes and prairie potholes are listed in Table 1.

The overarching objective of this review is to identify the commonalities and differences between kettle holes in

NCE and prairie potholes in the PPR regarding their ecohydrological characteristics, which have not been well documented in the literature. The comparison of kettle holes in NCE and prairie potholes in the PPR is useful due to their shared glacial origin and critical roles in regional hydrology and ecology, despite the ecohydrological differences influenced by distinct geomorphological and climatic conditions, as well as anthropogenic factors such as agriculture activities. These differences stem from factors such as soil composition — clay-rich tills in prairie potholes favor water retention, whereas sandy or loamy soils in kettle holes result in a lower water retention condition and a shorter groundwater residence time. Climatologically, the PPR's semi-arid conditions have led to ephemeral and seasonal flooding of prairie potholes, compared to the more stable hydroperiods of kettle holes influenced by temperate climates. Hydrological connectivity further distinguishes these systems: prairie potholes rely mainly on snowmelt runoff generated on the frozen soil and fill-spill mechanisms, while kettle holes are mainly in connection with their shallow groundwater system. Understanding these distinctions is important for tailored conservation, as both systems provide vital ecosystem services, including water storage, nutrient cycling, and biodiversity support, but are subject to unique pressures such as extensive drainage in the PPR and sedimentation in NCE (Savić et al. 2021). Comparative analysis offers insights into global wetland degradation, cross-regional conservation practices, and ecohydrological processes. These insights enable policymakers to develop targeted strategies for addressing specific challenges, such as managing hydroperiod variability and mitigating the impacts of agricultural activities. By synthesizing these perspectives, this review underscores the importance of integrating interdisciplinary knowledge to preserve these globally significant wetlands in the face of climate change and anthropogenic interferences. In light of this clear distinction, an enhanced understanding of their characteristics may be achieved, which in turn, allows wetland scientists to offer specific management measures to policy and decision makers for conservation purposes.

### Surface Hydrology of Prairie Potholes and Kettle Holes

As kettle holes and prairie potholes are a part of the hydrologic continuum, they allow us to detect the changes that occur to regional hydrological system and to trace water through the hydrologic cycle (Amado et al. 2018; Hayashi et al. 2016). From a qualitative perspective, kettle holes receive substantially larger inputs of pesticides (Lorenz et al. 2017), plant biomass, soil particles via event based erosion, and nutrients (e.g. fertilizers) (Nitzsche et al. 2017), in

**Table 1** General properties of kettle holes and prairie potholes distributed across NCE and the PPR

Characteristics	Kettle Holes	Prairie Potholes
Geomorphology	<ul style="list-style-type: none"> <li>- Formed by glacial retreat and ice block melting (Maizels 1977)</li> <li>- Typically smaller, varying from 1 ha to 10 ha, and more irregularly shaped</li> <li>- Depths generally &lt; 5 m</li> <li>- Often occur in groups in glaciated landscapes of North Central Europe (NCE)</li> <li>- Density varies from 4 to 8 per km<sup>2</sup>; the estimated number of kettle holes ranges from 150,000 to 300,000 (in north-eastern Germany) (Kalettka and Rudat 2006)</li> </ul>	<ul style="list-style-type: none"> <li>- Formed by the scouring and shearing actions of glaciers, the collapse of ice blocks (Kantrud et al., 1989a), and damming of ancient bedrock valleys by glacial drift materials (Flint, 1955)</li> <li>- Ranging from 0.1 ha to over 50 ha in size, and more uniform in shape</li> <li>- Depths range from shallow depressions to &gt; 5 m</li> <li>- Found in the Prairie Pothole Region (PPR) in clusters</li> <li>- Average density is about 16 per km<sup>2</sup> (before initialization of anthropogenic activities), and now from 3 to 10 per km<sup>2</sup> (depending on seasonal water level) (Winter and Rosenberry 1995); total number of prairie potholes is estimated to be 12.6 million (van der Valk and Pederson 2003)</li> </ul>
Soil	<ul style="list-style-type: none"> <li>- Predominantly sandy and silty soils separated by marly layers, classified as Histosols</li> <li>- Higher soil permeability</li> <li>- Organic matter accumulation in depressions (core of peat/mud or fossil soil horizon)</li> <li>- Lower water-holding capacity (Gerke et al. 2010)</li> </ul>	<ul style="list-style-type: none"> <li>- Typically, glacial till, clay loam to silty clay loam</li> <li>- Lower soil permeability</li> <li>- With higher organic content in wetland areas</li> <li>- Higher water-holding capacity (Euliss et al. 2004)</li> </ul>
Climatology	<ul style="list-style-type: none"> <li>- Temperate climate with significant seasonal variation</li> <li>- Average annual precipitation: 500–700 mm with major fraction of precipitation in summer months (June to August), a lower occurrence of snowfall</li> <li>- Average annual temperature: 7–10 °C</li> <li>- Influenced by both maritime and continental climate (Hattermann et al. 2015)</li> </ul>	<ul style="list-style-type: none"> <li>- Continental climate with extreme temperature variations</li> <li>- Average annual precipitation: 300–600 mm with major fraction of precipitation in the late spring and summer months (May to August), a higher occurrence of snowfall</li> <li>- Average annual temperature: 2–10 °C</li> <li>- Influenced by mid-continental climate factors (Winter 2000)</li> </ul>
Surface Hydrology	<ul style="list-style-type: none"> <li>- Seasonal wet-dry cycles, often with a more stable hydroperiod, i.e. semi-permanent kettle holes</li> <li>- Water sourced from precipitation and surface runoff generated on frozen soils</li> <li>- Hydrologically isolated with no surface outlet (Lischeid et al. 2018)</li> <li>- Range of electrical conductivity: 100–2500 µS/cm</li> </ul>	<ul style="list-style-type: none"> <li>- Water levels vary seasonally, often with short permanency, i.e. ephemeral and seasonal prairie potholes</li> <li>- Receives water from precipitation, snowmelt, and surface runoff</li> <li>- Hydrologically isolated with no surface outlet</li> <li>- Range of electrical conductivity: a few hundred to more than 10,000 µS/cm depending on their position within the landscape (Ali et al. 2017)</li> </ul>
Groundwater Hydrology	<ul style="list-style-type: none"> <li>- Their hydrological type is mostly dominated-flow through system</li> <li>- Being influenced mainly by their adjoining shallow groundwater</li> <li>- Dominance of groundwater in sustaining water levels, especially in dry periods</li> <li>- Affected by reversal groundwater flow (Steidl et al. 2023)</li> </ul>	<ul style="list-style-type: none"> <li>- Their hydrological type is mostly dominated-recharge system</li> <li>- Being influenced mainly by their adjoining shallow groundwater</li> <li>- Dominance of surface water (i.e. direct precipitation and surface runoff on frozen soils) in sustaining water levels</li> <li>- Affected by reversal groundwater flow (Rosenberry and Winter 1997)</li> </ul>
Ecology	<ul style="list-style-type: none"> <li>- Diverse flora and fauna, including aquatic plants</li> <li>- Dominant plants are <i>Phalaris arundinacea</i> (reed canary grass), <i>Carex</i> spp. (sedges), and <i>Phragmites australis</i> (common reed) (Pätzig and Düker 2021)</li> <li>- Sensitive to agricultural soil erosion and pollution</li> <li>- Often surrounded by croplands and only partially by forests (Pätzig et al. 2012)</li> </ul>	<ul style="list-style-type: none"> <li>- Supports a wide variety of wildlife, especially waterfowl</li> <li>- Dominant plants are <i>Typha</i> spp. (Cattails), <i>Scirpus</i> spp. (Bulrushes), and <i>Carex</i> spp. (Sedges) (Ogaard 1981)</li> <li>- Vulnerable to agricultural soil erosion and pollution</li> <li>- Surrounded by grasslands and agricultural lands (Doherty et al. 2016)</li> </ul>
Ecohydrology	<ul style="list-style-type: none"> <li>- Complex interactions between hydrology and vegetation</li> <li>- Plays a role in nutrient cycling, sediment deposition, and support habitat diversity</li> <li>- Sensitive to changes in land use and climate change (Onandia et al. 2018)</li> </ul>	<ul style="list-style-type: none"> <li>- Integral to the hydrology and ecology of the PPR</li> <li>- Supports nutrient cycling and provides habitat diversity</li> <li>- Vulnerable to agricultural practices and climate variability (Hayashi et al. 2016)</li> </ul>

comparison with larger water bodies due to their close connection to adjacent agricultural fields and in combination with their intrinsic shallow system. Similarly, agricultural practices and the presence of drainage systems can significantly influence the biogeochemical processes in the PPR and the water quality downstream (Evenson et al. 2018). In comparison to other natural wetlands, prairie potholes tend to experience a greater potential for sediment accumulation (Skagen et al. 2016), lower carbon storage due to frequent wet-dry cycles that accelerate organic matter decomposition through increased soil oxygen exposure (Euliss et al. 2006), and elevated nutrient concentrations during the growing season (Martin et al. 2019). Hence, understanding the hydrology of kettle holes and prairie potholes is crucial for identifying the processes that influence the quality and quantity of individual water balance components, as well as the feedbacks among them and their responses to climatic variability and land management practices (Rosenberry and Hayashi 2013).

Kettle holes and prairie potholes can play an important role in storing water, increasing evapotranspiration, and increasing focused groundwater recharge, thereby affecting the hydrological cycle in the glaciated landscape (Hayashi et al. 2003). They provide a wide range of ecosystem services, including water quality improvement, drought and flood impacts mitigation, wildlife habitat, and focused groundwater recharge (Vasić et al. 2020; Werner et al. 2013). With the purpose of expanding croplands, many of kettle holes and prairie potholes have been drained, filled, and removed (Renton et al., 2015) — although farmed depressions may not be as productive as uplands owing to poor soil quality, erosion, and water logging (Muth and Bryden 2012). For instance, analysis of aerial imagery and datasets has shown a significant decline in prairie potholes' areas in Canada as a result of agricultural practices, with estimates indicating that 40 to 70% of these wetlands have been lost in some regions due to drainage activities (Chizen et al. 2024; Mitsch and Gosselink 2000; Watmough and Schmoll 2007). In contrast, historical data from the United States suggest an even more severe impact, with up to 90% of prairie pothole wetlands have been drained over time in some regions (Dahl 1990; Dahl 2011). With respect to kettle holes, it is estimated that between 28 and 88% of them in the northeast of Germany were eliminated, especially between 1960 and 1975 (Kalettka et al. 2001). In some areas, instead of infilling, draining, or eliminating prairie potholes, two or more have been combined into a larger one in an effort to maintain certain hydrological functions — a practice known as wetland consolidation (McCauley et al. 2015).

