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

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26 Paper submitted to *Hydrological Processes*: 30 November 2017

27 28 29 30 **Abstract**

31 Perennial pools are common natural features of peatlands and their hydrological functioning and
32 turnover may be important for carbon fluxes, aquatic ecology and downstream water quality.

33 Peatland restoration methods such as ditch blocking result in many new pools. However, little is

34 known about the hydrological function of either pool type. We monitored six natural and six

35 artificial pools on a Scottish blanket peatland. Pool water levels were more variable in all seasons in

36 artificial pools having greater water level increases and faster recession responses to storms than

37 natural pools. Pools overflowed by a median of 9 and 54 times pool volume per year for natural and

38 artificial pools respectively but this varied widely because some large pools had small upslope

39 catchments and *vice versa*. Mean peat water-table depths were similar between natural and artificial

40 pool sites but much more variable over time at the artificial pool site, possibly due to a lower bulk

41 specific yield across this site. Pool levels and pool-level fluctuations were not the same as those of

42 local water tables in the adjacent peat. Pool level time-series were much smoother, with more
43 damped rainfall or recession responses than those for peat water tables. There were strong hydraulic
44 gradients between the peat and pools, with absolute water tables often being 20-30 cm higher or
45 lower than water levels in pools only 1-4 m away. However, as peat hydraulic conductivity was
46 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)
47 there was little deep subsurface flow interaction. We conclude that: 1) for peat restoration projects,
48 a larger total pool surface area is likely to result in smaller flood peaks downstream, at least during
49 summer months, because peatland bulk specific yield will be greater; and 2) surface and near-
50 surface connectivity during storm events and topographic context, rather than pool size alone, must
51 be taken into account in future peatland pool and stream chemistry studies.

52

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

54

55

56 **1. Introduction**

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

65
66 Peatlands are characterised by shallow water tables and are capable of storing very large volumes of
67 water since peat soils often have porosities > 95 % (Ingram, 1983; Hobbs, 1986). In addition to the
68 peat volumetric water store, peatlands often contain open-water pools (Glaser, 1998). Multiple
69 hypotheses have been proposed for natural pool formation and expansion in peatlands (cf. Belyea
70 and Lancaster, 2002), but surprisingly little is known about the hydrological functioning of peatland
71 pools. In some northern peatlands the surface area of pools can be as much as 90 % of the total
72 peatland area (e.g. Sjors, 1983) but pools more typically represent 5-30 % of the land area where
73 they are present (e.g. Foster and Glaser, 1985; Roulet *et al.*, 1994). Peatland pools are important for
74 aquatic biodiversity, particularly when there is a wide variety of pool sizes (Downie *et al.*, 1998;
75 Beadle *et al.*, 2015). They are also often 'hotspots' of carbon dioxide and methane emissions
76 (Hamilton *et al.*, 1994; Waddington and Roulet, 1996; Pelletier *et al.*, 2014) and as such they are
77 likely to process dissolved and particulate organic carbon altering dissolved and particulate carbon
78 concentrations and characteristics in pools (Pickard, 2016; Turner *et al.*, 2016), potentially
79 influencing downstream water chemistry. Their hydrological functioning is likely to control how
80 pools process carbon, yet little is known about hydrological processes associated with pools in
81 peatlands. During rainfall pools may spill over, delivering water to other parts of the peatland or to

82 nearby stream networks (Quinton and Roulet, 1998). Rates of pool water turnover have not been
83 reported but could affect overall water residence times in peatlands, which in turn may be important
84 in controlling peat decomposition rates (Beer and Blodau, 2007; Morris and Waddington, 2011) or
85 streamwater chemistry. However, these functions have not previously been tested for natural pool
86 systems in blanket peatlands.

87
88 Two previous short-term studies of pool hydrological function in fens and raised bogs in Canada
89 have shown that pools can provide significant depression storage for rainfall thereby greatly
90 reducing runoff from the system (Price and Maloney, 1994; Quinton and Roulet, 1998). Quinton
91 and Roulet (1998) studied a narrow, valley bottom pool-patterned fen for four months and found it
92 was dominated by two distinct phases of operation: (1) an overflow phase during spring melt and
93 one large summer storm when water supply exceeded the depression storage capacity and the pools
94 effectively coalesced producing diffuse surface runoff, and (2) a summer phase, without spill over,
95 when pools were disconnected, with slow rates of groundwater inputs which were around an order
96 of magnitude less than pool evaporation rates. A six-week study of a small fen and raised bog in
97 Labrador indicated that the catchment runoff ratio was < 0.15 with the pools enhancing evaporative
98 losses (Price and Maloney, 1994). For the systems studied, Price and Maloney (1994) noted that
99 pool position relative to the local topography and the location of peat pipes connected to pools were
100 both important for controlling pool inflows and outflows, although pipe flows, pool outflow rates
101 and pool levels were not directly measured. There have been no detailed studies of pool
102 hydrological function in blanket peatlands and no natural pool hydrological function studies for any
103 type of peatland that have continued for periods of more than a few months.

104

105

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108

109

110 Many northern peatlands have been drained for peat extraction, forestry and agriculture (e.g. Höper
111 *et al.*, 2008). For example, drainage ditch construction was common practice between the 1940s and
112 1980s in the UK, where blanket peat covers around 7 % of the land surface (Baird *et al.*, 2009).
113 Such drainage did not achieve its aim of enhancing agricultural productivity (Stewart and Lance,
114 1983), but led to environmental problems including erosion (Mayfield and Pearson, 1972; Holden *et*
115 *al.*, 2007) and, in some places, to enhanced losses of dissolved organic carbon into streams and
116 rivers (Mitchell, 1990; Mitchell and McDonald, 1995; Armstrong *et al.*, 2010). In common with
117 many areas of the world (*cf.* Höper *et al.*, 2008) where peatlands have been damaged by artificial
118 drainage, ditches in UK peatlands are being blocked. This restoration activity results in the creation
119 of thousands of small pools within the blocked ditches, which in sum can amount to a large area of
120 open water (Parry *et al.*, 2014; Brown *et al.*, 2016; Holden *et al.*, 2017). It is not known to what
121 extent the hydrological functioning of these artificial peatland pools is similar to that of natural
122 pools. Price *et al.* (2002) studied experimental artificial pools installed in a cutover plateau bog in
123 Québec. They did not measure pool water levels but measured the water tables and soil tension in
124 the surrounding peat on 76 days during the study compared to a control cutover treatment without
125 pool creation, showing that water-tables were more stable following pool creation. This reduction in
126 water-table variability has also been found on some sites with ditch-blocked pools in upland blanket
127 peat in the British Isles (Holden *et al.*, 2011). This is to be expected because the specific yield of a
128 pool is 1 whereas the specific yield of peat is substantially less than one; if a significant proportion
129 of a peatland is taken up by pools, its bulk specific yield will be higher than that of the peat itself.

