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Hydrogeomorphic types of glacially created kettle holes in North-East Germany

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Abstract

Kettle holes are glacially created, small, shallow, depressional wetlands collecting their water from internal or closed catchments in young moraine landscapes. Their water body is defined by having a maximum of 1 ha in extent. Mostly they undergo a wet-dry circle. In North-East Germany, kettle holes are widely spread, mostly on arable land. They are characterised by large differences in hydroperiod (HP), size, shape and edge steepness. They also have a high potential for both, geomorphic structural diversity and biological species diversity. However, kettle holes are subject to pollution, drainage and structural reduction that result from intensive land use practices.

Although kettle holes in Germany are protected by law, protection strategies are not specific enough with respect to the variability of kettle holes, especially of HP. Therefore, the study objective was to characterise hydrogeomorphic (HGM) kettle hole types to create a basis for a decision support system with regard to the selection of the type dependent conservation and management measures.

In three agricultural landscapes in North-East Germany, geomorphological and hydrological variables of 268 kettle holes (HP, shore overflow tendency, depth, area, form, shore width and slope) as well as those of their catchments (area, wetland to catchment area ratio, relief) were investigated from 1993 to 2003. By statistical analysis of datasets of 144 kettle holes, 10 HGM kettle hole types were defined. The basic types are "silted fen type" and "open-water type". Basic subtypes of the latter type are "storage type", "shore overflow type" and "puddle type". Differences in spreading of kettle hole types in dependency on landscape relief were found.

Keywords: Kettle holes; Potholes; Ponds; Depressional wetlands; Hydrogeomorphic types; Young moraine; North-East Germany

Introduction

Young moraine landscapes have a high percentage of gently rolling to hilly regions with a patchwork of internal or closed drainage catchments. Kettle holes are defined as small, shallow, glacially created depressional wetlands collecting their water from these catchments. The term "Kettle holes" is preferably used in Europe (e.g. Watznauer, 1989), whereas "potholes" is a synonym in Northern America (e.g. Mitsch & Gosselink, 1993). The term "ponds" is used in a general sense to include nonmoraine landscapes. Kettle holes are by nature closed flow systems lacking an integrated drainage network. They are characterised by a high

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variability of hydrogeomorphic (HGM) site conditions, especially of the hydroperiod (HP). Most of the kettle holes undergo severe wet–dry cycles. Especially on arable land, many of them tend towards high water marshy outflows. Therefore, kettle holes have a high potential for both, geomorphic structural diversity and biological species diversity.

Kettle holes are typical landscape elements of the young moraine regions in Northern Europe and Northern America. In North-East Germany, kettle holes are widely spread (up to 40 per km^2) on a total area of 38,000 km^2 ground and terminal moraines. Their estimated total number ranges from 150,000 to 300,000. Their depression size ranges from 0.01 to 3 ha. Their water body is defined with a maximum of 1 ha from limnological point of view. In Germany, standing waters >1 ha are defined as lakes. The fact that they are mostly situated in agricultural landscapes covering up to 5% of arable land caused increased conflicts between nature conservation aspects and farmers. The kettle holes are a hindrance to crop production and the farmers cannot profit from their function as habitats and other values without agricultural subsidy. The result is that kettle holes are subject to pollution, drainage, structure reduction and active removal due to intensive land use practices (Kalettka, 1999; Kalettka, Rudat, & Quast, 2001). Similar situations were detected in other young moraine landscapes, e.g. in Poland (Kochanowska, Pienkowski, & Woleko, 1998) and Northern USA (Kantrud, Krapu, & Swanson, 1989).

In North-East Germany, kettle holes are protected by law, but negative land use impacts are still affecting them and protection strategies are not specific enough with respect to their variability. A characterisation of different kettle hole types is required to carry out a specific assessment of kettle hole functions and their current ecological status in order to create a decision support system. From such decision support system, the selection of management practices and conservation policies can be fostered that are specific to a given kettle hole type.

The kettle holes were classified in Germany (Luthardt & Dreger, 1996) and in the USA (Kantrud et al., 1989; Stewart & Kantrud, 1971) by means of dominant vegetation in dependence on HP. The specification of habitat function, however, is a result of a more combined effect of different abiotic site variables. Therefore, Brinson (1993) developed a HGM approach for the classification and functional assessment of wetlands, now commonly used in the USA basic properties for classification are geomorphic setting, hydrodynamics and dominant water source. Within the HGM system, kettle holes are defined as isolated depressional wetlands with vertical water fluctuation and differences in dominant water source. However, such a HGM classification system is lacking for kettle holes in Europe.

It is known from studies in North-East Germany, that different geomorphological variables of kettle holes and their catchments influences the water regime (WR) and the tendency towards shore overflow during high water levels (Kalettka, 1999; Schmidt, 1996). Morphological variables have also been used to classify lake types (Succow & Kopp, 1985). The objective of this study was to develop a specific and more in-depth method for the classification of HGM kettle hole types in North-East Germany.