Prairie potholes are flooded in early spring owing to snowmelt runoff generated over the surrounding agricultural lands, in particular during wet periods in the context of

decadal-scale wet-dry fluctuations (Miller et al. 2012; Roth and Capel 2012). Similarly, flooding of the kettle holes of the Northeast of Germany by the winter runoff over frozen soils was reported (Gerke et al. 2010). While kettle holes are mostly located in agricultural lands, their water is not permitted for irrigation during drought conditions owing to regulations and conservation policies in Germany (Kalettka et al. 2001). During the periods of extreme wetness, kettle holes and prairie potholes can retain surface runoff and reduce flood peaks (Millett et al. 2009; Shook et al. 2013).

The connectivity of kettle holes in NCE and prairie potholes in the PPR to streams can arise due to spillage, sporadic surface runoff, and shallow groundwater flow (McDonough et al. 2015; Winter and LaBaugh 2003). The extent of this connectivity in time and space is highly variable, depending on local meteorological conditions (e.g. severe storm event/deluge, sustained drought) (Cohen et al. 2016; Leibowitz 2003). Pothole-to-pothole connectivity can be mainly explained by fill-spill mechanism (Hayashi et al. 2016; Shaw et al. 2012). In the “fill-spill” process, a topographic threshold is defined to indicate the volume of water that can be stored in a certain kettle hole/prairie pothole (Huang et al. 2013; Shaw et al. 2013). The flooded area in a prairie pothole varies with water depth, determining its additional water storage capacity at any time. This relationship is non-linear due to the hydrological “memory effect”, where total storage depends on the wetting-drying history over multiple years (Huang et al. 2011, 2013; Shook and Pomeroy 2011). The flooded area is also a function of land management practices (e.g. surface and subsurface drainage, cultivation, crop management), which affect the depth, duration, and aerial extent of ponds in prairie pothole (Upadhyay et al. 2019). Owing to the expansion of the flooded area during wet periods, prairie potholes can temporarily connect to one another. Although the processes controlling the surface connectivity between prairie potholes are well understood, the interconnection between a network of kettle holes and perennial streams in their vicinity is still a subject of ongoing studies in NCE (Kazempour Radi 2023; Taie Semiromi et al. 2022). Moreover, to the best of our knowledge, the fill-and-spill mechanism has not yet been studied for kettle holes in NCE.

The water quality of kettle hole ponds has a high degree of spatiotemporal variability (Bennion and Smith 2000; Gołdyn et al. 2015; Lischeid and Kalettka 2012). It is a function of land use and agricultural practices in their catchments, the water-level dynamics, and their position over landscape, which control their hydrological function (Igamberdiev et al. 2010). As postulated by Dempster et al. (2006), kettle holes' water quality can be a function of the exchange that occur between kettle holes and their groundwater domain. Being connected to their adjoining

shallow groundwater system, solutes can be transported from ponds to groundwater and vice versa. The water quality of temporary ponds is strongly influenced by factors such as morphological parameters, hydrology, and characteristics of the catchment area (Johnes 1996; Williams 2007). The significance of hydroperiod was emphasized by Espinar and Serrano (2009) and Goldyn et al. (2015), who identified it as the primary factor controlling a majority of the water quality parameters studied. Goldyn et al. (2015) showed that a longer hydroperiod of kettle hole resulted in a higher electrical conductivity (EC) and pH. Moreover, they found a longer hydroperiod led to a lower concentration of  $N - NO_3^-$ ,  $N - NH_4^+$ , and total phosphorus levels, indicating that shorter hydroperiods were associated with higher enrichment of nitrogen and phosphorus in the studied kettle holes. Dense submerged vegetation typical of kettle holes with longer hydroperiods actively absorbs nutrients, dissolved carbon dioxide, and  $HCO_3^-$ , thereby reducing nutrient concentrations and raising the pH value (Joniak et al. 2007).

Cieśliński et al. (2020) examined the water balance of kettle holes in northern Poland using the chemical composition of kettle holes' water. They showed that the atmospheric water was a major component of the water balance, based on a more dilute chemical composition of kettle hole water compared to lakes located in the same area. The land use pattern was an important factor affecting the variability of chemistry compositions; the closer the kettle holes were to croplands, the higher concentration of major ions they had.

In contrast to studies showing the water quality of kettle holes/prairie potholes is predominantly affected by the condition of the terrestrial conditions (e.g. land use), Lischeid et al. (2018) showed that the internal processes are the determining factor that influence the water quality of kettle holes. It is worth noting that the factors influencing the water quality of individual kettle holes or prairie potholes can be highly site-specific, highlighting the need for further research. It is also worth mentioning that kettle holes located in agricultural areas have a poorer water quality than those located in forested areas (Gałczyńska et al. 2011). Gałczyńska et al. (2011) found that water chemistry of kettle holes surrounded by trees show the lowest concentration of micro- and macroelements, required in relatively large and small amounts for biological and ecological functions, respectively, including mineral forms of nitrogen ( $N - NH_4^+$ ,  $N - NO_3^-$ ,  $N - NH_4^+$ ,  $N - NO_2^-$ ), phosphorus ( $P - PO_4^{3-}$ ), and the concentration of metal ions: K, Na, Ca, Mg, Fe, Zn, Cd, Li, Sr, Cu, and Mn) in comparison with the water chemistry of kettle holes encircled with meadows and villages.

In the PPR, previous studies have demonstrated that the weathering of reactive sulfide and carbonate minerals

along groundwater flow paths in glacial till plays a significant role in controlling the chemical composition of prairie potholes' water (e.g. Heagle et al. 2013; Nachshon et al. 2013). Carbonate mineral dissolution serves as a primary source of  $Ca^{2+}$  and  $Mg^{2+}$  ions, whereas the oxidation of pyrite contributes  $SO_4^{2-}$  to both groundwater and prairie potholes' water in the PPR. On both local and regional scales, the hydrochemistry of prairie potholes exhibits significant variability in salinity and solute composition (e.g. LaBaugh 1989). As salinity increases, the selective removal of calcium-rich carbonate phases results in wetland waters becoming progressively depleted in  $Ca^{2+}$  and enriched in  $Na^+$ ,  $Mg^{2+}$ , and  $SO_4^{2-}$  (Deocampo and Jones 2014). As salinity increases in prairie potholes with evaporitic enrichment, sulfate ( $SO_4^{2-}$ )-bearing minerals may eventually precipitate (Last and Ginn 2005). Hu et al. (2025) revealed recently that variability in meteorological conditions and the morphology of prairie potholes' catchments, represented as closed-basin wetlands and open-basin wetlands, significantly influenced hydrological processes and water chemistry in prairie potholes. They found that closed-basin wetlands exhibited higher concentrations of heavy isotopes and various dissolved ions — primarily due to increased evaporation and the absence of surface water outlet — as compared with the open-basin wetlands. In both wetland types, elevated phosphorus levels were closely associated with increased runoff from the surrounding catchment during periods of higher rainfall.

The hydroperiod of prairie potholes is strongly influenced by the inputs from direct precipitation and the runoff from uplands generated by snowmelt and summer heavy storm events (Brooks et al. 2018; Hayashi et al. 2016). On the contrary, the hydroperiod of kettle holes in the northeast of Germany is largely dependent on groundwater inflow, resulting from the shallow groundwater system through permeable sediments (Lischeid et al. 2017, 2018; Nitzsche et al. 2017; Steidl et al. 2023; Vyse et al. 2020). The contribution of these components to the water budget of kettle holes is highly dynamic. For instance, Dreger (2002) demonstrated that storm events that occur during the winter periods play a pivotal role in the hydroperiods of kettle holes, while only 3% of the summer storms may support the hydroperiods of kettle holes. This is, however, not the case for heavy storm events that occur when the ground is bare and uncovered by vegetation. In addition, the inputs from direct precipitation on the ponds and the runoff generated over the frozen soils during winter periods can increase the hydroperiod of kettle holes (Gerke et al. 2010). On the other hand, in the PPR, due to soil frost in winter season, infiltration capacity of soil is considerably reduced. Therefore, a major fraction of precipitation over uplands is partitioned off into direct runoff, which fills the lower-laying prairie potholes (Gray et

al. 2001; van der Kamp et al. 2003). By contrast, in summer season, owing to an increase in evapotranspiration over vegetated uplands, unfrozen soil becomes drier and thus only the most severe storm events can generate surface runoff over hillslopes (Hayashi et al. 1998). The pond permanence of kettle holes in NCE has not been extensively quantified in comparison to that of prairie potholes in the PPR. Therefore, it will be beneficial to adopt a wide range of methodological approaches developed thus far for prairie potholes, including hydrological and geochemical modeling, and stable water isotopes analysis to characterize and quantify the hydroperiod of kettle holes in NCE.

The pond permanence can vary over a decadal time scale depending on the variability in precipitation inputs (Hayashi et al. 2016), meaning that an observer may classify a particular wetland pond as “seasonal” in one decade and another observer may classify the same wetland pond as “semi-permanent” a decade later. As the pond permanence of prairie potholes is largely controlled by the inputs of runoff from surrounding uplands (i.e. internal catchment), farming practices can greatly affect the pond permanence. For example, tillage can destroy soil macropore network and reduce the infiltrability of frozen soil, thereby increasing snowmelt runoff inputs to prairie potholes (van der Kamp et al. 2003). Cattle grazing can also affect soil infiltrability and snowmelt runoff (Renton et al., 2015; van der Kamp et al. 2003).

Compared to a large number of water-balance studies in the PPR, fewer studies are available in NCE. However, Lehsten et al. (2011) simulated the water level fluctuations of kettle holes over a 50-year period in the central part of Mecklenburg, Western Pomerania in northeastern Germany, using a time series model. They demonstrated that cumulative evaporation in the growing season (April 1 to September 30) showed a strong correlation with the autumn low water levels in the following year. Similarly, annual precipitation calculated from April 1 correlated well with the spring high water levels of the subsequent year. While one might expect winter precipitation (October 1 to March 31) to correlate with spring high water levels, this relationship was not observed in the simulation results. Instead, the cumulative winter precipitation over two consecutive years demonstrated a strong correlation with the winter filling of the second year.

