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Water-level dynamics in natural and artificial pools in blanket peatlands

[1]Holden, J., [1]Moody, C., [1,2]Turner, T.E. [3,4]McKenzie, R., [1]Baird, A.J., [5]Billett, M.F., [1]Chapman, P.J., [6]Dinsmore, K.J., [1]Grayson, R.P, [3]Andersen, R., [1]Gee, C., [1]Dooling, G.

[1]water@leeds, School of Geography, University of Leeds, Leeds, LS2 9JT,

[2]Forestry Commission Scotland, Creebridge, Newton Stewart, Dumfries & Galloway, DG8 6AJ

[3]Environmental Research Institute, North Highland College, University of the Highlands and Islands, Castle Street, Thurso, Caithness, KW14 7JD, UK,

[4]Department of Geography, Loughborough University, Loughborough, Leicestershire LE11 3TU, UK,

[5]Biological & Environmental Sciences, Faculty of Natural Sciences, University of Stirling, Stirling, FK9 4LA,

[6]Centre for Ecology and Hydrology Edinburgh, Bush Estate, Penicuik, Midlothian, EH26 0QB, UK,

Corresponding author: Professor Joseph Holden, water@leeds, School of Geography, University of Leeds, Leeds, LS2 9JT, UK j.holden@leeds.ac.uk +44 113 343 3317

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Abstract

Perennial pools are common natural features of peatlands and their hydrological functioning and turnover may be important for carbon fluxes, aquatic ecology and downstream water quality. Peatland restoration methods such as ditch blocking result in many new pools. However, little is known about the hydrological function of either pool type. We monitored six natural and six artificial pools on a Scottish blanket peatland. Pool water levels were more variable in all seasons in artificial pools having greater water level increases and faster recession responses to storms than natural pools. Pools overflowed by a median of 9 and 54 times pool volume per year for natural and artificial pools respectively but this varied widely because some large pools had small upslope catchments and *vice versa*. Mean peat water-table depths were similar between natural and artificial pool sites but much more variable over time at the artificial pool site, possibly due to a lower bulk specific yield across this site. Pool levels and pool-level fluctuations were not the same as those of local water tables in the adjacent peat. Pool level time-series were much smoother, with more damped rainfall or recession responses than those for peat water tables. There were strong hydraulic gradients between the peat and pools, with absolute water tables often being 20-30 cm higher or lower than water levels in pools only 1-4 m away. However, as peat hydraulic conductivity was very low (median of 1.5×10^{-5} and 1.4×10^{-6} cm s^{-1} at 30 and 50 cm depths at the natural pool site) there was little deep subsurface flow interaction. We conclude that: 1) for peat restoration projects, a larger total pool surface area is likely to result in smaller flood peaks downstream, at least during summer months, because peatland bulk specific yield will be greater; and 2) surface and near-surface connectivity during storm events and topographic context, rather than pool size alone, must be taken into account in future peatland pool and stream chemistry studies.

Keywords: peatland, pools, water level, restoration, wetland, ponds

1. **Introduction**

Peatlands are important carbon stores (Yu, 2012) covering around 423 million hectares of the land surface (Xu *et al.*, 2018). Their expanse increased during the Holocene, particularly in the northern high latitudes after deglaciation, where a cool, wet climate is co-located with low-lying basins and other areas of poor drainage (Yu *et al.*, 2010). Even on upland terrain with slopes as great as 15°, blanket peatlands have developed in many temperate hyperoceanic regions including parts of Atlantic northwest Europe, eastern and western Canada, southern Alaska, Tasmania, the South Island of New Zealand, the southern tip of South America and eastern Russia (Gallego-Sala and Prentice, 2012).

Peatlands are characterised by shallow water tables and are capable of storing very large volumes of water since peat soils often have porosities > 95 % (Ingram, 1983; Hobbs, 1986). In addition to the peat volumetric water store, peatlands often contain open-water pools (Glaser, 1998). Multiple hypotheses have been proposed for natural pool formation and expansion in peatlands (cf. Belyea and Lancaster, 2002), but surprisingly little is known about the hydrological functioning of peatland pools. In some northern peatlands the surface area of pools can be as much as 90 % of the total peatland area (e.g. Sjors, 1983) but pools more typically represent 5-30 % of the land area where they are present (e.g. Foster and Glaser, 1985; Roulet *et al.*, 1994). Peatland pools are important for aquatic biodiversity, particularly when there is a wide variety of pool sizes (Downie *et al.*, 1998; Beadle *et al.*, 2015). They are also often 'hotspots' of carbon dioxide and methane emissions (Hamilton *et al.*, 1994; Waddington and Roulet, 1996; Pelletier *et al.*, 2014) and as such they are likely to process dissolved and particulate organic carbon altering dissolved and particulate carbon concentrations and characteristics in pools (Pickard, 2016; Turner *et al.*, 2016), potentially influencing downstream water chemistry. Their hydrological functioning is likely to control how pools process carbon, yet little is known about hydrological processes associated with pools in peatlands. During rainfall pools may spill over, delivering water to other parts of the peatland or to nearby stream networks (Quinton and Roulet, 1998). Rates of pool water turnover have not been reported but could affect overall water residence times in peatlands, which in turn may be important in controlling peat decomposition rates (Beer and Blodau, 2007; Morris and Waddington, 2011) or streamwater chemistry. However, these functions have not previously been tested for natural pool systems in blanket peatlands.

Two previous short-term studies of pool hydrological function in fens and raised bogs in Canada have shown that pools can provide significant depression storage for rainfall thereby greatly reducing runoff from the system (Price and Maloney, 1994; Quinton and Roulet, 1998). Quinton and Roulet (1998) studied a narrow, valley bottom pool-patterned fen for four months and found it was dominated by two distinct phases of operation: (1) an overflow phase during spring melt and one large summer storm when water supply exceeded the depression storage capacity and the pools effectively coalesced producing diffuse surface runoff, and (2) a summer phase, without spill over, when pools were disconnected, with slow rates of groundwater inputs which were around an order of magnitude less than pool evaporation rates. A six-week study of a small fen and raised bog in Labrador indicated that the catchment runoff ratio was < 0.15 with the pools enhancing evaporative losses (Price and Maloney, 1994). For the systems studied, Price and Maloney (1994) noted that pool position relative to the local topography and the location of peat pipes connected to pools were both important for controlling pool inflows and outflows, although pipe flows, pool outflow rates and pool levels were not directly measured. There have been no detailed studies of pool hydrological function in blanket peatlands and no natural pool hydrological function studies for any type of peatland that have continued for periods of more than a few months.