Study area

A total of 268 kettle holes were investigated in three young ground moraine regions of Eastern Brandenburg in North-East Germany (Fig. 1). The investigation areas (IA) are Parstein (250 ha, 51 kettle holes), Lietzen (700 ha, 20 kettle holes), Müncheberg (7296 ha, 197 kettle holes) and Eggersdorf (375 ha, 35 kettle holes), which is a subregion of Müncheberg. All regions are intensively used by agriculture (approx. 90% arable land, 10% grassland). There are differences in the landscape relief of the regions: Parstein is middle rolling to hilly, Lietzen is hilly and Eggersdorf is slightly to middle rolling. Müncheberg has a mixed relief.

In North-East Germany, the WR of the kettle holes is generally influenced by a subhumid climate with a negative climatic water balance (precipitation 450–600 mm yr^{-1}, potential evapotranspiration 600–650 mm yr^{-1}). According to the hydrological map (ZGI, 1980–1989) nearly all investigated kettle holes are assumed to be disconnected from the regional groundwater table.

Methods

Data collection of the geomorphological variables of kettle holes

The geomorphological variables of kettle holes were measured in the field. For practical use, differences in the height of the top shoreline were determined by the calculation of mean values from at least four measurements at different shore transects. The top shoreline of kettle holes is defined by the maximum filling capacity line of the depression for water from the morphological point of view.

1. *Kettle hole area at top shoreline (KA) (ha)*: The area of small kettle holes was calculated by taking measurements of the maximum length and width whereas big kettle holes were calculated by measuring the circumference at the top of the shoreline. As opposed to lakes, the important parameter for area calculation is not the water line, but the top of the

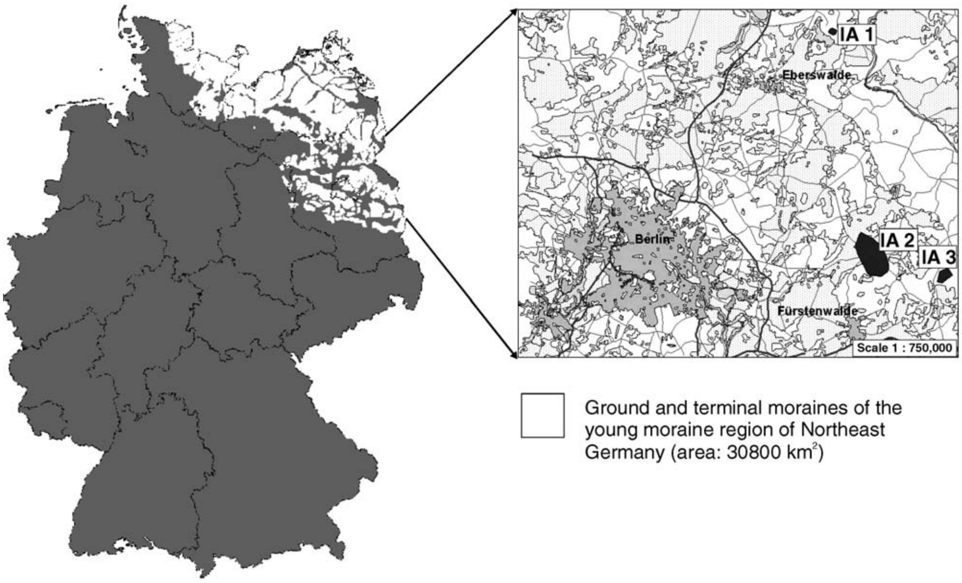

Fig. 1. Investigation areas (IA) in the young moraine landscape of North-East Germany.

shoreline. This is due to large water level fluctuations of kettle holes ranging from top shoreline overflow at high water levels to drying up. Such fluctuations can occur annually or in cycles of years.

2. *Middle maximum depth (MD); middle depth at bottom shoreline (BSD) (m)*: In shore transects, the depth was measured from top shoreline being zero point by levelling rule.
3. *Middle shore slope (SS) (%); middle shore width (SW) (m)*: In shore transects, the slope was measured by slope goniometer and levelling rule. The width was measured from top shoreline to bottom shoreline by levelling rule or calculation ($SW = BSD \tan SS^{-1}$).

Data collection of the geomorphological variables of kettle hole catchments

1. *Catchment area (CA) (ha), area ratio (AR)*: The area of the surface catchments of kettle holes was measured by connecting contour lines of topographic maps (1:10,000) and calculating the difference of the resulting area and the KA. The AR was calculated from $CA\,KA^{-1}$.
2. *Catchment relief (CR)*: The CR was estimated in the field on the basis of the German KA4-method (AG Boden, 1996). Classes are divided into "flat" (= No, no sloping), "slightly rolling" (= N1, very weak sloping), "middle rolling" (= N2, weak sloping), "strongly rolling" (= N3, middle sloping) and "hilly" (= N4, steep sloping).