In connection with surface runoff processes, soil erosion in agricultural croplands and subsequent sediment transport into prairie potholes have been studied in the PPR. In that regard, Zarrinabadi and Lobb (2023) found that in agriculture-dominated landscape of the PPR, significant rates of soil loss occur in the upland and middle slope positions, while a large amount of sediment is transported to the lowland and foot slope positions. However, soil erosion and sediment deposition in kettle holes of NCE have not received much

attention. Nonetheless, a notable study by Frielinghaus and Vahrson (1998) quantified the erosion from the croplands surrounding kettle holes and the associated sediment transport using  $^{137}\text{Cs}$  in northeastern Germany. They found a relatively low erosion rate (9000 to 15000  $\text{t ha}^{-1}\text{y}^{-1}$ ) on the upslope positions, increasing rate at mid-slope, and sediment deposition around and within the kettle holes of interest. They recommended two conservation management plans to reduce eutrophication and filling-up of kettle holes via sedimentation: (1) stop cultivating across the croplands surrounding the kettle holes and (2) create a 10 to 20 m wide buffer of grassland around the kettle holes. Using grassland restoration (e.g. replanting or reseeding, and planting new vegetation) to create buffer strips is a practical and ecologically sound approach to mitigating erosion and sediment delivery in and around kettle holes. By improving sediment trapping, enhancing water quality, and providing additional ecosystem services (e.g. habitat creation), these buffers contribute significantly to sustainable land and water management in agricultural landscapes.

### Groundwater Hydrology of Prairie Potholes and Kettle Holes

Kettle holes and prairie potholes are surrounded by uplands and seemingly are not channelized to one another as well as to nearby streams (Cohen et al. 2016; Leibowitz 2015). However, they are not isolated in an ecohydrological sense (Leibowitz 2015; Mushet et al., 2015a), because seemingly isolated kettle holes/prairie potholes can yet influence the watershed integrity, i.e. contributing as a medium to the ecological, biological, and hydrological connectivity of the surrounding landscape. In addition to occasional overflow (see above), groundwater flow provides hydrologic connection between kettle holes/prairie potholes and downstream waterbodies in areas that drain internally and have no surface-water outlet (Neff and Rosenberry 2018), as is the case in the PPR and NCE (e.g. the Uckermark region in the northeast of Brandenburg State, Germany) (Lischeid et al. 2018).

The water balance of prairie pothole is complex, driven by precipitation, evapotranspiration, runoff, and groundwater exchange (Brannen et al. 2015; Cieśliński et al. 2020; Schilling et al. 2019). Quantifying groundwater's role is challenging due to varying till conductivity (van der Kamp and Hayashi 2009), where high conductivity allows substantial transmissivity (van der Kamp and Hayashi 2009). Shallow groundwater predominates due to negligible deep groundwater flow through low conductivity till (Sloan 1972). Overall, the subsurface connection between prairie potholes is controlled by the hydraulic conductivity of geological materials (e.g. clay-rich till vs. glaciofluvial sand)

and the hydraulic gradient related to their topographic positions (Winter and LaBaugh 2003).

Likewise, at small scale, NCE is covered by the Pleistocene sediments, which horizontally and vertically represent a high heterogeneity. The subsurface layers are composed of till, interleaved with sands, perched water table, confined, and unconfined layers. In contrast, at large scale, we can clearly separate shallow aquifer with relatively high hydraulic conductivity (associated with the youngest Weichselian glaciation) from the underlying till (associated with the older Weichselian glaciation) (Merz and Steidl 2015; Merz et al. 2009). This distinction highlights the contrasting hydrogeological properties of these units, where the shallow aquifer likely facilitates more dynamic groundwater flow and recharge processes, whereas the underlying till acts as an aquitard, influencing groundwater storage, regional flow pathways, and the vertical exchange of water and solutes.

The role of kettle hole-groundwater interactions has been an important question regarding the hydrology of kettle holes in NCE. The early studies conducted in this region, especially in northeastern Germany (e.g. Uckermark) suggested that kettle holes are disconnected from groundwater (Kalettka et al. 2001). More recent studies have revealed that kettle holes are variably connected to shallow groundwater and may show seasonally variable interactions with their adjoining shallow groundwater system (Kalettka and Rudat 2006; Lischeid et al. 2017; Nitzsche et al. 2017; Vyse et al. 2020). This connection could potentially be related to the topographical position of a kettle hole with respect to its shallow groundwater system (Lischeid et al. 2018; Steidl et al. 2023; Vyse et al. 2020).

Despite several studies aiming to characterize and distinguish the water balance components of kettle holes, significant research gaps exist concerning the contribution of specific water components, in particular groundwater inflow, to the overall water balance. For instance, distinguishing between groundwater-dominated kettle holes and those dominated by precipitation and surface runoff, based on the primary source of water input, would be highly valuable. Furthermore, the importance of groundwater mounding caused by heavy storm events or prolonged wet periods, which can stagnate or even reverse the groundwater inflow or outflow, has been poorly documented in NCE (Steidl et al. 2023).

Given the widespread presence of tile drainage networks in the agricultural landscapes of NCE, it is important to investigate how these systems have altered subsurface flow pathways, potentially diverting flow away from kettle holes toward the adjacent shallow groundwater domain. This redirection may contribute to the drying of kettle holes or the transformation of permanent ponds into semi-permanent or intermittent ponds. In turn, the biodiversity of permanent

kettle holes with permanent pond, which are highly dependent on the sustenance of groundwater inflow, could potentially be threatened if proper conservation measures are not implemented to counterbalance the effects of the tile (Savić et al. 2021). Notwithstanding the pivotal role of groundwater inflow in sustaining the biodiversity of kettle holes with permanent pond, hillslope runoff and precipitation regulate the biodiversity of semi-permanent and seasonal kettle holes. Indeed, the hydroperiod of kettle holes influences ecohydrological functions and ecosystem services, such as species composition, water quality regulation, and sediment dynamics.

In the PPR, the findings of a comprehensive study conducted by Brown et al. (2017) on 42 prairie potholes revealed that drainage enhances agricultural conditions and nutrient availability, particularly in wetlands drained for 20 to 34 years, though benefits diminish after 36 years. Their results showed that longer drainage periods increased nitrification, elevated available  $PO_4^{-3}$  concentrations, and reduced phosphorus sorption. While drainage has improved nutrient availability for crops, it has also led to increased nutrient losses. Additional soil changes caused higher bulk density and reduced microaggregates, whereas drainage had minimal impact on macroaggregates, soil organic carbon, or mineralization. Indeed, while tile drainage can enhance agricultural productivity by improving soil drainage, it also poses significant challenges to prairie pothole wetlands, including altered hydrology, reduced hydroperiods, and increased nutrient loading. Addressing these challenges requires implementing conservation measures that balance agricultural needs with wetland preservation.

In summary, hydro(geo)logically, both systems rely on precipitation, but kettle holes depend more on groundwater inflow, while prairie potholes are mainly sustained by surface runoff, especially in cold, semi-arid climates where soil frost impedes infiltration. Kettle holes exhibit more stable hydroperiods, primarily due to temperate climatic conditions and the influence of subsurface flow. In contrast, prairie potholes typically have ephemeral to seasonal hydroperiods, driven by highly variable precipitation and evaporation rates. Prairie potholes are predominantly recharge or discharge systems with clay-rich tills limiting flow-through interactions. In contrast, kettle holes are mainly flow-through systems enabled by sandy and loamy soils that facilitate dynamic subsurface exchange. With respect to riparian vegetation, particularly aquatic plants like reeds and bulrushes, these species influence hydrological processes in both systems. In kettle holes, evapotranspiration and root water uptake by riparian plants can lower local water tables, even reversing groundwater flow directions (Steidl et al. 2023). Similarly, in prairie potholes, dense vegetation in the non-flooded riparian zone around the pond amplifies evapotranspiration,

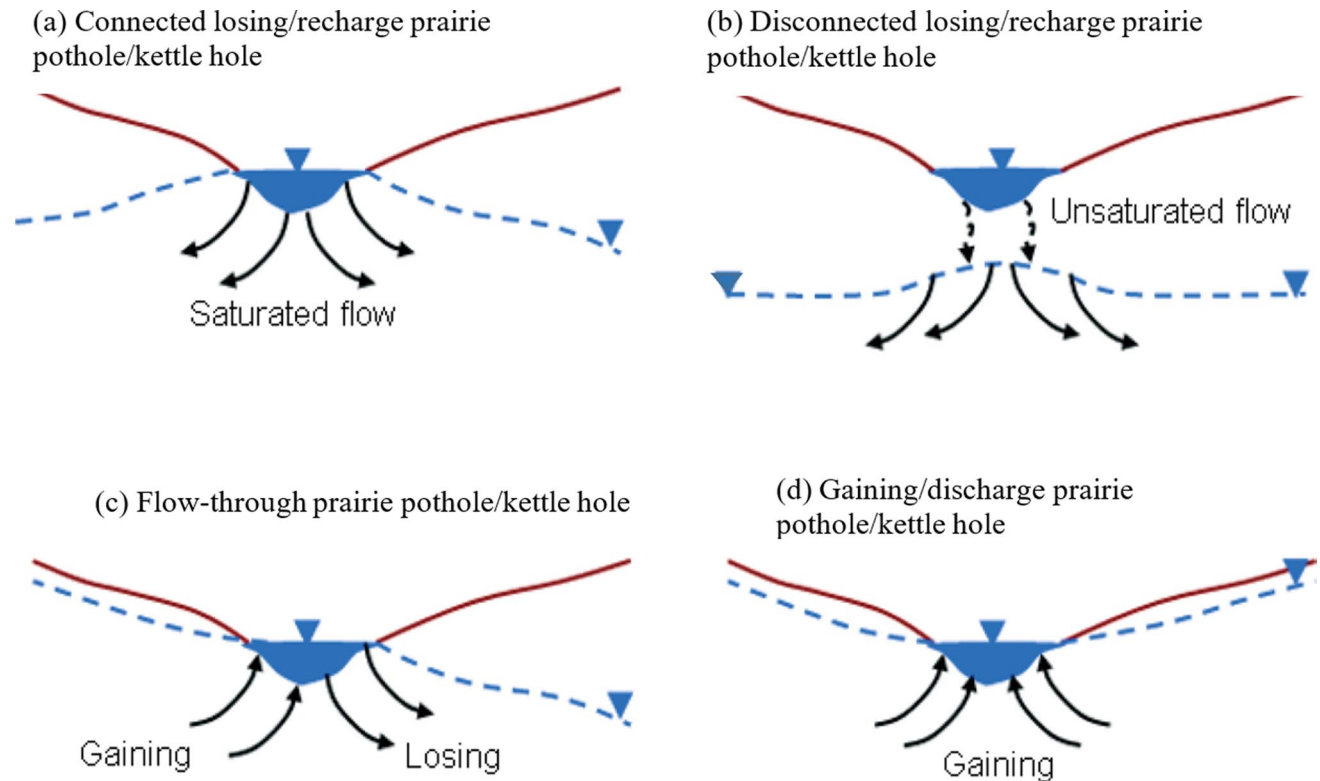
affecting hydroperiods, and soil moisture dynamics. These interactions highlight the integral role of vegetation in shaping wetland water budgets. Aquatic plants modulate water quality by influencing nutrient cycling and hydrological fluxes. For example, kettle holes with dense riparian vegetation exhibit reduced nutrient loads due to uptake, while prairie potholes display salinity-driven vegetation zonation.