130

131 The paucity of data on peatland pool hydrological functioning means that we lack understanding of
132 whether peatland open-water pool levels and their fluctuations are similar between artificial and
133 natural systems. There have been no detailed inter-annual studies of natural peatland pool

134 hydrological function. We also lack basic understanding of whether water levels in pools and their
135 fluctuations in response to rainfall or evaporation simply reflect those of the water table in the
136 surrounding peat. It may be that either: (1) pool water levels are well connected to local water-table
137 levels and fluctuations in the surrounding peat; or (2) the two systems are partly independent of
138 each other in terms of their hydrological functioning. Furthermore, pool water volume replacement
139 and spill over rates have never been measured in blanket peatlands before. Here we report on a
140 study in which we compared the hydrological functioning of natural and artificial blanket peatland
141 pools. For a site in which both pool types were in close proximity, we investigated pool water-level
142 dynamics, established rates of pool water replenishment (turnover), and examined water-table
143 fluctuations in the peat surrounding the pools.

144

145 **2. Methods**

146 Six natural pools (Pools 1-6) and six artificial pools (Pools 7-12) were chosen for investigation
147 (Figure 1) at Cross Lochs peatland in the Flow Country, northern Scotland (58° 22' N, 03° 57' W),
148 at ~215 m altitude (Figure 1) between 2013 and 2016. The Flow Country bog system is the UK's
149 largest single tract of peatland covering ~4000 km² (Ingram, 1987; Lindsay *et al.*, 1988). It has
150 many intact pool systems similar to those in a range of other blanket bog systems in Scotland (e.g.
151 Boatman, 1983; Ratcliffe and Oswald, 1988; Belyea, 2007) and peatland pool systems in
152 continental settings (e.g. Glaser, 1998). The climate of the area is cool with a mean annual
153 temperature for 1981-2010 of 7.6°C and a mean annual precipitation of 1196 mm for Altnaharra
154 meteorological station, ~30 km from Cross Lochs. While snowfall may occur at the site in winter, it
155 is synoptically controlled and will often melt completely within a few days. Rainfall is much more
156 common in winter than snow. Peat depths at the site were measured using rod probing and ranged
157 from 0.94 m to 4.00 m which is in line with earlier surveys in the area (Ratcliffe and Payne, 2016).
158 The underlying geology forms part of the Moine Supergroup with Pre-Cambrian migmatitic pelite
159 and semipelite metamorphic rocks. The vegetation is dominated by mosses, sedges and small

160 shrubs. Mosses mainly include *Sphagnum cuspidatum*, *S. denticulatum*, *S. fallax*, *S. capillifolium*, *S.*
161 *subnitens*, *S. papillosum* *S. tenellum* and *Racomitrium lanuginosum*. Liverworts such as *Plurozia*
162 *purpurea* are abundant at the site. Sedges, mainly *Eriophorum vaginatum* and *E. angustifolium* and
163 small shrubs, mainly *Calluna vulgaris* and *Erica tetralix*, are widespread.

164
165 The natural and artificial pool sites were close to each other (within c. 400 – 600 m; Figure 1). The
166 mean slope was 0.04 across the natural pool site and 0.05 m m⁻¹ across the artificial pool site. Pools
167 covered 8.6 % of the surface area of the natural pool site and 0.7 % of the artificial pool site. The
168 northwest section of Figure 1 shows a nearby block that was subject to plantation forestry which has
169 been felled. However, this forest restoration block is beyond the drainage divide and does not
170 interact with the natural or artificial pool sites we studied. The selected pools were deemed to be
171 representative of the pools across the site. Pools, particularly natural pools, often have uneven beds
172 and so transects in two directions across each pool were surveyed to calculate pool depths; for the
173 larger pools this resulted in around 30 depth measurements per pool whereas for small (~< 9m²)
174 pools there were 4-10 depth measurements per pool. Natural pools ranged in size from 9 m² to 868
175 m² (Table 1) while the range of sizes for artificial pools was much smaller at 1 m² to 6 m². The
176 catchment area for each pool was calculated based on surface topography and the approximate
177 length of the perimeter that received surface water from an upslope topographic area was also
178 determined (Table 1). For most of the natural pools more than half of their perimeter received water
179 from upslope, whereas for all of the artificial pools less than a third of their perimeter received
180 surface drainage water from upslope. The mean water heights above pool bed for natural and
181 artificial pools were comparable (38 cm and 39 cm respectively; Table 1). The artificial pools were
182 created behind peat dams constructed in 2002, located within artificial drainage ditches that had
183 been dug in the 1970s. The artificial pools were constructed in a typical manner for blanket
184 peatlands in the UK (Parry *et al.*, 2014) with peat excavated from one side of the ditch at the dam
185 location, thereby widening the ditch at the location where the pool is formed. The excavated peat

186 was used to form the dam, with the original vegetation layer from the excavated peat placed onto
187 the dam top to help stabilise it. Only one artificial pool per ditch was chosen for study.
188

189 Meteorological data were collected on site using a Davis Vantage Pro 2 automatic weather station.
190 Open water evaporation from the pools was calculated using the Penman (1948) open water
191 equation which is physically based and uses temperature, relative humidity, wind speed and solar
192 radiation data. The equation has been shown to be robust during comparison studies with other
193 equations or directly measured rates of open water evaporation (Linacre, 1993; McMahon *et al.*,
194 2016).

195

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

211 significance. For the repeated measures ANOVA, the data were tested using Mauchly's test for
212 sphericity, and a polynomial transformation carried out.