Data collection of the hydrological variables of kettle holes

Kettle holes are characterised by high water fluctuations ranging from filling up over top shoreline (= shore overflow) to drying up. The water level of the kettle holes was estimated in the field three times a year (spring, summer, autumn) from 1995 to 2003. The following variables were classified:

1. *Hydroperiod*: Classes 1: "no water", 2: "episodic" (usually long drying up starting in early summer, except in very wet years), 3: "periodic" (usually short drying up starting in autumn, except in very wet years), 4: "semi-permanent" (drying up only every few years following a perennial deficit in precipitation), 5: "permanent" (no drying up).
   The classification system for HP is similar to the widely used classification system in the USA (Cowardin, Carter, Golet, & LaRoe, 1979; Kantrud et al., 1989; Stewart & Kantrud, 1971), but obviously not strictly the same regarding the period (classes in USA: temporary, seasonal, semi-permanent, intermittent, permanent).
2. *Shore overflow tendency (SOT)*: Classes 1: "no shore overflow" (kettle holes that usually store all water input), 3: "partly shore overflow" (shore overflow in small shallow parts of the shore, usually in wet years only) and 5: "complete shore overflow" (shore overflow in most parts of the shore, usually every year). Shore overflow is defined as the filling of a kettle hole by water above the top shoreline. Shore overflow usually can be observed only in spring time,

especially during high runoff resulting from snow melt or from rain on frozen soil.

Statistical data analysis with respect to the derivation of HGM kettle hole types

The datasets of HGM variables were analysed stepwise by the following statistical methods with the aid of the software "Statistica" (Statsoft GmbH, Hamburg):

1. *Test of variables for normal distribution and classification*: Datasets were tested for normal distribution by means of the Kolmogorov–Smirnov test. In case of datasets of a variable with abnormal distribution, the data were transformed to logarithmic data and tested again. Datasets with normal and lognormal distribution, respectively, were classified in five classes of equal width by means of frequency tables. Classification is helpful to reduce data of variables for following cluster analysis.
2. *Factor analysis including correlation analysis of variables*: Correlations between classified variables were analysed by using the correlation coefficient after Pearson (range between -1 and $+1$; $0 =$ no correlation, -1 or $+1 =$ perfect correlation). On the basis of the resulting correlation matrix the set of correlated master variables could be selected for the factor analysis. The aim of the factor analysis was a further reduction of correlated variables to smaller sets of latent factors by factor rotation. The interpretation of the pattern of factor loadings gave additional information on the connection between variables.
3. *Cluster analysis*: The aim of the cluster analysis was to derive different kettle hole types from the set of classified variables which had been reduced in the factor analysis. By means of this method investigated kettle holes with different hydrogeomorphological properties were classified in clusters with kettle holes of the same properties. Agglomerating method and *K*-means method, both were tested.

Results and discussion

Statistical data analysis for the derivation of HGM kettle hole types

The geomorphological and hydrological variables from a total of 268 small wetlands with different HP and their catchments in three IA were measured or estimated. From these, 144 kettle holes were selected for statistics to derive HGM kettle hole types. Criteria for selection were the definition of the wetlands as typical kettle holes as well as their integrity (area at top shoreline < 3 ha, situated in the depression of an internal catchment, neither being an artificial pond or pit, nor a part of a big wetland complex > 3 ha from silted lake, nor severely impaired by drainage or dredging out).

The datasets of variables for all kettle holes were tested for normal distribution and classified in a system of five classes (Table 1). Classification was deemed to be necessary for the following reasons. First, problems in interpretating the results of the factor analysis due to different scale units of variables were avoided. Second, classification enhanced clarity of the results of the following cluster analysis. Furthermore, classification is suitable for the practical use of variables in a key to specify kettle hole types (Table 5).

Ten variables were highly significantly correlated (Table 2). The variables CR and ratio of length and width at top shoreline (L/W) lacked highly significance. Bottom shore depth (BSD) was only highly correlated with MD and SW only with SS. Both, BSD and SW, were expressed by their substitute MD and SS, respectively. AR was only highly correlated with kettle hole area (KA), because AR was calculated on the basis of KA. In consequence, it was legitimate to reject the variables CR, AR, L/W, BSD and SW in the following factor analysis with respect to the reduction in variables for the cluster analysis.

The factor analysis resulted in three factors (Table 3). Factors 1 and 2 were determined only by the selected correlated variables. Factor 1 showed a positive correlation between WR, CA, KA, MD and depth difference (MD$-$BSD) ($=$ CATCHMENT AND KETTLE HOLE SIZE FACTOR). Factor 2 showed a negative correlation between SOT and SS ($=$ OVERFLOW FACTOR). Despite of the result of the correlation matrix (Table 2), factor 3 was consisting of the two very little correlating variables CR and L/W. They were positively correlated in factor 3 ($=$ RELIEF AND SHAPE FACTOR).