Many northern peatlands have been drained for peat extraction, forestry and agriculture (e.g. Höper *et al.*, 2008). For example, drainage ditch construction was common practice between the 1940s and 1980s in the UK, where blanket peat covers around 7 % of the land surface (Baird *et al.*, 2009). Such drainage did not achieve its aim of enhancing agricultural productivity (Stewart and Lance, 1983), but led to environmental problems including erosion (Mayfield and Pearson, 1972; Holden *et al.*, 2007) and, in some places, to enhanced losses of dissolved organic carbon into streams and rivers (Mitchell, 1990; Mitchell and McDonald, 1995; Armstrong *et al.*, 2010). In common with many areas of the world (*cf*. Höper *et al.*, 2008) where peatlands have been damaged by artificial drainage, ditches in UK peatlands are being blocked. This restoration activity results in the creation of thousands of small pools within the blocked ditches, which in sum can amount to a large area of open water (Parry *et al.*, 2014; Brown *et al.*, 2016; Holden *et al.*, 2017). It is not known to what extent the hydrological functioning of these artificial peatland pools is similar to that of natural pools. Price *et al.* (2002) studied experimental artificial pools installed in a cutover plateau bog in Québec. They did not measure pool water levels but measured the water tables and soil tension in the surrounding peat on 76 days during the study compared to a control cutover treatment without pool creation, showing that water-tables were more stable following pool creation. This reduction in water-table variability has also been found on some sites with ditch-blocked pools in upland blanket peat in the British Isles (Holden *et al.*, 2011). This is to be expected because the specific yield of a pool is 1 whereas the specific yield of peat is substantially less than one; if a significant proportion of a peatland is taken up by pools, its bulk specific yield will be higher than that of the peat itself.

The paucity of data on peatland pool hydrological functioning means that we lack understanding of whether peatland open-water pool levels and their fluctuations are similar between artificial and natural systems. There have been no detailed inter-annual studies of natural peatland pool hydrological function. We also lack basic understanding of whether water levels in pools and their fluctuations in response to rainfall or evaporation simply reflect those of the water table in the surrounding peat. It may be that either: (1) pool water levels are well connected to local water-table levels and fluctuations in the surrounding peat; or (2) the two systems are partly independent of each other in terms of their hydrological functioning. Furthermore, pool water volume replacement and spill over rates have never been measured in blanket peatlands before. Here we report on a study in which we compared the hydrological functioning of natural and artificial blanket peatland pools. For a site in which both pool types were in close proximity, we investigated pool water-level dynamics, established rates of pool water replenishment (turnover), and examined water-table fluctuations in the peat surrounding the pools.

2. Methods

Six natural pools (Pools 1-6) and six artificial pools (Pools 7-12) were chosen for investigation (Figure 1) at Cross Lochs peatland in the Flow Country, northern Scotland (58° 22’ N, 03° 57’ W), at ~215 m altitude (Figure 1) between 2013 and 2016. The Flow Country bog system is the UK's largest single tract of peatland covering ~4000 km^2 (Ingram, 1987; Lindsay *et al.*, 1988). It has many intact pool systems similar to those in a range of other blanket bog systems in Scotland (e.g. Boatman, 1983; Ratcliffe and Oswald, 1988; Belyea, 2007) and peatland pool systems in continental settings (e.g. Glaser, 1998). The climate of the area is cool with a mean annual temperature for 1981-2010 of 7.6°C and a mean annual precipitation of 1196 mm for Altnaharra meteorological station, ~30 km from Cross Lochs. While snowfall may occur at the site in winter, it is synoptically controlled and will often melt completely within a few days. Rainfall is much more common in winter than snow. Peat depths at the site were measured using rod probing and ranged from 0.94 m to 4.00 m which is in line with earlier surveys in the area (Ratcliffe and Payne, 2016). The underlying geology forms part of the Moine Supergroup with Pre-Cambrian migmatitic pelite and semipelite metamorphic rocks. The vegetation is dominated by mosses, sedges and small shrubs. Mosses mainly include *Sphagnum cuspidatum*, *S. denticulatum*, *S. fallax*, *S. capillifolium*, *S. subnitens*, *S. papillosum S. tenellum* and *Racomitrium lanuginosum*. Liverworts such as *Plurozia purporea* are abundant at the site. Sedges, mainly *Eriophorum vaginatum* and *E. angustifolium* and small shrubs, mainly *Calluna vulgaris* and *Erica tetralix*, are widespread.

The natural and artificial pool sites were close to each other (within c. 400 – 600 m; Figure 1). The mean slope was 0.04 across the natural pool site and 0.05 m m^{-1} across the artificial pool site. Pools covered 8.6 % of the surface area of the natural pool site and 0.7 % of the artificial pool site. The northwest section of Figure 1 shows a nearby block that was subject to plantation forestry which has been felled. However, this forest restoration block is beyond the drainage divide and does not interact with the natural or artificial pool sites we studied. The selected pools were deemed to be representative of the pools across the site. Pools, particularly natural pools, often have uneven beds and so transects in two directions across each pool were surveyed to calculate pool depths; for the larger pools this resulted in around 30 depth measurements per pool whereas for small (~< 9m^2) pools there were 4-10 depth measurements per pool. Natural pools ranged in size from 9 m^2 to 868 m^2 (Table 1) while the range of sizes for artificial pools was much smaller at 1 m^2 to 6 m^2. The catchment area for each pool was calculated based on surface topography and the approximate length of the perimeter that received surface water from an upslope topographic area was also determined (Table 1). For most of the natural pools more than half of their perimeter received water from upslope, whereas for all of the artificial pools less than a third of their perimeter received surface drainage water from upslope. The mean water heights above pool bed for natural and artificial pools were comparable (38 cm and 39 cm respectively; Table 1). The artificial pools were created behind peat dams constructed in 2002, located within artificial drainage ditches that had been dug in the 1970s. The artificial pools were constructed in a typical manner for blanket peatlands in the UK (Parry *et al.*, 2014) with peat excavated from one side of the ditch at the dam location, thereby widening the ditch at the location where the pool is formed. The excavated peat was used to form the dam, with the original vegetation layer from the excavated peat placed onto the dam top to help stabilise it. Only one artificial pool per ditch was chosen for study.

Meteorological data were collected on site using a Davis Vantage Pro 2 automatic weather station. Open water evaporation from the pools was calculated using the Penman (1948) open water equation which is physically based and uses temperature, relative humidity, wind speed and solar radiation data. The equation has been shown to be robust during comparison studies with other equations or directly measured rates of open water evaporation (Linacre, 1993; McMahon *et al.*, 2016).

Wooden boarding was used at key locations to minimise the impacts of disturbance during site visits and snow shoes were used throughout the year to reduce the effects of foot traffic on the peat system. All pools were instrumented in late May 2013 with automated water-level loggers (In Situ Level TROLL 500, accuracy ± 3 mm) housed within slotted stilling wells and set to record at 15-minute intervals. Here we consider data collected between 1st July 2013 and 28th January 2016. Pool water level data are either reported as water height above pool bed or as depth-below-peat-surface' (DBPS) (distance from the peat surface on the pool edge down to the water surface in the pool). A peat-surface datum was used close to the stilling well in each pool. However, it should be noted that the topography of pool perimeters varies so that the distance from the peat surface to the pool water surface also varies along the pool perimeter. At some locations along the pool perimeter the DBPS may be several cm, while at other points along the perimeter it may be zero and water may be spilling out from the pool. A repeated-measures ANOVA was used to test for differences in DBPS between seasons (winter = December to February; spring = March to May, summer = June to August, autumn = September to November) and pool type. SAS v9.4 was used for statistical analysis; all data were checked for normal distribution and a p level of 0.05 was used for significance. For the repeated measures ANOVA, the data were tested using Mauchly's test for sphericity, and a polynomial transformation carried out.

For each pool, DBPS responses to the 20 largest storm events observed over the monitoring period were analysed. The DBPS values for each pool before each storm commenced, and the smallest DBPS values during or immediately after each storm, were determined along with the lag time from rain start to smallest DBPS. Pool level recession responses were also analysed by extracting the DBPS values 6 hours and 12 hours after the smallest DBPS values were recorded and a recession rate calculated in cm hr^{-1}. Two-sample *t*-tests were used to test for differences in storm response variables, including recession rates, between the natural and artificial pools.