### Implications of Geomorphic Setting of Prairie Potholes and Kettle Holes for Water and Solute Transport

For the purpose of understanding landscape-scale interaction of groundwater with prairie-pothole wetlands, Lissey (1971) developed a conceptual model, whereby topographically higher-laying wetlands recharge groundwater, and lower-laying wetlands receive groundwater discharge. The groundwater flow system connects wetlands at various landscape positions. Likewise, Rosenberry and Winter (1997) identified the continuous hydraulic gradients from prairie potholes positioned over a higher landscape towards those situated in a lower landscape. According to hydrologic connectivity of these kinds of wetlands with the adjoining shallow groundwater domain, kettle holes and prairie potholes are hydrologically classified into three types (Brock et al. 2009; Nitzsche et al. 2017; Vyse et al. 2020):

(1) the connected (or disconnected) losing/recharge type occurs when the water level within prairie potholes/ kettle holes is higher than that of the adjacent shallow groundwater, allowing direct aquifer recharge (Fig. 2a); the disconnected losing/recharge type is similar but occurs when the depression is perched above the water table, losing water through unsaturated zone infiltration without direct aquifer connection (Fig. 2b); (2) the flow-through type receives groundwater inflow on one side and discharges it on the other (Fig. 2c), although the flow can be hampered by the low hydraulic conductivity of the underlying geological materials (Cherkauer and Zager 1989); and (3) the gaining/discharge type occurs when the wetland water level is lower than that of the surrounding groundwater, receiving inflow from the upland (Fig. 2d).

In the context of the kettle hole position on a depression-rich landscape in Germany, Vyse et al. (2020) demonstrated a strong negative correlation between electrical conductivity (EC) of water in kettle holes and their elevation in the Uckermark region of northeastern Germany. It was found that upland kettle holes show a lower EC due to a less mineralized and younger water of upland kettle holes, while the lowland kettle holes show a higher EC owing to the accumulation of more dissolved ions, evaporitic enrichment, and input of mineral-rich water. Moreover, based on stable isotopic measurement, they proposed a conceptual



**Fig. 2** A conceptual scheme of possible groundwater-prairie pothole/kettle hole interactions: (a) connected losing/recharge type; (b) disconnected losing/recharge type; (c) flow-through type; and (d) gaining/discharge type, revised from Jolly et al. (2008)

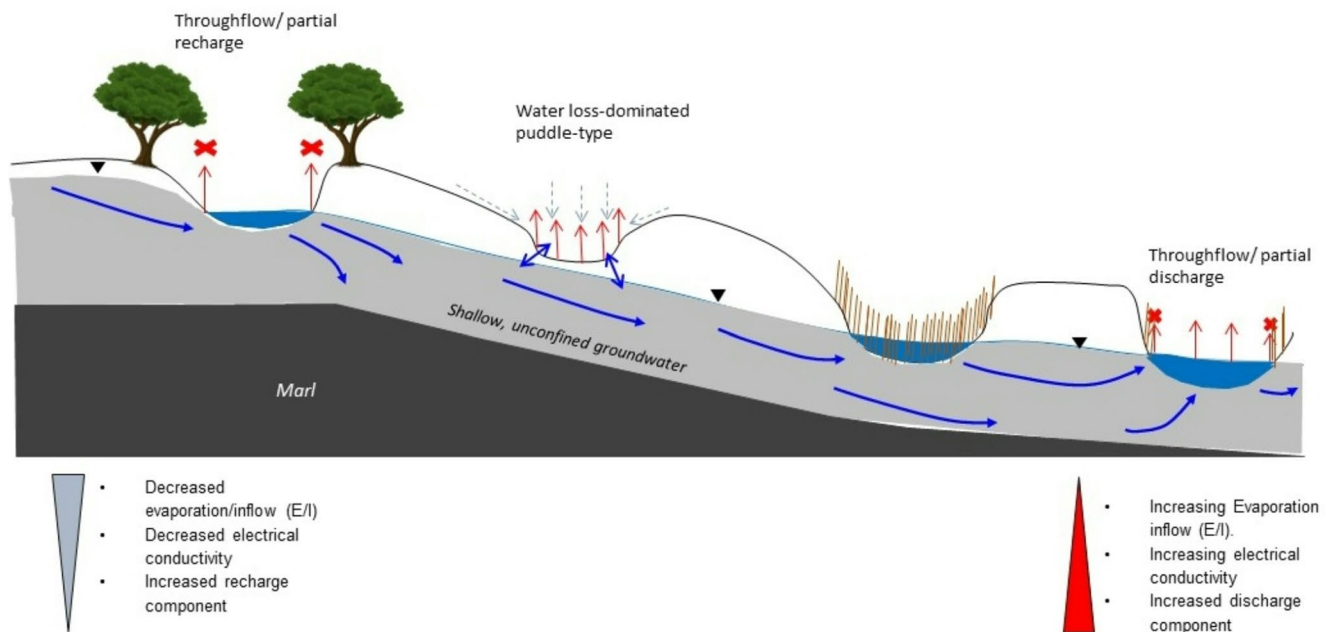
model, in which recharge-dominated kettle holes are located across the highest parts of the landscape, while discharge-dominated kettle holes are positioned over the lowest parts of the landscape. This suggests that the groundwater flow controlled by the geomorphic setting of kettle holes can transport solute within a hydrological continuum system across the landscape (Fig. 3). A lower solute concentration in recharge-dominated kettle holes is ascribed to dilution over time due to losing the solutes, while the lower-laying discharge-dominated kettle holes receive solutes and thus enrich their concentrations. However, it should be noted that solute transport can happen in regions where the hydraulic conductivity of glacial sediments is high enough to allow long-range transport of solutes (van der Kamp and Hayashi 2009).

The findings of Vyse et al. (2020) on the influence of geomorphic setting on kettle hole hydrology and solute transport in NCE are consistent with observations in the PPR (Euliss et al. 2004; Hayashi et al. 1998; Heagle et al. 2013; Lissey 1971; Rosenberry and Winter 1997; Winter and LaBaugh 2003). Due to the low hydraulic conductivity of unweathered till, the localized shallow groundwater flow in weathered till is the dominant pathway of water and solute rather than the deep regional groundwater flow (Sloan 1972). However, in places where the hydraulic conductivity is moderately high (e.g. glaciofluvial sediments),

a long-range regional hydrological system may significantly affect the water balance of prairie potholes (Euliss et al. 2004).

It is worth mentioning that the lower-positioned prairie potholes have larger and more permanent ponds than higher-positioned prairie potholes (LaBaugh et al. 1987; Miller et al. 1985). The spatiotemporal variability of pond permanence and salinity within a complex of multiple wetlands plays a pivotal role in diversity of ecological processes in the PPR (Euliss et al. 2004) and is expected to play in similar role for the kettle holes of NCE.

The hydrological behaviors of kettle holes may shift depending on precipitation amounts. During a prolonged dry period lasting for several years to a decade, the surface fill-spill mechanism becomes inactive, causing upland kettle holes to connect with lowland kettle holes through groundwater flow only. As a result of such a long-lasting drought condition leading to a water table drawdown, effective transmission zone between wetlands becomes disconnected. In contrast, both surface and subsurface flow can provide active connection between upland and lowland prairie potholes during a prolonged wet period (Euliss et al. 2004).



**Fig. 3** Conceptual model proposed for the hydrologic connection between higher-laying kettle holes and lower-laying kettle holes through a groundwater inflow in the Uckermark region of northern Brandenburg. The conceptual diagram was adopted using the data collected during the study undertaken by Vyse et al. (2020) and ideas from Hayashi et al. (1998) and Winter and LaBaugh (2003). Note that the

red X marks the water loss through evapotranspiration, while the grey and red arrows represent decreasing and increasing of the depicted mentioned processes from the upland to the lowland landscape. Recharge remains the dominant process, with higher rates occurring in the upland landscape. The solid blue lines indicate the groundwater flow direction and kettle hole-groundwater exchange

## Classification Schemes Proposed for Prairie Potholes in the PPR

The wetland classifications are influenced by several studies; of which the presently used classification system of Stewart and Kantrud (1971) takes a holistic approach and it is still in use for the classification of the prairie potholes in the US and Canada. The features of this classification are summarized as follows:

- Prairie potholes are zoned according to the vegetation in the center covering at least 5% of the total wetland area, which is further assigned to 7 major classes that represent hydroperiod regimes, including ephemeral, temporary, seasonal, semi-permanent, and permanent (alkali and fen) (Fig. 4).
- Corresponding zones are defined as wet meadow, shallow marsh, and deep marsh.
- The zones are typically classified and recognized as indicators of the hydroperiod regime, even though the distinct distribution patterns are exhibited by individual species in each zone. Consequently, deviations from these zonal patterns can provide valuable insights into the recent hydrologic history of a wetland catchment (Kantrud et al., 1989a).
- The zones are further subdivided into 5 subclasses of salinity with indicator species A, B, C, D, E, which denote fresh, slightly brackish, moderately brackish, brackish, and subsaline, respectively. Important difference in species composition of the characteristic plant communities within zones is correlated with differences in salinity of surface water. Moreover, many of the plant communities persist temporarily over widely overlapping ranges of salinity.

Prairie potholes are also classified into four types based on vegetation coverage and the extent of open water or bare soil (Fig. 5):

- Type 1: Dominated by closed stands of emergent vegetation, with open water or bare soil covering less than 5% of the wetland area.
- Type 2: Characterized by 5% to 95% open water or bare soil, interspersed with dense patches or a diffuse stand of emergents. This type also includes wetlands where closed stands of emergent vegetation occupy the central portion, surrounded by open water along the margins.
- Type 3: Defined by a central area of open water or bare soil (exceeding 5% of the wetland area), encircled by a peripheral band of emergent vegetation averaging at least 6 feet ( $\approx 1.8$  meters) in width.