The derivation of HGM kettle hole types in the cluster analysis was carried out with the selected variables of factors 1 and 2. Including the variables of factor 3 in the cluster analysis was not suitable for the differentiation of the clusters. Factor 3 showed that the ratio of length and width of kettle holes generally strengthens with increasing class of CR.

In the cluster analysis both, the agglomerating method and the *K*-means method were tested with datasets of classified and nonclassified variables. A problem was the diffuse separation of clusters when analysing the whole kettle hole population in one step. One reason for this was the non-uniform distribution of kettle holes with equal characteristics in the population of the investigated kettle holes. Another reason was the insufficient equality of kettle hole properties within the clusters. Consequently, only a stepwise use of the *K*-means method with classified variables produced clear

Table 1. Classification of hydrogeomorphic variables of kettle holes

Variables	Normal distribution[a]	Classes				
		1	2	3	4	5
CA (ha): catchment area	Lognormal	⩽1.0 Very small	⩽3.2 Small	⩽10.0 Middle	⩽31.6 Big	>31.6 Very big
AR = CA KA^{-1} area ratio	Lognormal (calculated)	⩽3 Very small	⩽10 Small	⩽32 Middle	⩽100 Big	>100 Very big
CR: catchment relief	Not normal (estimated)	Flat	Slightly rolling	Middle rolling	Strong rolling	Hilly
KA (ha): Kettle hole area	Lognormal	⩽0.03 Very small	⩽0.10 Small	⩽0.32 Middle	⩽1.00 Big	>1.00 Very big
MD (m): Middle maximum depth	Lognormal	⩽1.0 Very wadeable	⩽1.6 Wadeable	⩽2.5 Very shallow	⩽4.0 Shallow	>4.0 Deep
BSD (m): Middle depth at bottom shore	Lognormal	⩽1.0 Very wadeable	⩽1.6 Wadeable	⩽2.5 Very shallow	⩽4.0 Shallow	>4.0 Deep
MD−BSD: Difference of depth	Not normal (calculated)	⩽0.25 Very small	⩽0.5 Small	⩽1.0 Middle	⩽2.0 Big	>2.0 Very big
L/*W*: Ratio of length and width at top shoreline	Not normal (calculated)	⩽1.5 Roundish		⩽2.5 Oval		>2.5 Stretched
SW (m): Middle shore width	Not normal (nearly normal)	⩽4 Very narrow	⩽6 Narrow	⩽10 Middle	⩽16 Wide	>16 Very wide
SS (%): Middle shore slope	Normal	⩽10 Flat	⩽20 Sloping	⩽30 Very sloping	⩽40 Steep	>40 Very steep
HP: Hydroperiod	Not normal (estimated)	Never water	Episodic	Periodic	Semiper-manent	Permanent
SOT: Shore overflow tendency	Not normal (estimated)	Not		Partly		Completely

[a]Test for normal distribution by means of the Kolmogorov–Smirnov-test.

Table 2. Correlation matrix of hydrogeomorphic variables of kettle holes ($n = 144$)

	HP	SOT	CA	AR	CR	KA	MD	BSD	MD−BSD	*L*/*W*	SS	SW
HP	1.00	0.04	**0.55**	−0.33	0.22	**0.75**	**0.55**	0.33	**0.55**	0.13	−0.22	0.39
SOT	0.04	1.00	0.03	−0.16	−0.06	0.06	−0.28	−0.26	−0.10	0.06	**−0.57**	0.22
CA	**0.55**	0.03	1.00	0.12	0.26	**0.58**	0.29	0.12	0.37	0.15	−0.23	0.27
AR	−0.33	−0.16	0.12	1.00	−0.10	**−0.57**	−0.13	0.06	−0.27	−0.10	0.23	−0.13
CR	0.22	−0.06	0.26	−0.10	1.00	0.28	0.14	0.13	0.13	0.26	−0.10	0.15
KA	**0.75**	0.06	**0.58**	**−0.57**	0.28	1.00	0.40	0.19	**0.53**	0.21	−0.34	0.42
MD	**0.55**	−0.28	0.29	−0.13	0.14	0.40	1.00	**0.73**	**0.65**	0.00	0.22	0.29
BSD	0.33	−0.26	0.12	0.06	0.13	0.19	**0.73**	1.00	0.21	−0.05	0.25	0.39
MD−BSD	**0.55**	0.10	0.37	−0.27	0.13	**0.53**	**0.65**	0.21	1.00	0.10	−0.05	0.17
L/*W*	0.13	0.06	0.15	−0.10	0.26	0.21	0.00	−0.49	0.10	1.00	−0.12	0.06
SS	−0.22	**−0.57**	−0.23	0.23	−0.10	−0.34	0.22	0.25	−0.05	−0.12	1.00	**−0.61**
SW	0.39	0.22	0.27	−0.13	0.15	0.42	0.29	0.39	0.17	0.06	**−0.61**	1.00

Bold values = high correlation ($p<0.001$, values ⩾0.5).
Abbreviations see Table 1.

results whilst allowing the differentiation of kettle hole types (Figs. 2–4 and Table 4). The *K*-means method is suitable, if there is an image of the number of expected clusters. This was realised by the results of the factor analysis.