Crest-stage tubes (Burt and Gardiner, 1984), with holes placed flush with the peat surface were used to collect overland flow on the peat at the upslope end of each pool and at the downstream exit points of each pool. These tubes were checked during each site visit (47 in total between June 2013 and January 2016) and a record kept of whether they were full or empty. If they contained water they were emptied.

Ten PVC dipwells, with a 28.4 mm inside diameter and with 8 mm diameter holes drilled at 50 mm intervals along their length (two lines of holes along the dipwells), were installed in July 2013. A dipwell was installed in the peat 1 m away from each pool, but because Pools 3 and 4 were close to each other, and also Pools 5 and 6, one dipwell was located between each of these pairs (still around 1 m from pool edges), giving 10 dipwells in total. Water tables were manually measured using a dipmeter on each site visit until January 2016. In May 2015 an additional ten dipwells were installed with six located in the natural pool system and four in the artificial pool system, each of which was instrumented with an In Situ Level TROLL 500 logger to record water tables at 15-minute intervals. The instrumented dipwells at the natural site were located next to two pools, with a dipwell upslope, midslope (i.e., at the side of the pool) and downslope of Pool 1 (coded P1U, P1M, P1D) and Pool 4 (P4U, P4M, P4D). At the artificial site the instrumented dipwells were located upslope and downslope of Pools 8 and 11 (P8U, P8D, P11U, P11D). All dipwells were located between 1 and 4 m from pool edges (1.5 to 2 m away in the case of the artificial pools). Response time tests were carried out on the dipwells, with full recovery after slug withdrawal occurring within 15 minutes in all cases indicating that the dipwell data are reliable. A topographic survey of all dipwells and stilling wells at the two sites allowed the water-table depths to be compared between the pools and instrumented dipwells, relative to a datum at each site. Eleven large storm events occurred during the period when automated dipwell data were available. Water-table data were extracted from the automated dipwell records for these storms using the same approach as for pool levels described above, and were analysed using a one-way ANOVA with a post-hoc Tukey test.

Hydraulic conductivity (*K*) was measured in the peat at the natural pool site using piezometer slug withdrawal tests. Piezometers were constructed from high-density polyethylene, with a 3.2 cm outside diameter and 2.5 cm inside diameter, and were installed into pre-augured holes and then 'developed' to remove any smeared peat from around the intake holes (Baird *et al.*, 2004). The intakes were 10 cm long and had a pattern of perforation the same as that reported in Baird et al. (2004). *K* was determined at 20 locations where the intakes covered depths of 45 to 55 cm (hereafter termed 50 cm depth) and 20 locations where depths of 25-35 cm were sampled (hereafter termed 30 cm depth). *K* was calculated using the method (based on Hvorslev (1951)) reported in Baird et al. (2004) and were corrected to a temperature of 20^{o}C. Von Post scores for the peat at the intake depths, extracted when the piezometer holes were augered out, were determined using the descriptions given in Table 5.2 in Rydin and Jeglum (2006).

3. Results

DBPS values were significantly shallower for natural pools than for artificial pools ($p<0.01$), and the repeated-measures ANOVA showed that there were significant differences between seasons ($p<0.01$). Following a dry first summer (2013) after instrument installation (111 mm rainfall; Table 2), DBPS values in the 12 pools were greater throughout the subsequent winter than they were in the next two winters, showing inter-annual variability in pool levels even for winter months (Figure 2). The larger DBPS values- (i.e. lower water levels in pools) in winter 2013/14 compared to the other winters also stand out because 2013/14 was by far the wettest of the three winters studied (Table 2). The largest variability in DBPS occurred during summer. Except for autumn 2013, DBPS values in the artificial pools in all seasons and all years were more variable than those in the natural pools (Table 2).

Irrespective of pool type, evaporation losses were equivalent to around 42 % of direct rainfall inputs to the pools across the whole study. During summer, evaporative losses from pools exceeded direct input rainfall, whereas for the remaining seasons evaporative losses were lower than direct rainfall received by the pools (Table 2). However, the depth of evaporative loss was larger in two of the summers than the mean difference between winter and summer pool levels for both natural and artificial pools showing that pools must receive some inflow water from overland flow or from the surrounding peat. The net surplus of water at other times of the year means that pools must overflow and send water downslope. Considering the topographic contributing area for each pool and evaporation losses, the net outflow from pools across or through the peat downslope equated to a median of 9 and 54 times pool volume per year for the natural and artificial pools respectively (Table 3). However, there was a wide variability in the number of times per year the equivalent pool water volume was replaced between pools (2 to 402 for natural pools and 19 to 714 for the artificial pools), largely driven by the fact that some large pools (e.g. Pool 1) had a small upslope contributing area compared to the pool area (Table 1). Holden *et al*. (2017) showed that the catchment areas of ditches on a Welsh blanket bog could not be determined from their topographic surface area alone. Therefore, the subsurface catchment area for the pools may not exactly match their surface catchment area and our values of pool catchment area should be considered estimates.

Overland flow was a common occurrence across the site. On average (median) the upslope crest-stage tubes had captured overland flow between visits 83 and 84% of the time for the natural and artificial pools respectively, while for the downslope sites overland flow occurred between 77 and 83% of visits for the natural and artificial pools respectively.

There was a significant difference (p=0.01) in the changes in water height above pool bed during storm events between the two types of pools; the artificial pools had a significantly greater water level change in response to rain (mean change 3.6 cm) than the natural pools (mean change 1.9 cm). A regression analysis showed the relationship between cumulative rain in an event and the change in pool water height above bed was: [Natural pool surface level change (cm) = 0.016 × mm of rain + 1.420] and [Artificial pool water level change (cm) = 0.016 × mm of rain + 2.894], both having the same gradients. There was a significant difference between the mean response time for pools to reach peak level between the two treatments (p=0.03; natural mean = 17.6 hrs, artificial mean = 14.6 hrs). Pool water heights above bed fell significantly (p<0.01) more quickly in the 6 and 12 hour periods after rainfall in the artificial pools compared to the natural pools (Table 4). The mean recession rate was greater for every artificial pool compared to any of the natural pools. Tests of correlation between annual pool outflow or turnover frequency (Table 3) and all of the storm response variables shown in Table 4 were conducted but only two combinations of variables were significantly correlated: annual pool outflow and smallest DBPS during storm (natural pools, r=0.80, p=0.03); annual pool outflow and 6-hr recession rate (artificial pools, r=0.74, p=0.04).

Mean water-table depths in the manually measured dipwells over the entire study period were 4.7 cm in the peat around the natural pool system and 3.7 cm in the peat around the artificial pool system. However, water-table depths tended to have a greater range in the peat around the artificial pools than in the peat around the natural pools (Figure 3).