- Type 4: Composed of more than 95% open water or bare soil. This type also includes small ponds with only minimal emergent vegetation, confined to narrow marginal bands averaging less than 6 feet in width.

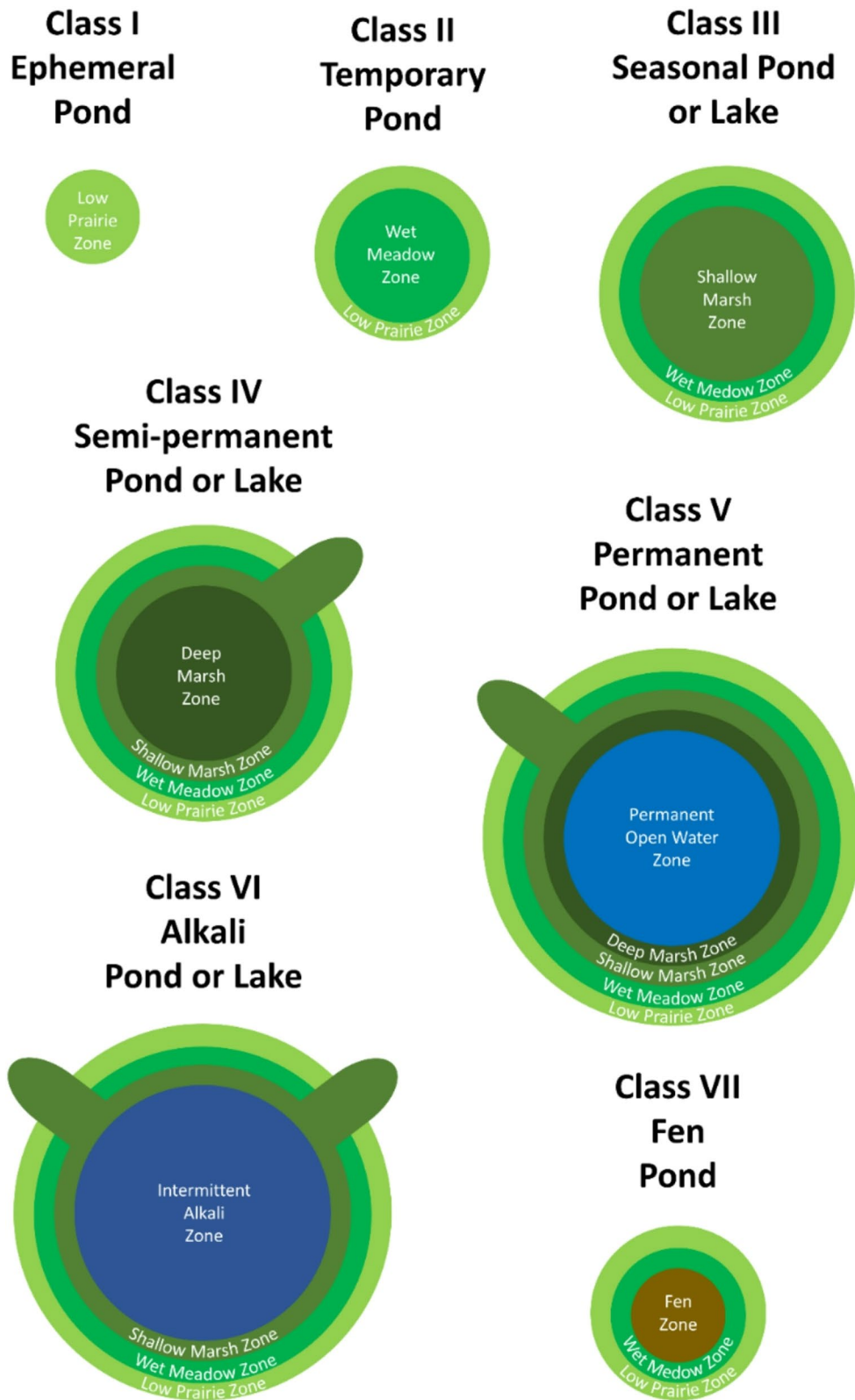
These types are linked to seasonal drawdown phases and successional stages but do not incorporate morphological indicators such as basin shape or slope. In this classification, species list is also available for normal emergent, natural drawdown, and open water phase, but no morphological indicators are included.

Therefore, to enhance the applicability and ecohydrological relevance of the Stewart and Kantrud (1971) classification, it is recommended to integrate hydromorphological characteristics and water quality indicators, placing particular emphasis on water quantity dynamics rather than focusing solely on water chemistry. Based on the proposed characteristics, prairie potholes are categorized by dominant vegetation types as proposed by Stewart and Kantrud (1971), which correspond to specific hydroperiod regimes, as illustrated in Fig. 4. These categories include the following zones:

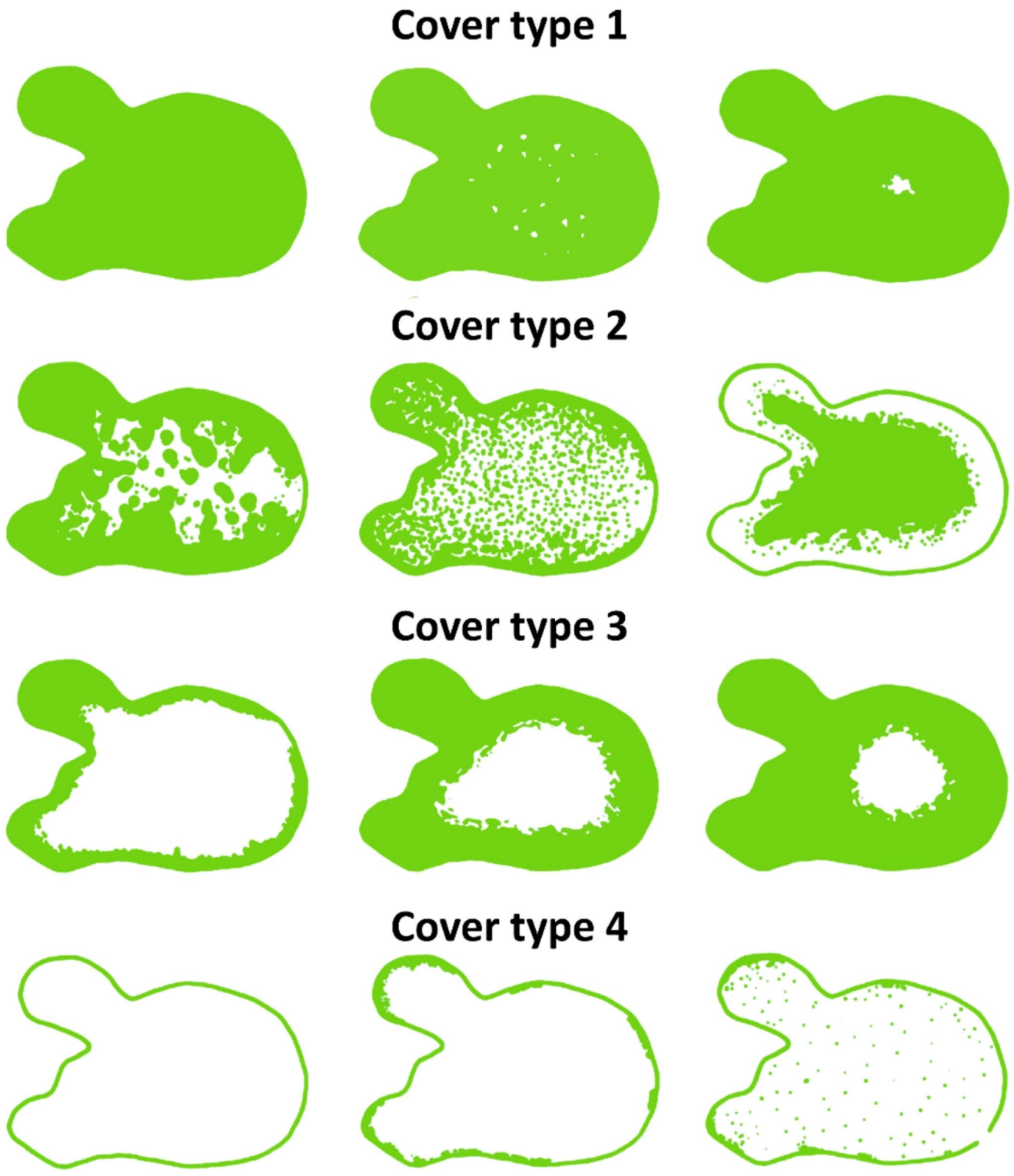
- Wetland-low-prairie zone: The outermost transition zone between upland prairie and wetland, characterized by drought-resistant grasses and forbs that can tolerate periodic saturation.
- Wet-meadow zone: A seasonally saturated zone dominated by moisture-dependent species such as *Poa palustris* and various sedges.
- Shallow marsh zone: An area with prolonged surface water presence, supporting emergent vegetation such as *Carex*, *Sparganium*, and *Eleocharis*, which thrive in shallow standing water.
- Deep marsh zone: The deepest vegetated portion of the wetland, with semi-permanent to permanent water, typically dominated by robust emergent species like *Scirpus* (bulrush), *Typha* (cattail), and *Phragmites* (reed).
- Open water zone: The central, permanently inundated portion of the wetland, which lacks emergent vegetation but may support floating or submerged aquatic plants, depending on depth and water clarity.

## Classification Schemes Proposed for Kettle Holes in NCE

Classification of kettle holes in NCE has evolved through both biotic and abiotic approaches. A widely used system was first introduced by Hamel (1988) and later refined by Luthardt and Dreger (1996). This classification is grounded in expert knowledge and species-specific field observations, identifying approximately 300 vascular plant species.



**Fig. 4** Vegetational zones as represented by their spatial relation, following Stewart and Kantrud (1971)



**Fig. 5** Differentiation of natural ponds and lakes with respect to their vegetation cover. Note that white zones indicate open water or bare soil, and tinted areas show emergent vegetation as per Stewart and Kantrud (1971)

The resulting classification, detailed in Table 2, differentiates kettle holes by succession stages into four main types (open water, edge, full, and woody), further subdivided by dominant vegetation. However, this scheme only considers edge vegetation and largely overlooks open-water and zonal dynamics.