213

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

221

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

227

228 Ten PVC dipwells, with a 28.4 mm inside diameter and with 8 mm diameter holes drilled at 50 mm
229 intervals along their length (two lines of holes along the dipwells), were installed in July 2013. A
230 dipwell was installed in the peat 1 m away from each pool, but because Pools 3 and 4 were close to
231 each other, and also Pools 5 and 6, one dipwell was located between each of these pairs (still around
232 1 m from pool edges), giving 10 dipwells in total. Water tables were manually measured using a
233 dipmeter on each site visit until January 2016. In May 2015 an additional ten dipwells were
234 installed with six located in the natural pool system and four in the artificial pool system, each of
235 which was instrumented with an In Situ Level TROLL 500 logger to record water tables at 15-
236 minute intervals. The instrumented dipwells at the natural site were located next to two pools, with

237 a dipwell upslope, midslope (i.e., at the side of the pool) and downslope of Pool 1 (coded P1U,
238 P1M, P1D) and Pool 4 (P4U, P4M, P4D). At the artificial site the instrumented dipwells were
239 located upslope and downslope of Pools 8 and 11 (P8U, P8D, P11U, P11D). All dipwells were
240 located between 1 and 4 m from pool edges (1.5 to 2 m away in the case of the artificial pools).
241 Response time tests were carried out on the dipwells, with full recovery after slug withdrawal
242 occurring within 15 minutes in all cases indicating that the dipwell data are reliable. A topographic
243 survey of all dipwells and stilling wells at the two sites allowed the water-table depths to be
244 compared between the pools and instrumented dipwells, relative to a datum at each site. Eleven
245 large storm events occurred during the period when automated dipwell data were available. Water-
246 table data were extracted from the automated dipwell records for these storms using the same
247 approach as for pool levels described above, and were analysed using a one-way ANOVA with a
248 post-hoc Tukey test.

249
250 Hydraulic conductivity (K) was measured in the peat at the natural pool site using piezometer slug
251 withdrawal tests. Piezometers were constructed from high-density polyethylene, with a 3.2 cm
252 outside diameter and 2.5 cm inside diameter, and were installed into pre-augured holes and then
253 ‘developed’ to remove any smeared peat from around the intake holes (Baird *et al.*, 2004). The
254 intakes were 10 cm long and had a pattern of perforation the same as that reported in Baird *et al.*
255 (2004). K was determined at 20 locations where the intakes covered depths of 45 to 55 cm
256 (hereafter termed 50 cm depth) and 20 locations where depths of 25-35 cm were sampled (hereafter
257 termed 30 cm depth). K was calculated using the method (based on Hvorslev (1951)) reported in
258 Baird *et al.* (2004) and were corrected to a temperature of 20°C. Von Post scores for the peat at the
259 intake depths, extracted when the piezometer holes were augered out, were determined using the
260 descriptions given in Table 5.2 in Rydin and Jeglum (2006).

261
262
263 **3. Results**
264

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

275

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

291 surface area alone. Therefore, the subsurface catchment area for the pools may not exactly match
292 their surface catchment area and our values of pool catchment area should be considered estimates.

293

294 Overland flow was a common occurrence across the site. On average (median) the upslope crest-
295 stage tubes had captured overland flow between visits 83 and 84% of the time for the natural and
296 artificial pools respectively, while for the downslope sites overland flow occurred between 77 and
297 83% of visits for the natural and artificial pools respectively.

298

299 There was a significant difference ($p=0.01$) in the changes in water height above pool bed during
300 storm events between the two types of pools; the artificial pools had a significantly greater water
301 level change in response to rain (mean change 3.6 cm) than the natural pools (mean change 1.9 cm).

302 A regression analysis showed the relationship between cumulative rain in an event and the change
303 in pool water height above bed was: [Natural pool surface level change (cm) = $0.016 \times \text{mm of rain}$
304 + 1.420] and [Artificial pool water level change (cm) = $0.016 \times \text{mm of rain} + 2.894$], both having
305 the same gradients. There was a significant difference between the mean response time for pools to
306 reach peak level between the two treatments ($p=0.03$; natural mean = 17.6 hrs, artificial mean =
307 14.6 hrs). Pool water heights above bed fell significantly ($p<0.01$) more quickly in the 6 and 12
308 hour periods after rainfall in the artificial pools compared to the natural pools (Table 4). The mean
309 recession rate was greater for every artificial pool compared to any of the natural pools. Tests of
310 correlation between annual pool outflow or turnover frequency (Table 3) and all of the storm
311 response variables shown in Table 4 were conducted but only two combinations of variables were
312 significantly correlated: annual pool outflow and smallest DBPS during storm (natural pools,
313 $r=0.80$, $p=0.03$); annual pool outflow and 6-hr recession rate (artificial pools, $r=0.74$, $p=0.04$).

314

315 Mean water-table depths in the manually measured dipwells over the entire study period were 4.7
316 cm in the peat around the natural pool system and 3.7 cm in the peat around the artificial pool

317 system. However, water-table depths tended to have a greater range in the peat around the artificial
318 pools than in the peat around the natural pools (Figure 3).

319

320 The automated water-table records are only available from May 2015 to January 2016. During this
321 period the average water-table depth (relative to the peat surface) at the natural site was 5.0 cm,
322 compared with 4.0 cm at the artificial site, although this (apparent) difference was not significant.
323 ($p=0.28$). As with the manual dipwell measurements, the standard deviations of the water-table
324 depth were generally larger in the peat around the artificial pools than in the peat around the natural
325 pools (Table 5). Using water-table responses to individual rainfall events (rise to rain ratios (e.g.
326 Bourgault *et al.*, 2017)) we estimated the mean specific yield for the upper 20 cm of peat to be 0.24
327 (standard error = 0.04) and 0.25 (standard error = 0.03) for the natural and artificial pool sites
328 respectively. The storm event data showed that the relationship between water-table depth (cm) and
329 the ratio of water-table rise to rainfall (unitless) was linear, increasing over depth with a gradient of
330 0.57. This is equivalent to a non-linear gradient of decline in specific yield with peat depth of: $[1.75$
331 $/(water-table\ depth, cm)]$. As the storm events studied did not cover periods of very deep water
332 tables, we used the above relationship to extend estimates of specific yield to a peat depth of 40 cm,
333 equivalent to the mean depth of the pools. This resulted in a mean specific yield of 0.22 for the
334 upper 40 cm of peat.