The automated water-table records are only available from May 2015 to January 2016. During this period the average water-table depth (relative to the peat surface) at the natural site was 5.0 cm, compared with 4.0 cm at the artificial site, although this (apparent) difference was not significant. (p=0.28). As with the manual dipwell measurements, the standard deviations of the water-table depth were generally larger in the peat around the artificial pools than in the peat around the natural pools (Table 5). Using water-table responses to individual rainfall events (rise to rain ratios (e.g. Bourgault *et al.*, 2017)) we estimated the mean specific yield for the upper 20 cm of peat to be 0.24 (standard error = 0.04) and 0.25 (standard error = 0.03) for the natural and artificial pool sites respectively. The storm event data showed that the relationship between water-table depth (cm) and the ratio of water-table rise to rainfall (unitless) was linear, increasing over depth with a gradient of 0.57. This is equivalent to a non-linear gradient of decline in specific yield with peat depth of: [1.75 /(water-table depth, cm)]. As the storm events studied did not cover periods of very deep water tables, we used the above relationship to extend estimates of specific yield to a peat depth of 40 cm, equivalent to the mean depth of the pools. This resulted in a mean specific yield of 0.22 for the upper 40 cm of peat.

When comparing pool levels and peat water-table heights for the period when automated records were available for both, the range of water levels was smallest in the natural pools (mean range = 7.6 cm) and largest in peat water tables at the artificial pool site (mean range = 19.3 cm). The range in water level was significantly different between the pools and peat dipwells at both the natural and artificial sites (one-way ANOVA on mean range water level, $p < 0.01$).Post-hoc Tukey tests showed the range was significantly lower in the natural pools than for artificial pools or peat water tables. There was no significant difference in range between water levels recorded in natural pool site dipwells and artificial pools, but a significantly higher range in the artificial pool site dipwells than pool levels at either site or than in the natural pool site dipwells. The mean relative water level for Pool 1 and the three nearest peat dipwells showed the downslope dipwell (P1D) had a lower absolute water-table height, the mid-slope dipwell (P1M) had a similar mean water-table height to the pool level and the upslope dipwell (P1U) had a higher mean water table (Figure 4). The mean difference in relative water height between Pool 1 and the water table in the peat was -7.1, 0.5 and 10.9 cm (P1U, P1M and P1D respectively). For Pool 4 the peat water tables were very different from pool water level (differences of -5.9, 22.5 and 30.3 cm for P4U, P4M and P4D respectively). At the artificial pool site, Pool 8 mean water level was 23.3 cm lower than mean water-table height at P8U and 11.0 cm higher than at P8D while Pool 11 mean level was 24.0 cm lower than water-table height at P11U and 9.0 cm higher than at P11D.

The automated water-table records followed a similar seasonal pattern to the pools; the deepest mean water-tables were in summer (summer mean of 6.6 cm at the natural site and 5.8 cm at the artificial site) and shallowest in winter (winter mean of 2.9 cm at the natural site and 1.9 cm at the artificial site). However, the automated record shows that pool-level fluctuations did not simply reflect local water-table dynamics (e.g. Figure 5). Peat water tables tended to decline more rapidly than pool levels during dry periods and there was a greater variability in water-table depth than pool level change. The pool level records show a much smoother, damped signal to rainfall or recession periods than the peat water-table records. In response to storm events water-table changes in the peat around artificial and natural pools were not significantly different. However, water-table changes in the peat were significantly different from water-level changes in both the natural and artificial pools; pool hydrological responses were significantly different between pool types (one-way ANOVA, $p<0.01$, confirmed with a post-hoc Tukey test). After peak levels had been achieved during storms, water heights fell significantly faster in the peat around the pools than water levels within the pools (one-way ANOVA, $p<0.01$). Recession rates were significantly higher for dipwells at the artificial sites than the water levels both in the natural and artificial pools (one-way ANOVA, $p<0.01$) in the 6 and 12 hour period after peak water levels, but there were no significant differences in the 6 and 12 hour recession responses in the peat water tables between the natural and artificial sites. There was a significant difference between the mean response time to reach peak level between the pools and the dipwells (one-way ANOVA, $p<0.01$), and the water level responded fastest at the natural site in the peat around the pools, and slowest in the natural pools themselves.

Given that dipwells were typically around 1 to 4 m away from pools, our results for relative height differences between peat water tables and pool levels (Figures 4 and 5, Table 5) suggest that there are strong hydraulic gradients on site. Deep flows between pools and the peat and *vice versa* must be very slow as peat water tables and pool levels are rather different, with absolute peat water-table levels often being 20 to 30 cm higher or lower than water levels in pools only a metre away. This is corroborated by our hydraulic conductivity data for the site. Median hydraulic conductivity at 30 cm and 50 cm depths was 1.5×10^{-5} cm s^{-1} (interquartile range 2.2×10^{-5} cm s^{-1}) and 1.4×10^{-6} cm s^{-1} (interquartile range 6.6×10^{-6} cm s^{-1}) respectively. Von Post scores ranged from 2 to 9 at 30 cm depth (median = 7, n=20) and 5 to 10 at 50 cm depth (median = 8, n=20).

4. Discussion

The DBPS values were significantly deeper and much more variable over time for the artificial pools than the natural pools. Thus, biogeochemical and carbon cycling processes within natural pools are unlikely to be replicated in artificial pools as their hydrological function is quite different. Artificial pool levels fell at a significantly faster rate immediately following rainfall events than water levels in natural pools. This enhanced fluctuation of pool levels in the artificial pools compared to natural pools may result in more frequent aeration of pool walls followed by flushing of the resultant dissolved organic carbon that may have been produced (Hamilton *et al.*, 1994). Water-table variability was also greater in the peat at the artificial pool site than in the nearby natural pool site, although both locations had relatively shallow mean water tables (within 5 cm of the peat surface).

There are several reasons why pool level variability and water-table variability were so much greater at the artificial pool site. It may be that during high flow the artificial pools still retain some connectivity to the old ditch system with pools overflowing along the course of the old ditches enabling pool levels to fall more quickly after peak than in the natural pool system. The rapid rise and fall of pool levels at the artificial pool site was not simply a function of small catchment areas for each pool. Pools 10 and 12 were both among the top six largest combined catchment areas of all pools studied (i.e. pool area plus contributing area; Table 1) and yet had more rapid water level recessions (6 hr and 12 hr) after storms than any of the six natural pools. However, the mean slope was slightly greater at the artificial pool site (0.05 m m^{-1} compared with 0.04 m m^{-1}) and the ratio of catchment area to pool area was typically greater for the artificial pools (Table 1). Thus we might expect a more rapid increase in pool level in response to rainfall for the artificial pools. It may also be that some peat properties affected by ditch drainage had not recovered in the 11 to 13 years since restoration and there may be enhanced macropore and pipe drainage in the peat around the artificial pools (Holden, 2005; Holden *et al.*, 2006). Holden *et al.* (2011) found for a blanket peatland in northern England that 6 to 7 years after ditch blocking at a site where drains predominantly ran across slope (roughly parallel to the contour), the peat water tables were still significantly deeper and much more variable than those in nearby undrained peat, but slightly less variable than those in nearby drained peat without drain blocking. Evidence from other sites suggests that where blanket peatland drains run largely downslope, similar to those at our site, ditch blocking may only have a very small impact on local water tables and peatland function, at least in the short term (Green *et al.*, 2017; Holden *et al.*, 2017). Another important factor which could affect water-table and pool-level fluctuations is the bulk specific yield of the peatland. At the natural pool site there was a far greater proportion of the landscape that was open water than at the artificial pool site. The mean pool depth was ~40 cm and so considering only the upper 40 cm of the peatland, a specific yield of pools =1 , and mean specific yield for the upper 40 cm of peat = 0.22, the bulk specific yield of the natural pool site was 0.28 while it was 0.22 for the artificial pool site. Therefore, given the same water input, the water level fluctuations would be expected to be greater at the artificial pool site than at the natural pool site. However, we also showed that pool levels and water-tables in the nearby peat were somewhat disconnected, with steep hydraulic gradients forming between the peat and nearby pools due to very low peat hydraulic conductivity. Therefore, the bulk specific yield concept may be of limited use in understanding the overall hydrological dynamics of blanket peat systems with pools. Nevertheless, the fact that pool DBPS values were on average 15 cm, still allows us to conclude that creating larger pool area in peatland restoration schemes may be beneficial in reducing downstream flood risk for some storms. These benefits may not be fully realised on occasions when the pools are already ‘full’ which is more likely in winter months when evaporation rates are small.