Efforts to link vegetation with environmental gradients began with Dreger (2002), while Rudat (2005) proposed the first numerical classification system based on bioindication using vegetation mapping across 20 kettle holes. Using cluster and canonical correspondence analysis, 13 distinct biotic-abiotic types were identified based on the composition of aquatic and amphibian zone species. This approach, while integrative, is limited by its exclusion of terrestrial zones and assumption of fixed morphological zones, as illustrated in Fig. 6. The resulting classification is vulnerable to misinterpretation, especially during dry periods when aquatic species may be absent (Patzig et al. 2012).

In parallel, abiotic-based classifications have also been developed. Kalettka and Rudat (2006) analyzed 268 kettle holes across northeastern Germany, considering geomorphological and hydrological variables such as hydroperiod, shore slope, and catchment characteristics. This led to

the definition of 10 hydrogeomorphic types, including the “silted fen” and subdivided “open-water” types (storage, shore overflow, puddle), as illustrated in Fig. 7.

Despite such advances, current systems fail to holistically integrate spatiotemporal vegetation dynamics with physical attributes. Recent studies by Pätzig and Düker (2021) indicated that prolonged dry periods shift community composition toward terrestrial and nitrophilous species, particularly in “storage-type” kettle holes, suggesting a transition toward wood-dominated systems. These successional shifts may drive landscape homogenization and diminish critical wetland functions. Bergholz et al. (2023) further highlighted that species richness declines toward kettle hole centers, while hygrophilic species increase, emphasizing the ecological importance of small-scale heterogeneity.

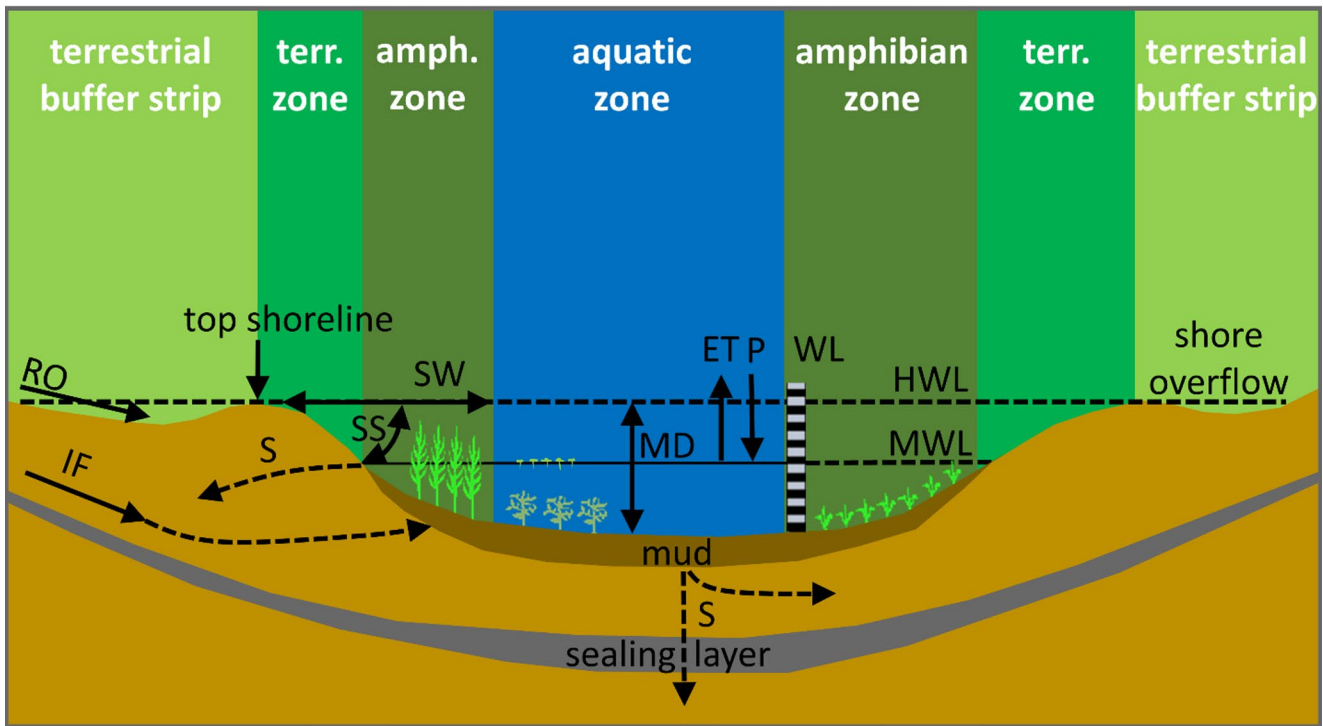
Overall, while multiple classification approaches exist, a comprehensive, dynamic system integrating both abiotic and biotic indicators remain lacking for kettle holes in NCE.

For future research on the classification of kettle holes, the following considerations should be taken into account:

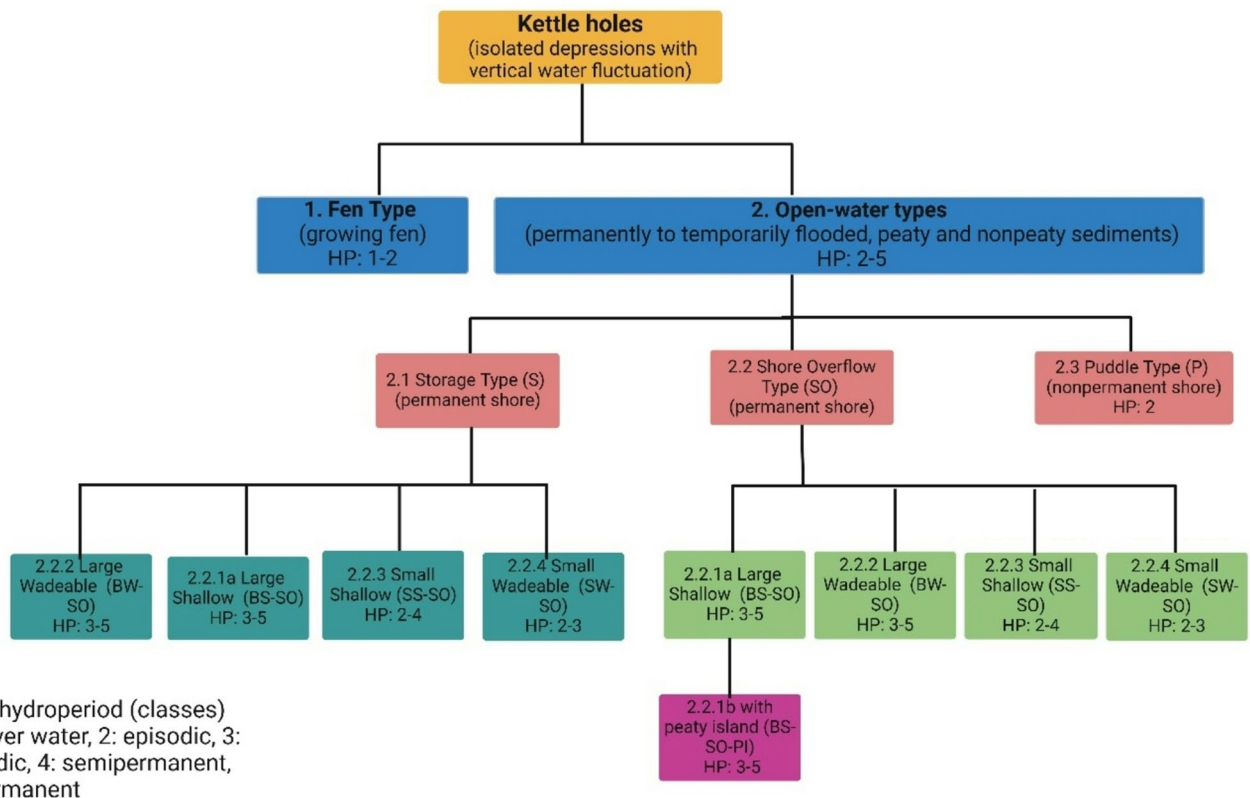
- The identification of dynamic vegetation zones shows promising potential.

**Table 2** Classification of kettle holes according to successional stages proposed by Hamel (1988) and Luthardt and Dreger (1996), which was later improved by Rudat (2005)

Land use in the catchment	Major category (Hamel 1988)	Subtype (Kalettka and Rudat 2000; Luthardt and Dreger 1996)	Characteristics
Arable land and grassland	Open type	None	Arable land and grassland (Mowing, meadow)
	Edge type	covered with reed covered with canary grass covered with sedge covered with ruderal Riparian groves	• Distinct water body • Amphibian and terrestrial plants with edge type covering < 75% of the kettle hole area
	Full reed type	covered with reed covered with canary grass covered with sedge covered with bulrush covered with ruderal	• No distinct water body • Amphibian and terrestrial plants with edge type covering ≥ 75% of the kettle hole area
	Woody type	covered with grey willow covered with birch covered with alder	• Dominated by woods at the center of kettle holes
Forest	Edge type	Riparian groves Herbaceous forest species	see above
	Full reed type	covered with reed covered with sedge covered with bulrush covered with ruderal	see above
	Woody type	covered with grey willow covered with birch Covered with alder	see above



**Fig. 6** Schematic of vegetation zones vis-à-vis hydrogeomorphic properties of kettle holes reflected in shore width (SW), shore slope (SS), maximum depth (MD), water level (WL), high water level (HWL), mean water level (MWL), evapotranspiration (ET), precipitation (P), seepage (S), runoff (RO), and interflow (IF). Taken from Patzig et al. (2012)



**Fig. 7** Classification of kettle holes in the agricultural landscapes of the Northeast of Germany, following Kalettka and Rudat (2006)

- Existing vegetation classifications for kettle holes in NCE insufficiently incorporate developmental stages of vegetation cover, such as succession from aquatic to terrestrial plants or transitions driven by environmental factors.
- Most studies on kettle hole vegetation focus primarily on surface hydrology — such as water level fluctuations and soil moisture — while paying little attention to groundwater flow and subsurface processes. However, these subsurface dynamics play a significant role in shaping vegetation patterns, especially at the edges and centers of kettle holes, by influencing nutrient availability and moisture. Their omission leads to an incomplete understanding of vegetation distribution.
- Salinity is not adequately considered in current classification systems for kettle holes in NCE, despite the existence of subclasses A (fresh) and B (slightly brackish) that are based on salinity levels.