335

336 When comparing pool levels and peat water-table heights for the period when automated records
337 were available for both, the range of water levels was smallest in the natural pools (mean range =
338 7.6 cm) and largest in peat water tables at the artificial pool site (mean range = 19.3 cm). The range
339 in water level was significantly different between the pools and peat dipwells at both the natural and
340 artificial sites (one-way ANOVA on mean range water level, $p < 0.01$). Post-hoc Tukey tests showed
341 the range was significantly lower in the natural pools than for artificial pools or peat water tables.
342 There was no significant difference in range between water levels recorded in natural pool site

343 dipwells and artificial pools, but a significantly higher range in the artificial pool site dipwells than
344 pool levels at either site or than in the natural pool site dipwells. The mean relative water level for
345 Pool 1 and the three nearest peat dipwells showed the downslope dipwell (P1D) had a lower
346 absolute water-table height, the mid-slope dipwell (P1M) had a similar mean water-table height to
347 the pool level and the upslope dipwell (P1U) had a higher mean water table (Figure 4). The mean
348 difference in relative water height between Pool 1 and the water table in the peat was -7.1, 0.5 and
349 10.9 cm (P1U, P1M and P1D respectively). For Pool 4 the peat water tables were very different
350 from pool water level (differences of -5.9, 22.5 and 30.3 cm for P4U, P4M and P4D respectively).
351 At the artificial pool site, Pool 8 mean water level was 23.3 cm lower than mean water-table height
352 at P8U and 11.0 cm higher than at P8D while Pool 11 mean level was 24.0 cm lower than water-
353 table height at P11U and 9.0 cm higher than at P11D.

354

355 The automated water-table records followed a similar seasonal pattern to the pools; the deepest
356 mean water-tables were in summer (summer mean of 6.6 cm at the natural site and 5.8 cm at the
357 artificial site) and shallowest in winter (winter mean of 2.9 cm at the natural site and 1.9 cm at the
358 artificial site). However, the automated record shows that pool-level fluctuations did not simply
359 reflect local water-table dynamics (e.g. Figure 5). Peat water tables tended to decline more rapidly
360 than pool levels during dry periods and there was a greater variability in water-table depth than pool
361 level change. The pool level records show a much smoother, damped signal to rainfall or recession
362 periods than the peat water-table records. In response to storm events water-table changes in the
363 peat around artificial and natural pools were not significantly different. However, water-table
364 changes in the peat were significantly different from water-level changes in both the natural and
365 artificial pools; pool hydrological responses were significantly different between pool types (one-
366 way ANOVA, $p < 0.01$, confirmed with a post-hoc Tukey test). After peak levels had been achieved
367 during storms, water heights fell significantly faster in the peat around the pools than water levels
368 within the pools (one-way ANOVA, $p < 0.01$). Recession rates were significantly higher for dipwells

369 at the artificial sites than the water levels both in the natural and artificial pools (one-way ANOVA,
370 $p < 0.01$) in the 6 and 12 hour period after peak water levels, but there were no significant differences
371 in the 6 and 12 hour recession responses in the peat water tables between the natural and artificial
372 sites. There was a significant difference between the mean response time to reach peak level
373 between the pools and the dipwells (one-way ANOVA, $p < 0.01$), and the water level responded
374 fastest at the natural site in the peat around the pools, and slowest in the natural pools themselves.

375

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

385

386 **4. Discussion**

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

395 natural pool site, although both locations had relatively shallow mean water tables (within 5 cm of
396 the peat surface).

397

398 There are several reasons why pool level variability and water-table variability were so much
399 greater at the artificial pool site. It may be that during high flow the artificial pools still retain some
400 connectivity to the old ditch system with pools overflowing along the course of the old ditches
401 enabling pool levels to fall more quickly after peak than in the natural pool system. The rapid rise
402 and fall of pool levels at the artificial pool site was not simply a function of small catchment areas
403 for each pool. Pools 10 and 12 were both among the top six largest combined catchment areas of all
404 pools studied (i.e. pool area plus contributing area; Table 1) and yet had more rapid water level
405 recessions (6 hr and 12 hr) after storms than any of the six natural pools. However, the mean slope
406 was slightly greater at the artificial pool site (0.05 m m^{-1} compared with 0.04 m m^{-1}) and the ratio of
407 catchment area to pool area was typically greater for the artificial pools (Table 1). Thus we might
408 expect a more rapid increase in pool level in response to rainfall for the artificial pools. It may also
409 be that some peat properties affected by ditch drainage had not recovered in the 11 to 13 years since
410 restoration and there may be enhanced macropore and pipe drainage in the peat around the artificial
411 pools (Holden, 2005; Holden *et al.*, 2006). Holden *et al.* (2011) found for a blanket peatland in
412 northern England that 6 to 7 years after ditch blocking at a site where drains predominantly ran
413 across slope (roughly parallel to the contour), the peat water tables were still significantly deeper
414 and much more variable than those in nearby undrained peat, but slightly less variable than those in
415 nearby drained peat without drain blocking. Evidence from other sites suggests that where blanket
416 peatland drains run largely downslope, similar to those at our site, ditch blocking may only have a
417 very small impact on local water tables and peatland function, at least in the short term (Green *et*
418 *al.*, 2017; Holden *et al.*, 2017). Another important factor which could affect water-table and pool-
419 level fluctuations is the bulk specific yield of the peatland. At the natural pool site there was a far
420 greater proportion of the landscape that was open water than at the artificial pool site. The mean

421 pool depth was ~40 cm and so considering only the upper 40 cm of the peatland, a specific yield of
422 pools = 1, and mean specific yield for the upper 40 cm of peat = 0.22, the bulk specific yield of the
423 natural pool site was 0.28 while it was 0.22 for the artificial pool site. Therefore, given the same
424 water input, the water level fluctuations would be expected to be greater at the artificial pool site
425 than at the natural pool site. However, we also showed that pool levels and water-tables in the
426 nearby peat were somewhat disconnected, with steep hydraulic gradients forming between the peat
427 and nearby pools due to very low peat hydraulic conductivity. Therefore, the bulk specific yield
428 concept may be of limited use in understanding the overall hydrological dynamics of blanket peat
429 systems with pools. Nevertheless, the fact that pool DBPS values were on average 15 cm, still
430 allows us to conclude that creating larger pool area in peatland restoration schemes may be
431 beneficial in reducing downstream flood risk for some storms. These benefits may not be fully
432 realised on occasions when the pools are already 'full' which is more likely in winter months when
433 evaporation rates are small.