Evaporation between rainfall events played a strong role in controlling pool level drawdown in the summer months meaning that variability in water levels was greatest at this time of year. The pool water levels were most drawn down during summer 2013, the first summer of monitoring. The subsequent winter was very wet but DBPS values in both the natural and artificial pool systems were generally greater in winter 2013 compared to the other two winters studied. It is not clear what caused this effect but such inter-annual variability in pool water levels, even in winter months may have implications for carbon cycling and release and the hydrological function of the peatland. It may be that the near-surface peat and pool sides became desiccated and cracked during the unusually warm, dry summer of 2013 and this meant that in the subsequent winter (which was very wet) more water could percolate out of the pool sides near the top of the peat. Desiccation cracking is common in peatlands on bare peat faces during dry weather (Evans and Warburton, 2007) and macropore flow can be a very important pathway for water in near-surface blanket peat (Holden, 2009). It may have taken more than one winter for cracks to close up or seal with biofilms.

We surveyed for natural peat pipes around our 12 study pools using an underwater camera and we were unable to detect them. Therefore unlike the Labradorean small fen and raised bog study of Price and Maloney (1994), pipes did not play a large role in pool functioning in our 12 study pools. However, we did observe piping at some of the other pools at the study site, where pipes provided one of several drainage routes for some pools and a water supply for other pools. We also found some cases where pipes connected pools to one another. Further work is required to establish whether the hydrological function of pipe-connected pools is different from those disconnected from peatland pipe networks.

The smaller artificial pools spilled out, on average, water equivalent to 54 times the mean volume of the pool per year. This relative value was six times lower for the natural pools although the actual volume of water that flowed out of the six natural pools was around ten times greater than that from the artificial pools. These rates of pool ‘turnover’ may be important for peatland chemistry and peat accumulation rates (Beer and Blodau, 2007; Morris and Waddington, 2011) and for understanding aquatic carbon fluxes from peatlands with pools, particularly if the carbon processing is different between natural and artificial pool systems. Pools with longer water residence times may be subject to enhanced photochemical processing of dissolved organic carbon (e.g. Pickard *et al.*, 2017) (all pools were $\leq$ 50 cm deep); hence the quality of dissolved organic carbon may vary between pools which could be important for downstream water treatment for potable supply (Worrall and Burt, 2009; Moody and Worrall, 2017). On the other hand, the slower turnover of water in some larger pools may mean that the remaining carbon is largely recalcitrant and little further processing can occur, whereas in smaller pools processing of carbon can continue for longer periods if the pool water volume is replaced more frequently. McEnroe *et al.* (2009) showed that smaller pools had consistently larger carbon dioxide and methane fluxes than larger pools in a raised bog in Canada. It should also be noted that we found that the rates of pool water replacement were highly variable and the volumes of water produced were not related simply to pool size as the upslope catchment area of each pool was also critical. Some very large natural pools had a relatively small upslope catchment area. Thus when sampling blanket peatland pools for their aquatic chemistry (Turner *et al.*, 2016) and also when considering potential impacts of pool processes on downstream river water chemistry, including aquatic carbon fluxes, and their role on carbon gas release to the atmosphere, it will be important in the future to consider pool topographic context and upslope contributing area in addition to pool dimensions. Pools of an equivalent size cannot be assumed to play an equivalent role in influencing aquatic fluxes from the peatland; pool size and their contributing area are both important.

Water levels and their fluctuations in pools were not the same as water-table depths and fluctuations in the nearby peat. Pool water level changes were much more subdued and less variable than water-table changes in the nearby peat. It would be expected that peat water tables would be more variable during storm events than pool water levels. Even as little as 2 mm of rainfall can often raise peat water tables by 2 to 4 cm as much of the pore space, even in unsaturated peat, is typically occupied by water and there is little available space for fresh rainwater (Gilman, 1994; Evans *et al.*, 1999; Bourgault *et al.*, 2017; University of Leeds Peat Club, 2017). However, the long-term difference between pool levels and peat water-table heights at the study site was also striking. This is an important finding as it shows that the hydrological function of pools, even small artificial ones, is quite different from the hydrological function of the peat mass. The absolute water-table height and nearby pool water levels were generally not the same and there were often steep hydraulic gradients on site. However, as the peat hydraulic conductivity at depths of 30 cm and 50 cm was very low, very little subsurface flow may be occurring and so connectivity between the pools and the peat system must be greatest at the peat surface or within a few cm of the peat surface. Thus storm events are important for connecting the peat system to pool systems, enabling pool water replenishment and for flushing out of pools of potentially significant volumes of carbon and other nutrients that may have been processed within the pool.

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Table 1. Pool physical characteristics

Pool	Pool surface area (m^2)	Length of pool perimeter (m)	Length of pool perimeter receiving surface water from topographic area above pool (m)	Mean pool water height above bed (m)	Upslope surface catchment area (m^2)	Catchment area / Pool area
Natural						
Pool 1	868	246	231	0.50	427	0.5
Pool 2	39	25	21	0.42	1325	34.0
Pool 3	9	19	8	0.30	1387	154.1
Pool 4	115	58	44	0.43	177	1.5
Pool 5	15	21	11	0.31	31	2.1
Pool 6	24	19	10	0.30	89	3.7
Artificial						
Pool 7	6	12	3.0	0.34	45	7.5
Pool 8	2	8	2.5	0.37	77	38.5
Pool 9	6	13	2.5	0.38	57	9.5
Pool 10	4	8	1.5	0.39	1264	316.0
Pool 11	1	7	2.0	0.43	21	21.0
Pool 12	2	2	0.5	0.47	203	101.5

Table 2. Mean DBPS, cm (top row in each cell) and interquartile range, cm (bottom row in each cell). Summer = JJA, Autumn = SON, Winter = DJF, Spring = MAM. *2015/16 does not include data from 29 January onwards.