In a first step, two types of kettle holes were excluded from further cluster analysis. The first type "Silted Fen Type" was represented in the three IA by only one kettle hole (fen, usually not flooded) whereas the second type "Puddle Type" was represented by only two kettle holes (nonpermanent shore, very small, wadeable, in dry years completely used as arable land). They obviously differed a lot from the other kettle holes (Table 4). These kettle holes can be defined as types because it is known that

Table 3. Factor analysis of hydrogeomorphic variables of kettle holes

Variables	Factor 1	Factor 2	Factor 3
HP	**0.86**	0.13	−0.12
SOT	−0.06	**0.85**	0.07
CA	**0.65**	0.19	−0.27
CR	0.18	−0.05	**−0.76**
KA	**0.81**	0.24	−0.24
MD	**0.75**	−0.43	0.07
MD–BSD	**0.81**	−0.14	0.03
L/*W*	0.03	0.08	**−0.77**
SS	−0.16	**−0.86**	0.11
Explained variance (value)	3.10	1.80	1.36
Part of total variance %	34	20	15

Bold values = high correlation ($p<0.001$, values $\geqslant 0.5$).
Extraction: main components; factor rotation: varimax; results: factor loadings of variables, bold values = loadings $\geqslant 0.65$.
Abbreviations see Table 1.

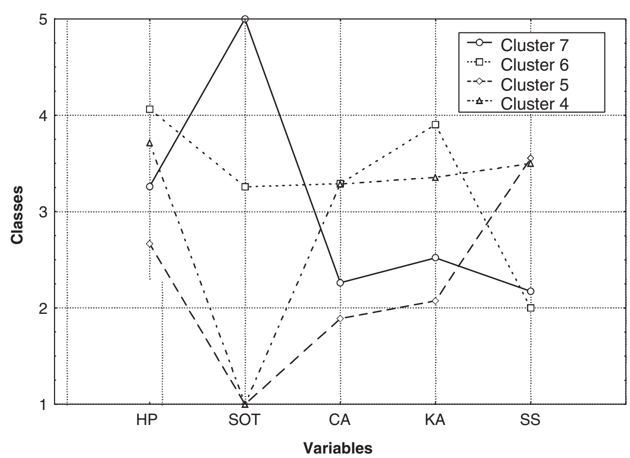

Fig. 2. Clusters of shallow kettle holes ($n = 95$, mean values, *K*-means-cluster analysis).

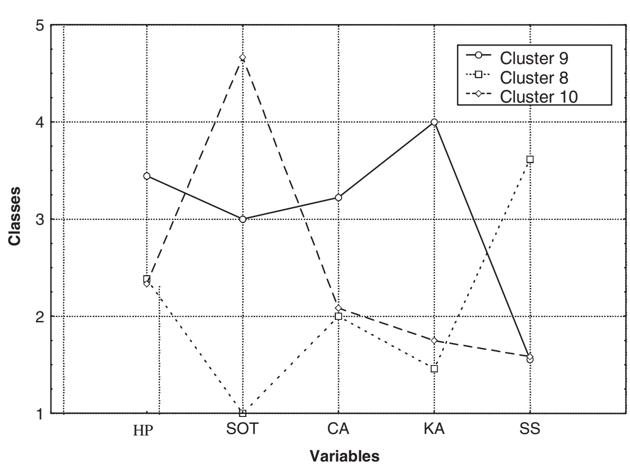

Fig. 3. Clusters of wadeable kettle holes ($n = 35$, mean values, *K*-means-cluster analysis).

some kettle holes of these two very characteristic types have also been observed in other young moraine regions of North-East Germany (Dreger & Schmidt, pers. comm.; Klafs, Jeschke, & Schmidt, 1973; Luthardt & Dreger, 1996; Schmidt, 1996). But, until now there are no measurements on HGM features of these two types in these other regions.

In a second step, it was necessary to divide open-water kettle holes into three groups regarding their depth (deep, shallow, wadeable). In a third step, the pre-selected clusters were further analysed in a cluster analysis. As a result, deep kettle holes were defined as one cluster (Table 4). Shallow kettle holes were divided into four clusters, wadeable kettle holes into three clusters (Figs. 2 and 3 and Table 4). In total, only four kettle holes were not clustered into a group.