434

435 Evaporation between rainfall events played a strong role in controlling pool level drawdown in the
436 summer months meaning that variability in water levels was greatest at this time of year. The pool
437 water levels were most drawn down during summer 2013, the first summer of monitoring. The
438 subsequent winter was very wet but DBPS values in both the natural and artificial pool systems
439 were generally greater in winter 2013 compared to the other two winters studied. It is not clear what
440 caused this effect but such inter-annual variability in pool water levels, even in winter months may
441 have implications for carbon cycling and release and the hydrological function of the peatland. It
442 may be that the near-surface peat and pool sides became desiccated and cracked during the
443 unusually warm, dry summer of 2013 and this meant that in the subsequent winter (which was very
444 wet) more water could percolate out of the pool sides near the top of the peat. Desiccation cracking
445 is common in peatlands on bare peat faces during dry weather (Evans and Warburton, 2007) and

446 macropore flow can be a very important pathway for water in near-surface blanket peat (Holden,
447 2009). It may have taken more than one winter for cracks to close up or seal with biofilms.

448

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

457

458 The smaller artificial pools spilled out, on average, water equivalent to 54 times the mean volume of
459 the pool per year. This relative value was six times lower for the natural pools although the actual
460 volume of water that flowed out of the six natural pools was around ten times greater than that from
461 the artificial pools. These rates of pool ‘turnover’ may be important for peatland chemistry and peat
462 accumulation rates (Beer and Blodau, 2007; Morris and Waddington, 2011) and for understanding
463 aquatic carbon fluxes from peatlands with pools, particularly if the carbon processing is different
464 between natural and artificial pool systems. Pools with longer water residence times may be subject
465 to enhanced photochemical processing of dissolved organic carbon (e.g. Pickard *et al.*, 2017) (all
466 pools were ≤ 50 cm deep); hence the quality of dissolved organic carbon may vary between pools
467 which could be important for downstream water treatment for potable supply (Worrall and Burt,
468 2009; Moody and Worrall, 2017). On the other hand, the slower turnover of water in some larger
469 pools may mean that the remaining carbon is largely recalcitrant and little further processing can
470 occur, whereas in smaller pools processing of carbon can continue for longer periods if the pool
471 water volume is replaced more frequently. McEnroe *et al.* (2009) showed that smaller pools had

472 consistently larger carbon dioxide and methane fluxes than larger pools in a raised bog in Canada. It
473 should also be noted that we found that the rates of pool water replacement were highly variable
474 and the volumes of water produced were not related simply to pool size as the upslope catchment
475 area of each pool was also critical. Some very large natural pools had a relatively small upslope
476 catchment area. Thus when sampling blanket peatland pools for their aquatic chemistry (Turner *et*
477 *al.*, 2016) and also when considering potential impacts of pool processes on downstream river water
478 chemistry, including aquatic carbon fluxes, and their role on carbon gas release to the atmosphere, it
479 will be important in the future to consider pool topographic context and upslope contributing area in
480 addition to pool dimensions. Pools of an equivalent size cannot be assumed to play an equivalent
481 role in influencing aquatic fluxes from the peatland; pool size and their contributing area are both
482 important.

483

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

498 events are important for connecting the peat system to pool systems, enabling pool water
499 replenishment and for flushing out of pools of potentially significant volumes of carbon and other
500 nutrients that may have been processed within the pool.

501
502

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669 Table 1. Pool physical characteristics

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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

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676 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,
 677 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 6.7	23.2 8.0	17.5 0.5	18.2 1.2	19.6 4.3	16.7 2.5	14.9 0.9	15.4 1.0	16.0 1.6	14.6 1.9	11.9 0.6
Pool 2	29.2 8.2	24.3 10.8	18.0 0.4	19.0 1.6	21.7 5.5	18.3 2.0	16.8 0.4	17.7 1.4	19.5 3.0	18.4 2.7	15.9 0.4
Pool 3	28.2 6.5	22.3 4.1	18.5 0.6	19.3 1.4	21.0 4.2	18.1 2.3	16.5 0.6	17.3 1.6	18.2 2.3	17.1 2.5	15.2 0.4
Pool 4	26.2 7.1	20.9 7.2	15.4 0.5	16.2 1.5	18.8 5.4	15.5 3.3	13.4 0.7	14.3 2.0	15.3 2.4	14.2 2.4	11.8 0.6
Pool 5	19.2 5.6	12.6 3.6	9.8 0.6	10.3 1.6	12.1 4.9	9.4 2.8	7.5 0.9	7.9 1.6	8.7 2.3	7.7 2.2	5.9 0.3
Pool 6	24.9 6.7	18.4 4.1	15.2 0.5	16.1 1.7	18.0 5.2	15.1 2.8	13.4 0.6	14.3 1.3	15.3 2.1	14.3 1.5	13.0 0.3
All natural pools	25.8 6.8	20.3 6.4	15.7 0.5	16.5 1.5	18.5 4.9	15.5 2.6	13.7 0.6	14.5 1.4	15.5 2.3	14.4 2.2	12.3 0.4
Pool 7	19.8 9.3	13.0 1.8	11.0 0.6	11.3 1.8	12.3 3.9	10.2 2.1	9.1 1.2	10.2 2.3	10.7 2.2	10.2 1.8	8.4 0.7
Pool 8	18.1 10.2	9.5 2.2	7.6 1.0	9.0 2.3	9.9 3.9	7.7 3.2	5.9 1.4	7.4 2.6	8.8 2.9	7.2 2.4	5.3 1.4
Pool 9	23.6 8.3	16.7 2.7	14.3 0.9	15.2 2.3	16.1 3.6	14.4 2.8	12.8 1.1	13.8 1.9	14.8 2.1	14.1 2.9	12.0 1.0
Pool 10	21.9 9.5	12.4 3.1	9.4 1.2	10.6 2.1	12.6 6.4	10.1 3.1	8.1 1.4	9.4 2.0	10.5 3.3	9.6 3.1	7.2 1.3
Pool 11	29.2 7.7	20.0 3.3	17.0 1.5	18.3 2.6	20.2 6.3	17.5 3.6	15.0 2.1	16.8 2.7	19.0 3.9	17.8 4.0	14.7 1.9
Pool 12	25.9 9.6	16.0 3.6	12.7 2.0	14.4 4.1	16.4 8.0	13.0 4.9	10.3 0.9	11.7 3.1	13.7 6.1	12.7 5.0	9.2 0.8
All artificial pools	23.1 9.1	14.6 2.7	12.0 1.1	13.2 2.5	14.6 5.4	12.2 3.3	10.2 1.4	11.5 2.2	12.9 3.3	11.9 3.1	9.5 1.1