Season	Summer 2013	Autumn 2013	Winter 2013/14	Spring 2014	Summer 2014	Autumn 2014	Winter 2014/15	Spring 2015	Summer 2015	Autumn 2015	Winter 2015/16*
Precipitation, cm	110.8	251.4	460.6	268.3	250.0	209.8	298.4	174.6	143.0	153.0	180.4
Pool evaporation, cm	248.2	57.8	2.0	75.1	293.8	61.6	1.7	57.6	195.8	54.2	0.9
Pool 1	27.3	23.2	17.5	18.2	19.6	16.7	14.9	15.4	16.0	14.6	11.9
	6.7	8.0	0.5	1.2	4.3	2.5	0.9	1.0	1.6	1.9	0.6
Pool 2	29.2	24.3	18.0	19.0	21.7	18.3	16.8	17.7	19.5	18.4	15.9
	8.2	10.8	0.4	1.6	5.5	2.0	0.4	1.4	3.0	2.7	0.4
Pool 3	28.2	22.3	18.5	19.3	21.0	18.1	16.5	17.3	18.2	17.1	15.2
	6.5	4.1	0.6	1.4	4.2	2.3	0.6	1.6	2.3	2.5	0.4
Pool 4	26.2	20.9	15.4	16.2	18.8	15.5	13.4	14.3	15.3	14.2	11.8
	7.1	7.2	0.5	1.5	5.4	3.3	0.7	2.0	2.4	2.4	0.6
Pool 5	19.2	12.6	9.8	10.3	12.1	9.4	7.5	7.9	8.7	7.7	5.9
	5.6	3.6	0.6	1.6	4.9	2.8	0.9	1.6	2.3	2.2	0.3
Pool 6	24.9	18.4	15.2	16.1	18.0	15.1	13.4	14.3	15.3	14.3	13.0
	6.7	4.1	0.5	1.7	5.2	2.8	0.6	1.3	2.1	1.5	0.3
All natural pools	25.8	20.3	15.7	16.5	18.5	15.5	13.7	14.5	15.5	14.4	12.3
	6.8	6.4	0.5	1.5	4.9	2.6	0.6	1.4	2.3	2.2	0.4
Pool 7	19.8	13.0	11.0	11.3	12.3	10.2	9.1	10.2	10.7	10.2	8.4
	9.3	1.8	0.6	1.8	3.9	2.1	1.2	2.3	2.2	1.8	0.7
Pool 8	18.1	9.5	7.6	9.0	9.9	7.7	5.9	7.4	8.8	7.2	5.3
	10.2	2.2	1.0	2.3	3.9	3.2	1.4	2.6	2.9	2.4	1.4
Pool 9	23.6	16.7	14.3	15.2	16.1	14.4	12.8	13.8	14.8	14.1	12.0
	8.3	2.7	0.9	2.3	3.6	2.8	1.1	1.9	2.1	2.9	1.0
Pool 10	21.9	12.4	9.4	10.6	12.6	10.1	8.1	9.4	10.5	9.6	7.2
	9.5	3.1	1.2	2.1	6.4	3.1	1.4	2.0	3.3	3.1	1.3
Pool 11	29.2	20.0	17.0	18.3	20.2	17.5	15.0	16.8	19.0	17.8	14.7
	7.7	3.3	1.5	2.6	6.3	3.6	2.1	2.7	3.9	4.0	1.9
Pool 12	25.9	16.0	12.7	14.4	16.4	13.0	10.3	11.7	13.7	12.7	9.2
	9.6	3.6	2.0	4.1	8.0	4.9	0.9	3.1	6.1	5.0	0.8
All artificial pools	23.1	14.6	12.0	13.2	14.6	12.2	10.2	11.5	12.9	11.9	9.5
	9.1	2.7	1.1	2.5	5.4	3.3	1.4	2.2	3.3	3.1	1.1

Table 3. Rates of pool outflow and recharge

	Pool outflow, m^3 yr^{-1}	Number of times the equivalent pool volume was recharged, yr^{-1}
Pool 1	818.4	1.9
Pool 2	1047.8	64.4
Pool 3	1079.0	402.3
Pool 4	201.7	4.1
Pool 5	32.4	7.1
Pool 6	82.4	11.4
Natural median	510.0	9.2
Pool 7	37.7	19.2
Pool 8	59.2	69.7
Pool 9	47.2	22.2
Pool 10	980.4	714.3
Pool 11	17.1	38.5
Pool 12	158.4	194.2
Artificial median	53.2	54.1

Table 4. Mean pool water level responses to 20 storm events

	Pool level change (cm)	Smallest DBPS in storm (cm)	Time from rain start to smallest DBPS (h)	Increase in DBPS6 hrs after smallest depth (cm h^{-1})	Increase in DBPS12 hrs after smallest depth (cm h^{-1})
Pool 1	2.2	15.5	19.5	0.10	0.08
Pool 2	1.7	17.7	18.4	0.05	0.04
Pool 3	2.0	17.1	17.6	0.08	0.06
Pool 4	1.9	14.5	19.3	0.07	0.04
Pool 5	1.9	8.1	14.2	0.09	0.06
Pool 6	2.0	14.1	16.5	0.09	0.05
Natural mean	1.9	14.5	17.6	0.08	0.06
Pool 7	2.4	8.7	14.2	0.16	0.10
Pool 8	3.5	4.9	11.8	0.27	0.16
Pool 9	3.0	11.8	12.4	0.23	0.14
Pool 10	3.2	7.3	16.9	0.12	0.09
Pool 11	5.1	13.2	16.9	0.22	0.19
Pool 12	4.4	9.2	15.3	0.20	0.16
Artificial mean	3.6	9.2	14.6	0.20	0.14

Table 5. Water level in the pools and surrounding peat, m, relative to a local datum for 21st May 2015 to 28th January 2016. Note that one datum point was used for the natural pool site and a different datum point was used for the artificial pool site.

Pool/Dipwell	Mean	Std deviation	IQR	Minimum	Maximum	Range
Pool 1	99.729	0.019	0.038	99.693	99.781	0.088
Pool 2	99.689	0.020	0.036	99.643	99.723	0.081
Pool 3	99.574	0.017	0.023	99.534	99.605	0.072
Pool 4	98.682	0.018	0.034	98.639	98.716	0.077
Pool 5	98.327	0.015	0.027	98.290	98.363	0.073
Pool 6	98.216	0.013	0.021	98.180	98.243	0.063
Dipwell P1U	99.800	0.014	0.020	99.758	99.833	0.074
Dipwell P1M	99.724	0.023	0.036	99.662	99.770	0.109
Dipwell P1D	99.621	0.051	0.080	99.474	99.686	0.212
Dipwell P4U	98.741	0.024	0.033	98.657	98.778	0.122
Dipwell P4M	98.457	0.021	0.033	98.391	98.501	0.110
Dipwell P4D	98.380	0.028	0.047	98.316	98.449	0.133
Pool 7	99.570	0.016	0.021	99.517	99.608	0.091
Pool 8	100.215	0.021	0.034	100.159	100.265	0.106
Pool 9	100.969	0.018	0.029	100.929	101.017	0.088
Pool 10	97.8618	0.022	0.032	97.796	97.927	0.130
Pool 11	101.400	0.029	0.042	101.320	101.484	0.154
Pool 12	99.886	0.033	0.049	99.809	99.964	0.155
Dipwell P8U	100.449	0.045	0.041	100.300	100.522	0.222
Dipwell P8D	100.104	0.027	0.026	99.992	100.142	0.150
Dipwell P11U	101.641	0.032	0.040	101.556	101.759	0.203
Dipwell P11D	101.311	0.025	0.036	101.230	101.372	0.142

Figure captions

Figure 1. Location of the 12 study pools. Natural pools are shown in red and artificial pools in green. Also shown are 2 m contours and the area of felled forest. The location within the UK is shown in the inset map. Imagery used with permission from Esri, image taken 2016.

Figure 2. Time-series of pool levels, DBPS, 15-minute interval data, and daily rainfall.