Fig. 4 gives an overview on the HGM kettle hole types. A short key to classify the types was developed (Table 5). Basic types are characterised as follows:

1. *Silted Fen Type*: This type is silted by peat (fen) and usually not flooded by surface water. Exceptionally, partly flooding up to 20 cm depth over some days can occur in very wet spring. Such kettle holes are rare in arable land, but typical in woodlands. They are assumed to be relictic fens in tilled landscapes, protected from flooding and soil erosion since medieval deforestation due to small catchments (Klafs et al., 1973).
2. *Storage Type* (Fig. 5): That type has sufficient volume to store all incoming water. Usually, no shore overflow to surrounding edges or agriculturally used areas could be observed.
3. *Shore Overflow Type* (Fig. 6): That type has insufficient volume for water storage. Usually, water overflows the top shoreline up to surrounding edges or agriculturally used areas. That type cause most conflicts with regard to arable land use due to periodic crop losses. Three kettle holes with a peaty island in their middle were found to be a subtype of the Big Shallow Shore Overflow Type (Fig. 4).
4. *Puddle Type* (Fig. 7): This type is very small and characterised by a nonpermanent shore due to periodic complete use as arable land, especially in dry periods.

The developed typology is restricted to usage in agricultural landscapes with dominating arable land for two different reasons. First, the classification of Storage Type and Shore Overflow Type is strictly speaking only applicable if a top shoreline is noticeably visible. This is usually the case at kettle holes in agricultural landscapes due to the accumulation of soil and other materials at top shore by land use practices. In woodlands, the top shoreline can be absent. Second, in Northern America, a significantly lower water table as well as

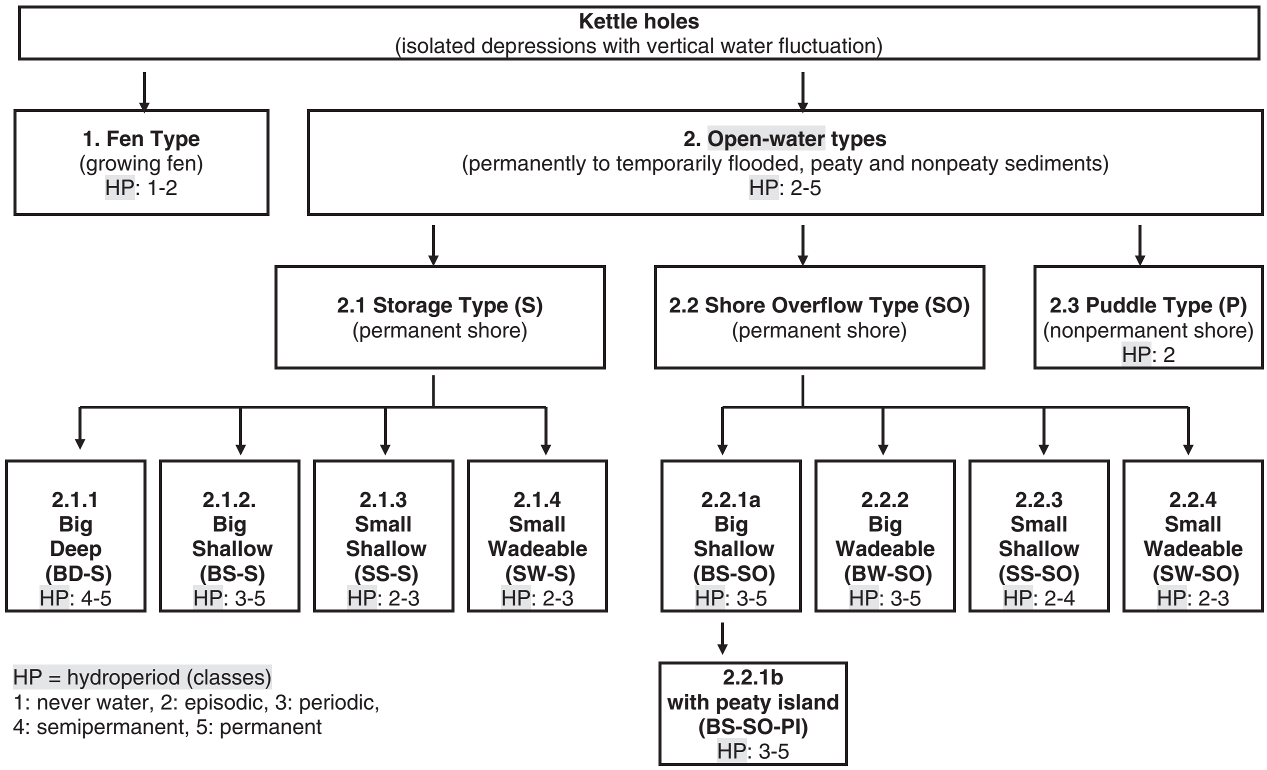

Fig. 4. Hydrogeomorphic kettle hole types in agricultural young moraine landscapes of North-East Germany.

lower fluctuation of the water level was detected at kettle holes in grassland landscapes compared with kettle holes in tilled agricultural landscapes (Euliss & Mushet, 1996; Van der Kamp, Stolte, & Clark, 1999).