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679 Table 3. Rates of pool outflow and recharge

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	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

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

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	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

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692 Table 5. Water level in the pools and surrounding peat, m, relative to a local datum for 21st May
 693 2015 to 28th January 2016. Note that one datum point was used for the natural pool site and a
 694 different datum point was used for the artificial pool site.
 695

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

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698 **Figure captions**

699

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

703

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

705

706 Figure 3. Manually measured water-table depths in the peat 1 m from natural pools (black) and
707 artificial pools (grey). The box shows the interquartile range, error bars show range, crosses show
708 1st and 99th percentiles, solid square box shows mean and the horizontal dashed line shows the
709 median.

710

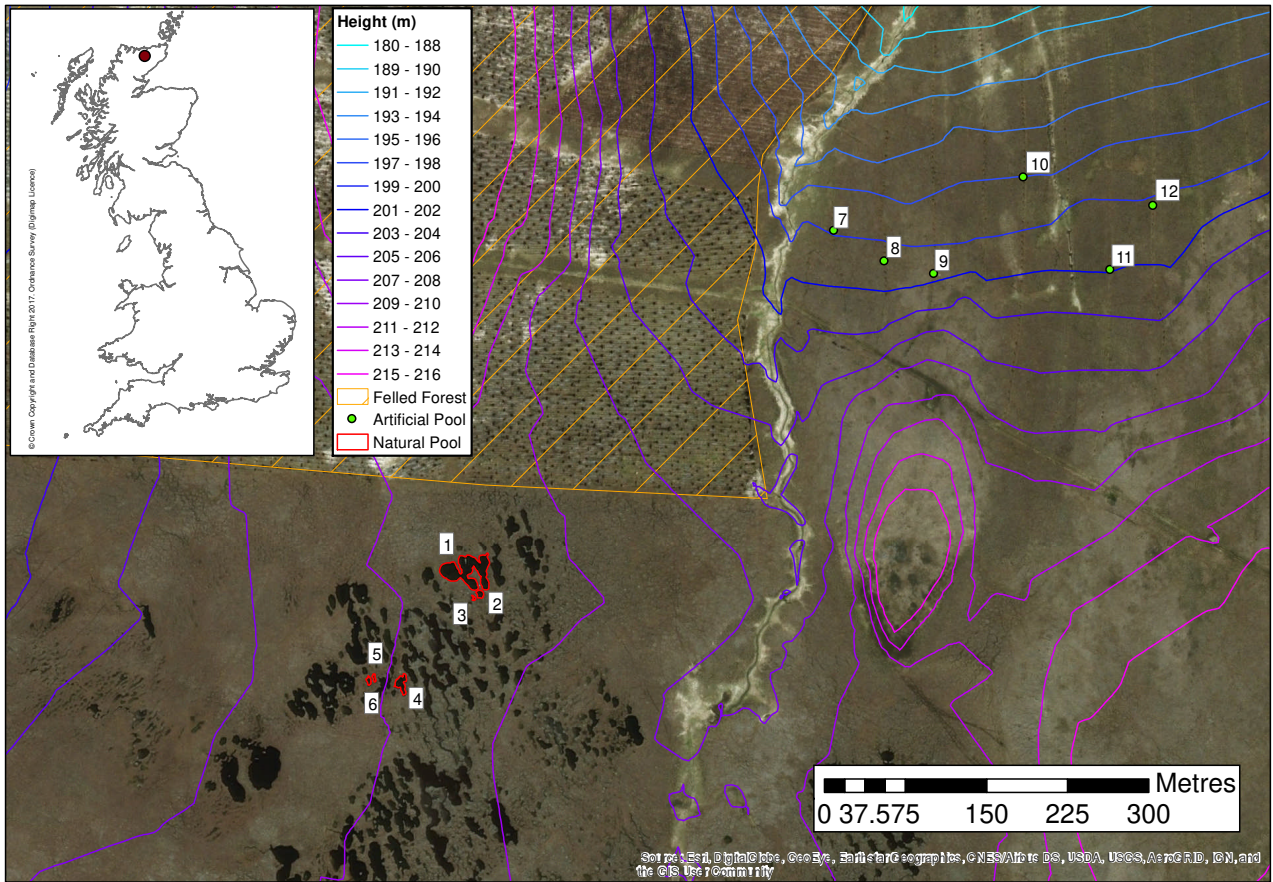
711 Figure 4. Comparisons of relative pool water level and water-table height in the peat nearby for
712 Pools 1, 4, 8 and 11, based on automated records. The box shows the interquartile range, error bars
713 show range, crosses show 1st and 99th percentiles, solid square box shows mean and the grey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