Figure 3. Manually measured water-table depths in the peat 1 m from natural pools (black) and artificial pools (grey). The box shows the interquartile range, error bars show range, crosses show 1st and 99th percentiles, solid square box shows mean and the horizontal dashed line shows the median.

Figure 4. Comparisons of relative pool water level and water-table height in the peat nearby for Pools 1, 4, 8 and 11, based on automated records. The box shows the interquartile range, error bars show range, crosses show 1st and 99th percentiles, solid square box shows mean and the grey line shows median. U = upslope of pool, M = adjacent to pool, D = downslope from pool.

Figure 5. Examples of pool level and water-table time-series from Pool 4 in the natural pool system (upper panel) and Pool 8 in the artificial pool system (lower panel). Water levels shown in each plot are all relative to the same local datum; one datum was used for the natural pool site while a different datum was used at the artificial pool site.

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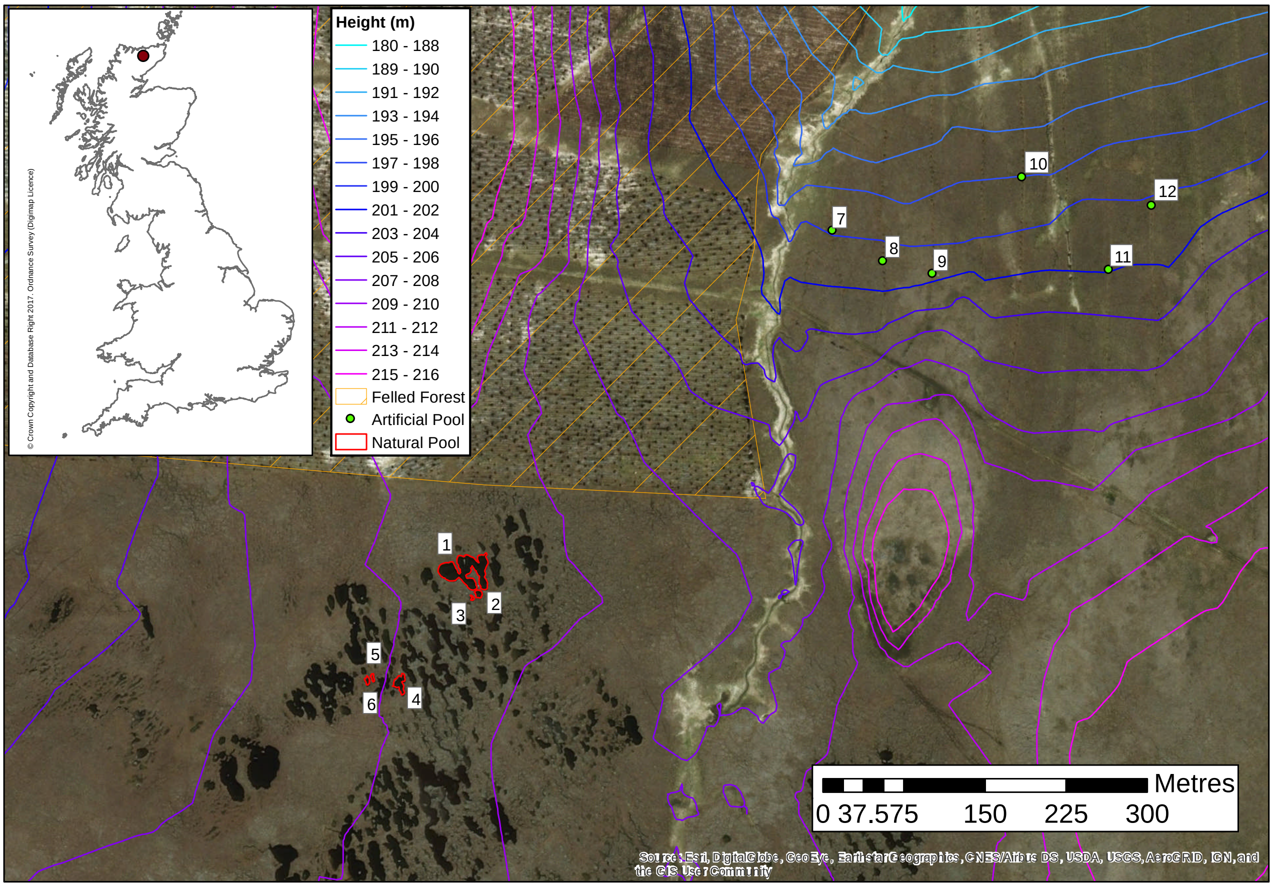
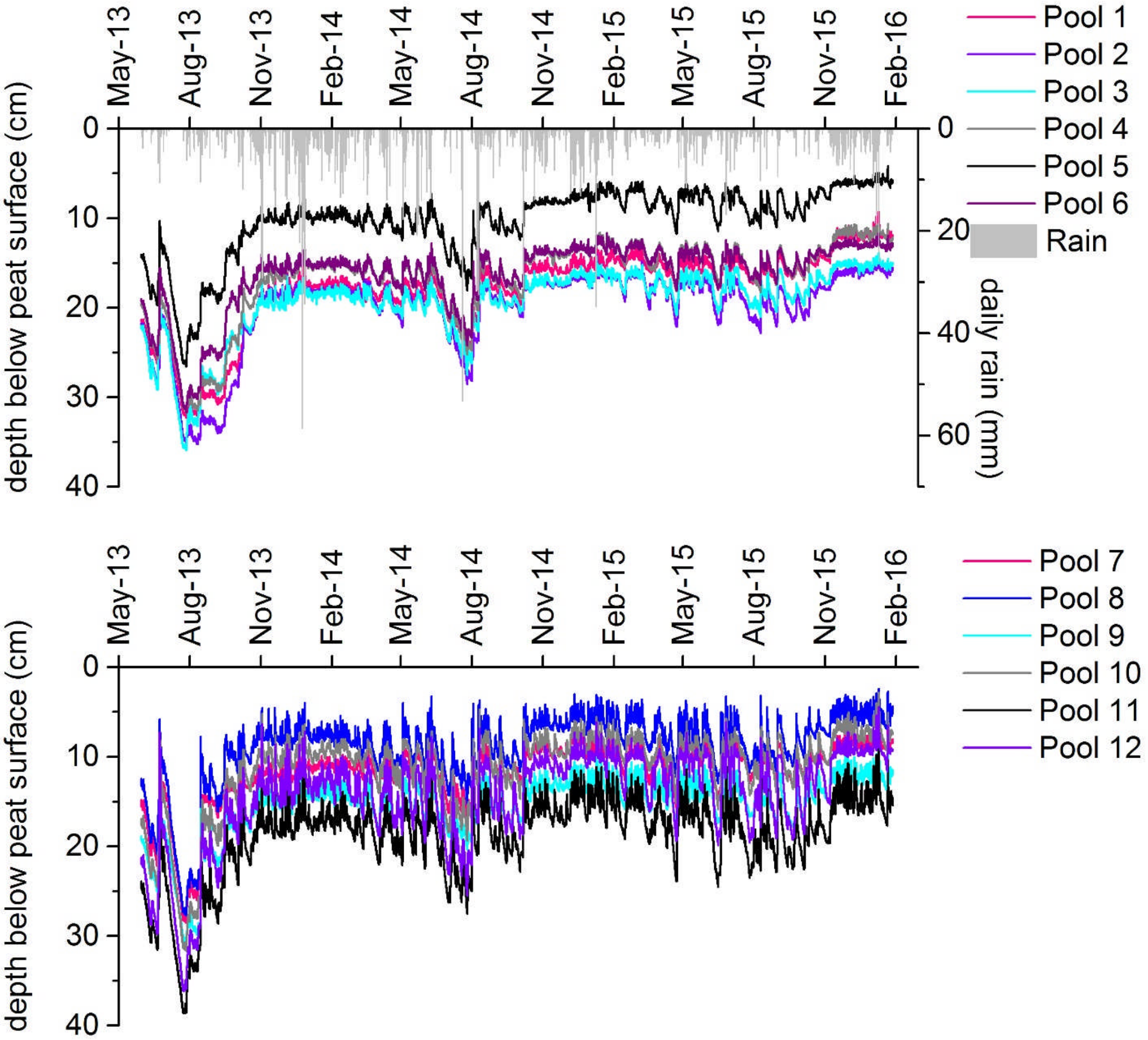


Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 2. Time-series of pool levels, DBPS, 15-minute interval data, and daily rainfall.