**Dynamic Classification Proposed for Prairie Pothole and Kettle Holes**

To overcome the limitations of static wetland classifications, Euliss et al. (2004) introduced the dynamic “wetland continuum” concept for prairie potholes, later refined

by Mushet et al. (2018) (Figs. 8 and 9). This framework integrates hydrological position in the landscape and atmospheric inputs to explain how water source (groundwater vs. precipitation), hydroperiod, and salinity affect vegetation dynamics. Hayashi et al. (2016) extended this idea by replacing the groundwater axis with a hydrological position axis and suggested incorporating surface water processes in addition to groundwater processes to explain the hydrological condition of wetlands.

By placing wetland vegetation in a two-dimensional space — hydrological position on the x-axis and atmospheric relation on the y-axis — the model predicts vegetation types at any point, including potential shifts between alternate stable states during extreme drought or deluge events (Fig. 9). Salinity, strongly influenced by water residence time (Stewart and Kantrud 1972), plays a key role: recharge wetlands are fresher, discharge wetlands are saltier, and flow-through types fall in between (Euliss et al. 2004). Vegetation follows these gradients, from terrestrial drought-tolerant species in dry periods to submerged aquatic plants during wetter phases.

Altenfelder et al. (2014) noted that in kettle holes, hydroperiod has a stronger influence on plant diversity than land use. Temporary kettle holes, while less species-rich, are essential habitats for rare species (Cérèghino et al. 2008).

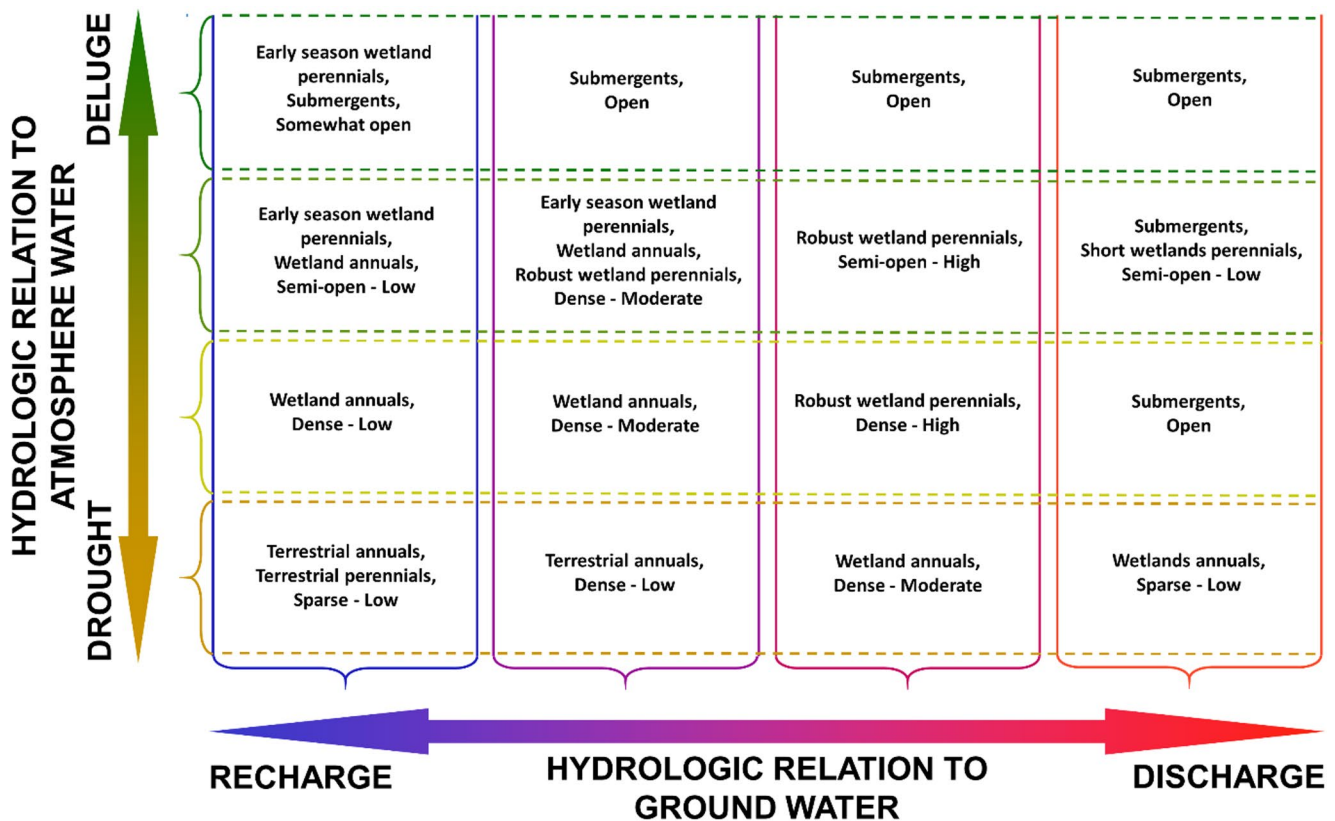
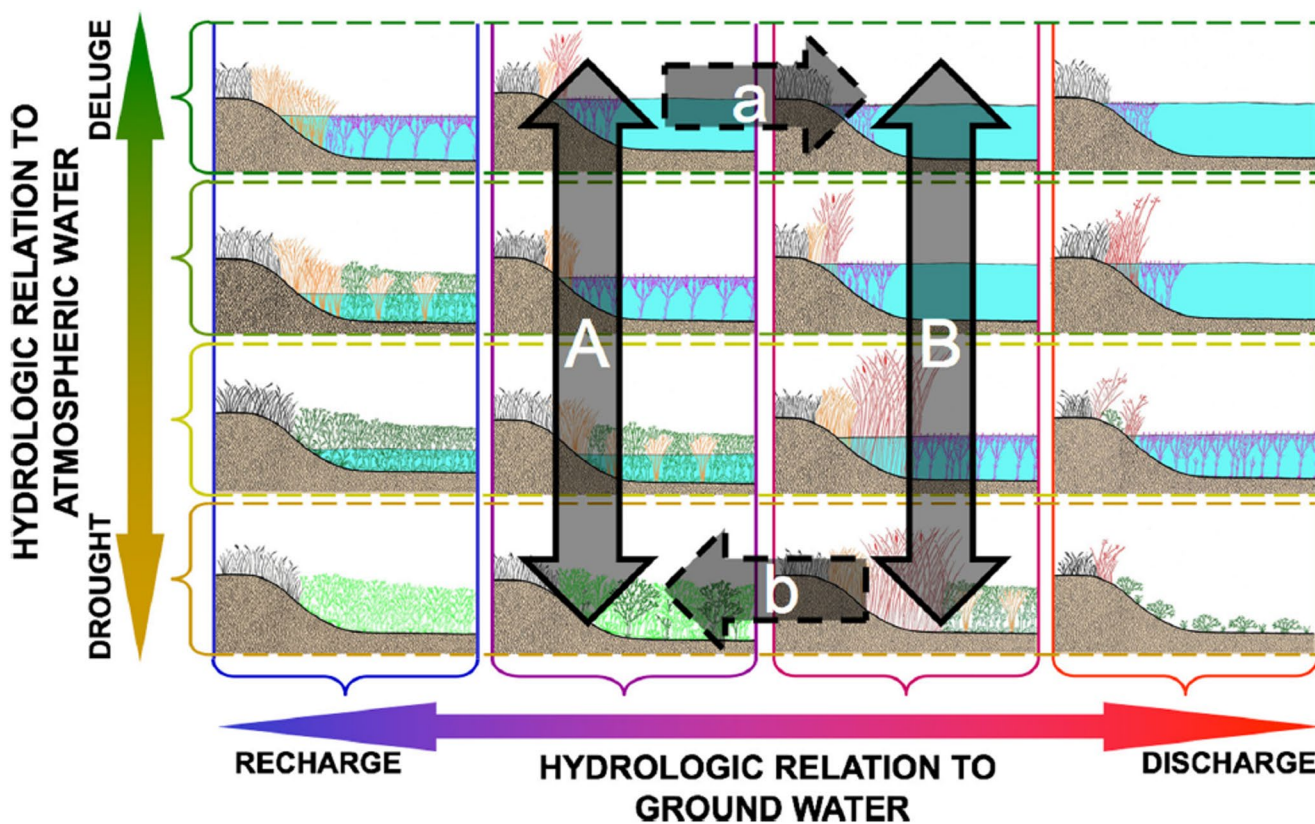


Fig. 8 Variability of vegetation species in relation to the hydrological system of prairie potholes of the PPR (x-axis) and drought/wet condition (y-axis), following Euliss et al. (2004)



**Fig. 9** The revised wetland continuum conceptual framework incorporating abiotic properties suggested by Mushet et al. (2018). Note that potential biotic communities, represented by arrows of “a” and “b”, can be switched, due to prolonged extreme periods along the drought-

to-deluge axis, between alternate states (represented by arrows of “A” and “B”). The prairie potholes located at the extreme groundwater conditions, reflected by recharge and discharge systems, are supposedly less sensitive to these shifts

Similarly, Mushet et al. (2015b) emphasized that hydrogeochemical variability supports unique ecological communities. In prairie potholes, the vegetation found in the deepest areas provides a more reliable indicator of long-term water level and salinity than single or short-term water chemistry measurements (Kantrud et al. 1989b).

In contrast, kettle holes in NCE have not yet been classified according to ecohydrological types, especially in relation to groundwater fluctuations. Boe and Stabell (2001) found a strong link between vegetation shifts and water-table drawdown in Norwegian kettle holes around 4000 BP (Before Present), driven by regional climatic changes.

Future research should prioritize ecohydrological classification of kettle holes, identifying dynamic vegetation zones using high-resolution remote sensing, big data, and machine learning (Hill et al. 2021). This will improve predictions of vegetation response to hydrological and climatic changes, enhancing wetland management. Furthermore, as eutrophication alters species composition, nutrient status should be integrated into classification systems, distinguishing between oligotrophic, mesotrophic, and eutrophic kettle holes (Whigham and Jordan 2003).

Although the prairie pothole wetland continuum (Fig. 9) does not explicitly include late successional stages (e.g. shrub or tree dominance), its core principles are adaptable to the kettle holes of NCE, underscoring its broader applicability across diverse wetland systems.

### Lessons Learned from Prairie Potholes for Management and Conservation of Kettle Holes Ecosystems

Extensive and long-term research on prairie potholes in North America has yielded valuable insights that can guide conservation and management strategies for kettle holes in NCE. Despite recent legal protections in Germany, current conservation strategies often lack specificity concerning the diverse habitat functions of kettle hole types, which are shaped by a range of ecohydrological and geomorphological factors (Berger et al. 2003; Kalettka et al. 2001). This calls for an integrated conservation approach that reflects both ecological functions and local environmental filters. Building upon this need for specificity, we explore how ecohydrological classification and catchment characteristics influence conservation priorities.