715

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

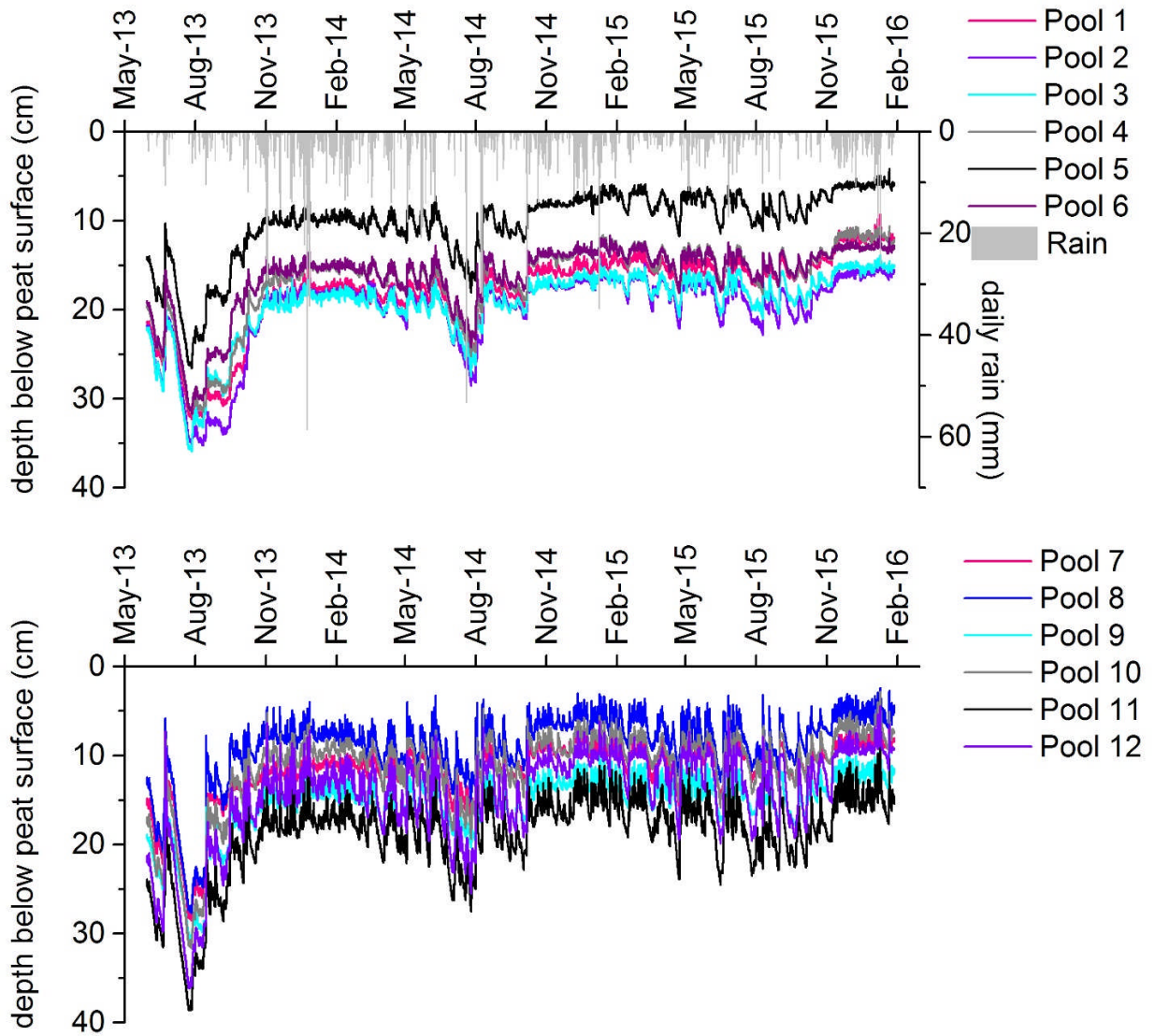
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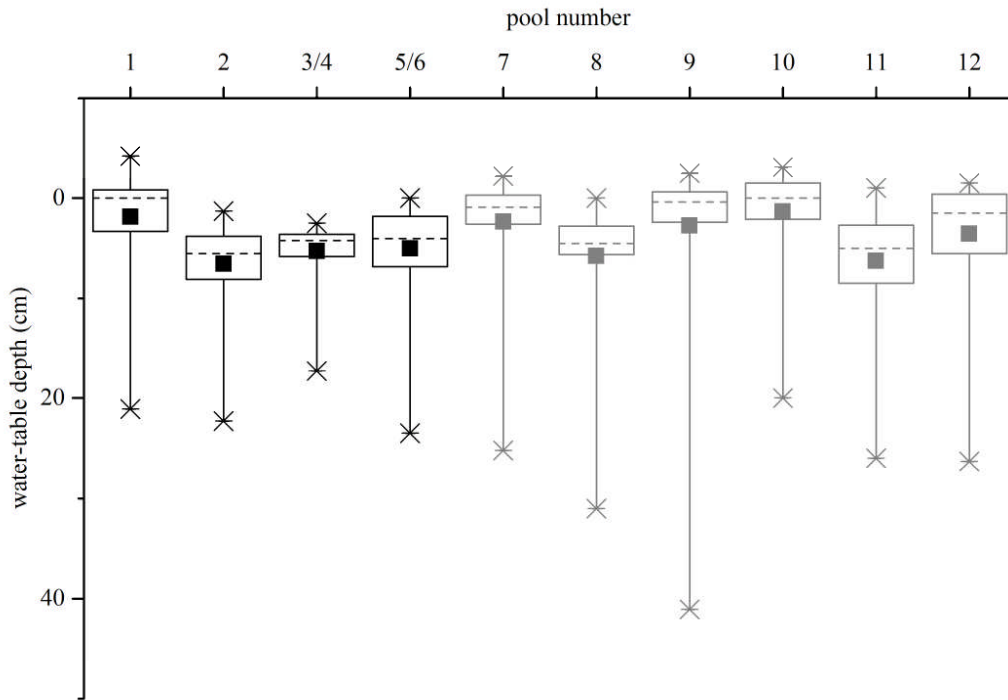
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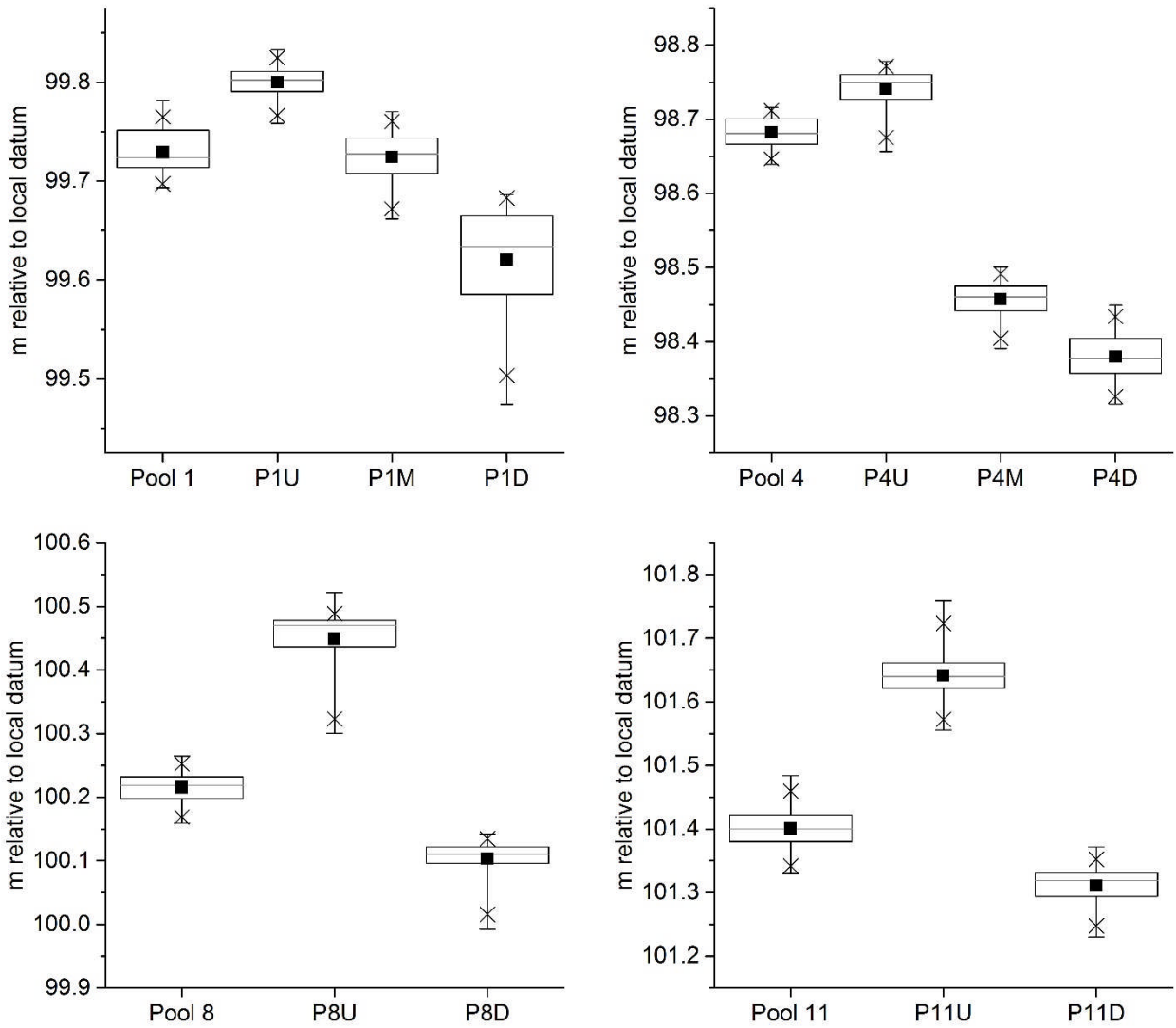
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741 median.