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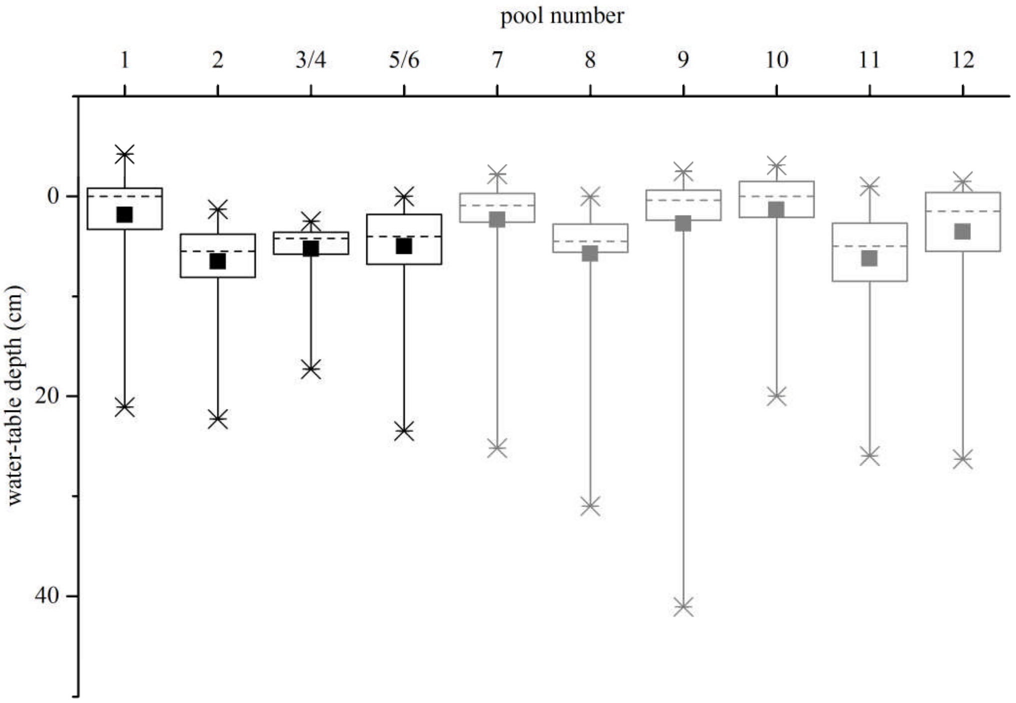

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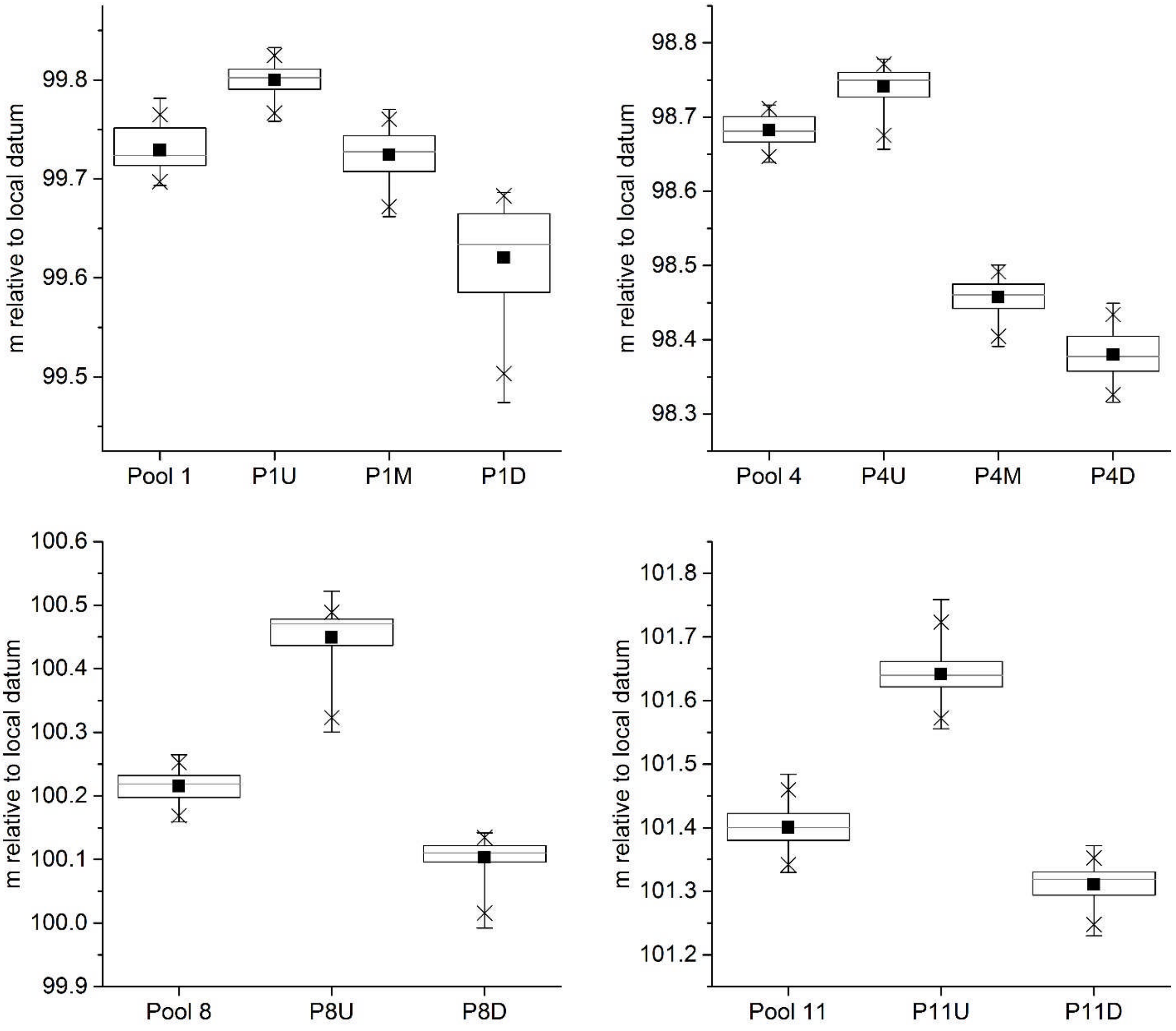

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