Water sources of HGM kettle hole types

When using the HGM classification of Brinson (1993), "isolated depressional wetlands with vertical water fluctuation" (= kettle holes or potholes, respectively) can be differentiated by dominating water sources. They are precipitation and surface flow as well as ground water discharge from interflow and regional groundwater table. Nearly all of the investigated open-water kettle holes are assumed to be disconnected from the regional groundwater table (hydrological map). Additionally, kettle holes in agricultural landscapes are generally highly influenced by lateral surface flow and interflow from their surrounding catchments. Especially snowmelt and runoff on frozen soil during springtime periodically causes kettle holes to fill rapidly, thus increasing the potential for shore overflow by water. Kettle holes lose water by evapotranspiration and groundwater recharge, which is limited to the regional groundwater table due to sealing layers of clayey loam. Under conditions of negative climatic water balance in North-East Germany, water levels of kettle holes generally decrease during the hydrological summer half-year causing the drying up of particularly the small wadeable and shallow kettle holes (Kalettka, 1999; Schindler, 1996).

Evidence for a dominant influence of the regional groundwater table on kettle holes can be a permanent WR and a low catchment-to-kettle hole AR. Such a WR was detected at big kettle holes. However, only the mean values for the WR of the Big Shallow Shore Overflow Type and the Big Deep Storage Type were higher than class 4. Kettle holes with a low AR (classes 1 and 2) were included in all types. However, only the mean values of the AR of the two Big Shore Overflow Types were lower than class 3 (Table 4). Furthermore, some of the big kettle holes with permanent WR in the region Lietzen are suspected to be additionally influenced by the regional groundwater table (hydrological map). They belong to the Big Shallow Shore Overflow Type.

The dominating water source of the investigated silted peaty kettle hole is obviously interflow due to its catchment properties. The question remains, if other kettle holes of this type could be influenced by discharge from the regional groundwater table. That can be assumed by hints on preferably small catchment to wetland AR of such types (Klafs et al., 1973).

In consequence, surface flow and groundwater discharge from interflow are dominating water sources of the open-water HGM kettle hole types. An additional

Table 4. Descriptive statistics of variables (as classes) of open-water hydrogeomorphic kettle hole types (classification see Table 1)

Basic type	Permanent shore								Nonpermanent shore
	Storage type (S)				Shore overflow type (SO)				
Subtype	Big deep S	Big shallow S	Small shallow S	Small wadeable S	Big shallow SO	Big wadeable SO	Small shallow SO	Small wadeable SO	Puddle type (P)
Cluster number	3	4	5	8	6	9	7	10	2
n	9	14	27	13	31	8	23	14	2
Variables of kettle holes									
MD	5	3–3.6–4	3–3.1–4	1–1.9–2	3–3.2–4	1–1.8–2	3–3.1–4	1–1.7–2	1
BSD	3–3.6–5	2–2.6–3	1–2.4–4	1–1.6–2	1–1.9–3	1–1.4–3	2–2.4–4	1–1.3–2	1
MD−BSD	4–4.8–5	2–2.9–4	1–2.3–3	1–1.6–3	2–3.2–5	1–2.1–3	1–2.5–4	1–1.9–3	1
KA	3–4.4–5	3–3.4–5	1–2.1–3	1–1.5–3	3–3.9–5	3–4.1–5	1–2.5–3	1–1.9–3	1
L/W	1–3.3–5	1–2.7–5	1–2.4–5	1–2.2–5	1–2.5–5	1–3.0–5	1–3.0–5	1–2.7–5	—
SS	1–2.9–5	3–3.5–5	3–3.6–5	3–3.6–5	1–2.0–3	1–1.5–3	1–2.2–3	1–1.6–2	—
SW	2–3.8–5	1–2.7–4	1–2.4–4	1–1.5–2	1–3.2–5	1–3.1–4	2–3.0–5	1–3.0–5	—
SOT	1	1	1	1	3–3.3–5	3	5	3–4.6–5	—
HP	4–4.8–5	3–3.7–5	2–2.7–4	2–2.4–3	3–4.1–5	3–3.5–5	2–3.3–4	2–2.4–4	2
Variables of catchments									
CA	3–3.5–4	3–3.3–4	1–1.9–3	1–2.0–3	2–3.3–4	3–3.4–4	1–2.3–3	1–2.1–3	1
AR	2–3.1–4	2–3.5–4	1–3.2–5	2–4.1–5	1–2.6–5	1–2.8–4	1–3.0–4	2–3.6–5	—
CR	3–4.6–5	1–3.6–5	1–2.9–5	1–2.6–5	1–3.4–5	1–3.5–5	1–3.0–5	1–3.4–5	—

x–$\underline{x.x}$–x = minimum–mean value–maximum; n = number; MD = middle maximum depth; BSD = middle depth at bottom shore; MD-BSD = difference of depth; KA = kettle hole area at top shore; SS = shore slope; SW = shore width; SOT = shore overflow tendency; HP = hydroperiod; AR = area ratio; CR = catchment relief; CA = catchment area; L/W = length/width at top shore.