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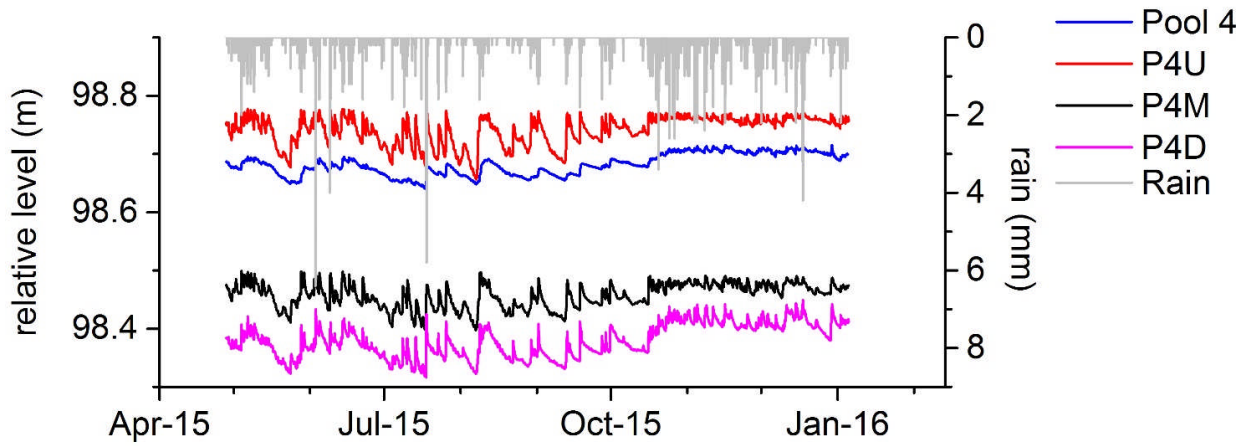
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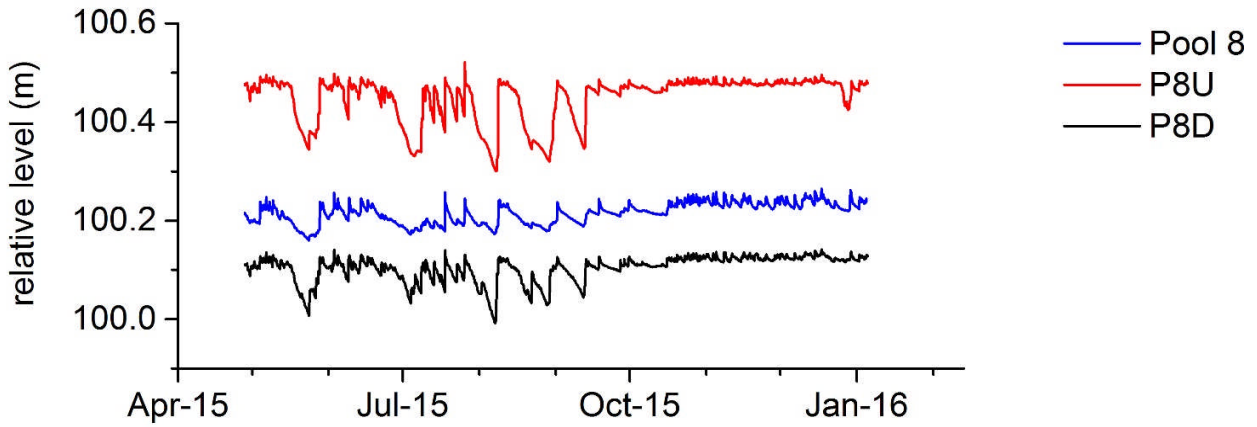


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752 panel) and Pool 8 in the artificial pool system (lower panel). Water levels shown in each plot are all relative
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754 artificial pool site.
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