Ecohydrological classification, as applied in the PPR, is essential for differentiating kettle holes based on water source and nutrient status. Recharge-dominated kettle holes, though rare, are nutrient-poor and oligotrophic, while discharge and flow-through types are more prone to eutrophication due to nutrient inflows. Peat bogs — precipitation-dominated systems — offer paleoclimatic insights and are often nutrient-limited, or ombrotrophic (Karasiwicz 2019). These hydrotypes are closely tied to sedimentation and terrestrialization processes, which further shape their ecological trajectory.

Management strategies should consider susceptibility to sedimentation across different kettle hole morphologies. These sedimentation dynamics, particularly in slope kettle holes, are compounded by surrounding land use practices that exacerbate soil erosion and nutrient inflow. Slope kettle holes are especially susceptible to sedimentation from adjacent erosion-prone croplands, while flat kettle holes are more vulnerable to nutrient accumulation through subsurface flows (Kalettka and Rudat 2006). Particular attention is needed for “storage-type” kettle holes, which are especially vulnerable to terrestrialization and sediment accumulation. Preventative measures should focus on controlling water and wind erosion in surrounding areas. It is worth mentioning that the resulting sediment layers also reflect long-term ecosystem changes, such as peat formation and hydroperiod variation, underscoring the need for sediment monitoring to support restoration strategies (Corti et al. 2012; Kleeberg et al. 2016). In turn, these physical characteristics are intimately connected to the diversity of plant and animal life found in kettle holes.

Understanding these biodiversity patterns requires examining abiotic and biotic filters, where both local filtering and regional dispersal influence species sorting (Lozada-Gobilard et al. 2019). Hydrogeomorphic properties such as depth, shore width, and conductivity are critical in predicting plant diversity and community composition (Bergholz et al. 2023; Patzig et al. 2012). Abiotic filters and connectivity strongly influence species sorting mechanisms, particularly in dynamic, isolated habitat patches like kettle holes (Cain et al. 2000; Cottenie and De Meester 2004; Lozada-Gobilard et al. 2019). Consequently, environmental gradients should be preserved to maintain beta (variation among kettle holes/ prairie potholes) and gamma diversity (landscape-level biodiversity), which supports landscape-scale resilience. Connectivity also plays a vital role in shaping biotic communities within and among kettle holes. This means that even small-scale changes in water regime or catchment structure can significantly affect species composition and ecosystem resilience. The decline of plant species (Altenfelder et al. 2014) and amphibians (Berger et al. 2011) in intensively farmed areas calls for integrative strategies

that balance conservation and agricultural needs (Barraquand and Martinet 2011; Tschardt et al. 2012). One such approach, proposed by Savoie et al. (2010), involves harvesting woody vegetation around prairie potholes every 4–5 years to produce renewable energy, improve soil and moisture conditions, and reduce eutrophication by nutrient removal. Therefore, management practices should account for spatial configurations and the broader ecological networks in which kettle holes are embedded. These findings reinforce the importance of recognizing kettle holes as biodiversity hotspots in agricultural settings.

In agricultural landscapes, kettle holes are increasingly influenced by human-induced pressures, which can mask or alter their natural functioning. As kettle holes are mainly embedded in agricultural landscapes, land use practices such as tillage (e.g. zero vs. conventional), crop rotations, fertilization, and drainage have widespread effects on kettle hole hydrology and sediment biogeochemistry (Gerke et al. 2010; Nitzsche et al. 2017). These changes can alter infiltration and runoff patterns, thus influencing kettle hole hydrology and ecohydrological function. Similarly, conventional tillage practices may hinder efforts to restore seasonal prairie potholes to their natural states by affecting infiltration and wet-dry hydrological cycles (Detenbeck et al. 2002). Whereas studies on prairie pothole have primarily focused on drainage impacts (Detenbeck et al. 2002), research in NCE has highlighted the effects of tillage-induced erosion and agrochemical inputs. Effective sedimentation monitoring is essential for understanding elemental input, settling dynamics, and internal cycling processes in kettle holes (Kleeberg et al. 2016). Such insights are critical for designing targeted restoration and management strategies. As sediment cores reveal historical pollution trends, they also serve as archives of hydroperiod variation and organic matter turnover (Nitzsche et al. 2017). These long-term records help illustrate how climate and anthropogenic activities interact to reshape kettle hole ecosystems.

The dual influence of climate variability and land use further complicates conservation planning. Land use changes such as deforestation can alter kettle hole hydrology, impacting moisture levels, trophic status, vegetation composition, peat development, and accumulation rates. These impacts imply that conservation strategies should not only target kettle holes themselves but also their surrounding catchments. Understanding a kettle hole’s developmental history and its response to land use changes can improve conservation outcomes (Lamentowicz et al. 2007). Climate change affects prairie potholes and kettle holes differently. In the PPR, rising precipitation may increase pond permanence and lower salinity, while in NCE, heightened evapotranspiration is expected to intensify wet-dry cycles and desiccation (Mushet et al. 2015b; Nitzsche et al. 2017). These

changes exacerbate erosion, nutrient leaching, and sediment accumulation (Jefferson 2015; Lischeid and Kalettka 2012), further influencing hydrological regimes and vegetation succession. Such transitions necessitate continuous monitoring and adaptive conservation strategies.

To effectively implement adaptive conservation strategies, it is essential to integrate modern tools and robust frameworks. A notable example is the decision support system developed by Kalettka et al. (2005), which helps prioritize kettle holes for conservation based on their ecological types and specific management requirements. This system evaluates key factors such as biodiversity potential, hydroperiod variability, and other environmental drivers that influence habitat functionality. Complementary technologies such as unmanned aerial vehicles (UAVs) and remote sensing enhance these assessments by enabling the monitoring of seasonal water level changes, sedimentation patterns, and vegetation dynamics. Together, these tools provide critical support for evidence-based, long-term sustainability (Correa Martins et al. 2023; Igamberdiev et al. 2010).

Sustainable management also requires integrating conservation actions at the pond-catchment level. Research by Davies et al. (2008) shows that small-scale interventions in pond catchments can yield significant biodiversity benefits and are often more feasible than large-scale measures. For example, vegetative buffer strips around kettle holes can reduce agrochemical inputs, enhance amphibian habitat, and mitigate erosion (Berger et al. 2003; Kalettka et al. 2005). These targeted interventions illustrate how localized actions can contribute to broader landscape-scale conservation outcomes.

In conclusion, insights from prairie potholes underscore the importance of functional classification, catchment-based management, adaptive monitoring, and integrated policy as key components of effective kettle hole conservation. By adapting these principles to the specific hydroclimatic and geomorphological conditions of NCE, we can enhance the resilience of kettle holes and safeguard their capacity to deliver essential ecosystem services. This is especially critical in intensively managed agricultural landscapes, where these small wetlands play a pivotal role as biodiversity refuges under increasing environmental pressures.

## Conclusion

Despite originating from similar glacial processes, prairie potholes in North America and kettle holes in North Central Europe (NCE) have diverged in ecohydrological function due to regional climatic, geomorphological, and land use differences. Lessons from the long-standing research and conservation practices in the Prairie Pothole Region

(PPR) offer valuable insights for the more recently emerging efforts to protect kettle holes in NCE.

One of the most transferable lessons from the PPR is the importance of wetland classification systems that integrate ecohydrological parameters. The wetland continuum framework, emphasizing gradients in groundwater and atmospheric water interactions, has allowed prairie potholes to be dynamically categorized in terms of water source, hydroperiod, salinity, and vegetation response. Although this model does not explicitly account for late successional stages (e.g. woody vegetation), it remains adaptable for kettle holes, where ecohydrological zoning is still in early stages. Applying a similar dynamic classification to kettle holes would enhance the ability to monitor state shifts driven by climate extremes and land use pressures.

The integration of hydrological type into conservation planning is also crucial. In the PPR, identifying recharge, discharge, and flow-through wetlands helps assess vulnerability to eutrophication, salinization, and hydroperiod shifts. For kettle holes, similar categorization reveals that recharge-dominated systems, although rarer, are less prone to nutrient enrichment, while flat, flow-through types are more vulnerable due to subsurface nutrient inflows. Therefore, targeted strategies are needed: slope kettle holes should focus on erosion control, while flat ones require nutrient input management.

Technological advances such as UAV-based remote sensing and high-resolution monitoring have facilitated large-scale assessment and biodiversity surveys in both regions. Their application in kettle hole landscapes should be intensified to improve spatial-temporal understanding of vegetation patterns, especially under drought-driven succession dynamics.

Agricultural practices remain a major driver of wetland degradation in both environments. Whereas prairie potholes are affected by drainage and altered infiltration due to tillage, kettle holes face sedimentation from erosion and fertilizer runoff. Historical tillage and land use continue to impede restoration in both systems. Conservation plans should therefore align with local agricultural practices. For kettle holes, this includes adapting crop rotation and tillage methods to mitigate runoff, while in the PPR, addressing long-term drainage impacts is essential.

The role of wetlands as ecosystem service providers is increasingly recognized, ranging from flood mitigation and water purification to biodiversity conservation. However, ecosystem service provisioning is often threatened by single-focus policy frameworks. In Germany, for example, biodiversity receives more attention than other services. Broader, integrated policies are needed to reflect the multifunctionality of kettle holes and prairie potholes alike.

Climate change poses contrasting hydrological futures for the two systems: increased precipitation in the PPR may enhance pond permanence and reduce salinity, whereas kettle holes in NCE will likely face intensified wet-dry cycles and droughts. These divergent trajectories underscore the need for region-specific climate adaptation strategies. Nevertheless, both systems, due to their sensitivity and small size, serve as effective indicators of landscape-scale climate responses and should be central to regional climate resilience planning.

Ultimately, both prairie potholes and kettle holes act as ecological focal points within agricultural landscapes. Maintaining their diversity, particularly through the preservation of environmental gradients and hydroperiod variability, is essential for sustaining regional biodiversity. This calls for conservation strategies that not only target individual wetlands but also their catchments, surrounding land uses, and broader landscape connectivity. By adopting a dynamic, integrative, and context-sensitive approach — drawing on both historical insights and modern technologies — effective management and restoration of these globally significant wetland systems can be achieved.

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## Declarations

**Competing Interests** The authors declare no competing interests.

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