Table 5. Short key for hydrogeomorphic kettle hole types (classes of variables see Table 1)

Kettle hole type	Step 1	Step 2	Step 3	Step 4		Step 5			
	Fen	MD	NP	SS	SOT	KA	CA	HP	CR⩾3
Fen type	X	—	—	—	—	—	—	—	—
Puddle type	—	1	X	—	—	1	1	2	—
Small wadeable Shore overflow type	—	1–2	—	1–2	(3–)5	1–3	1–3	2–3(–4)	—
Big wadeable Shore overflow type	—	1–2	—	1–2(–3)	3	(3–)4–5	3–4	3–4(–5)	—
Small wadeable Storage type	—	1–2	—	3–4(–5)	1	1–3	1–3	2–3	—
Small shallow Shore overflow type	—	3–4	—	1–3	5	1–3	1–3	(2–)3–4	—
Big shallow Shore overflow Type	—	3–4	—	1–3	3(–5)	3–5	(2–)3–4, 2 only if KA 4–5	3–5	—
Small shallow Storage type	—	3–4	—	3–5	1	1–3	1–2(–3), 3 only if KA 1–2	2–3(–4)	—
Big shallow Storage type	—	3–4	—	3–5	1	3–5	3–4	3–4(–5)	—
Big deep Storage type	—	5	—	1–5	1	3–5	3–4	4–5	X

Values in brackets are exceptions. MD = middle maximum depth; NP = nonpermanent shore; SS = middle shore slope; SOT = shore overflow tendency; KA = kettle hole area; HP = hydroperiod; CR = catchment relief.

Fig. 5. Storage type.

Fig. 6. Shore overflow type.

influence by groundwater discharge from the regional groundwater table can be partly expected at big kettle hole types, especially at the Big Shallow Shore Overflow Type. More research is needed in Germany on the share of surface flow and interflow with respect to an additional differentiation of HGM kettle hole types. Field studies carried out in Northern USA and Canada suggest that a differentiation of kettle holes with regard to discharge, flowthrough or recharge of groundwater can be accomplished (Richardson, Arndt, & Montgomery, 2001, Chap. 3; Richardson, Wilding, & Daniels, 1992; Van der Kamp, 1998).

Regional distribution of HGM kettle hole types

Despite the fact that there was only a very little correlation of the CR with other tested variables, differences in the distribution of HGM kettle hole types depending on the landscape relief were detected (Table 6). In the hilly ground moraine, big shallow to deep kettle hole types were dominating (87.5%). Wadeable kettle holes were rare (6.3%), small shore overflow types were missing. In the slightly to middle rolling ground moraine, a high percentage of small wadeable to shallow kettle hole types occured (78.3%). Storage types occurred more often in hilly landscapes (62.6%) than in rolling landscapes (48.6%). The reason is that internal catchments in the hilly landscape have a larger area, more depth and longer slopes compared to those in the rolling landscape. Kochanowska et al. (1998) also found a relationship between kettle hole types and the landscape geomorpholgy. In tendency, increased landscape relief enhanced the number of large permanent to semi-permanent kettle holes.

Fig. 7. Puddle type.

Summary and conclusion

A concept for the classification of HGM kettle hole types was developed by a statistical analysis of datasets from kettle holes with 12 hydrological and geomorphological variables. The six variables ‘‘maximum depth’’, ‘‘shore slope’’, ‘‘kettle hole area’’, ‘‘catchment area’’, ‘‘shore overflow tendency’’ and ‘‘water regime’’ were selected as key variables for classification. In contrast to the system of morphological lake types by Succow and Kopp (1985), the ratio of length and width was deemed to be not suitable for the classification of HGM kettle hole types. Therefore, the shape does not explain the water dynamics of kettle holes. The result of this study is an increase in the classification of isolated depressional wetlands in the HGM system (Brinson, 1993) with a more in-depth differentiation of kettle holes. The validity of the typology is preliminary restricted to intensively used agricultural landscapes in sub-humid northern European climate. There is a need for further testing of the typology in other young moraine landscapes with respect to the calibration of the types as well as to the influence of other land use conditions (e.g. pasture land), different climate and the dominating water source. The developed kettle hole typology forms the basis for more specific assessment methods as well as for conservation and management strategies regarding the different functions of the kettle hole types. Furthermore, the results on the distribution of HGM kettle hole types in dependence on landscape properties like relief could be used to develop regional target images for kettle holes.

Table 6. Distribution of hydrogeomorphic kettle hole types in dependence on landscape relief

Kettle hole types	% Eggersdorf Slightly to middle rolling ground moraine	% Lietzen Hilly ground moraine
Storage types (ST)		
Big deep ST	2.7	**18.75**
Big shallow ST	5.4	**31.25**
Small shallow ST	**29.7**	6.3
Small wadeable ST	10.8	6.3
Shore overflow types (SOT)		
Big shallow SOT	10.8	**37.5**
Big wadeable SOT	2.7	0
Small shallow SOT	**16.2**	0
Small wadeable SOT	**21.6**	0

Bold values = dominance.

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