THE DESIGN AND EFFECT OF BLOCKING DEEP, MINERAL-BASED PEAT PIPES ON A DEGRADED BLANKET BOG

MoorLIFE 2020

Prepared by:

Moors for the Future Partnership, December 2022

Suggested citation:
Pilkington, M. & West-Samuel, A. (2022) The design and effect of blocking deep, mineral-based peat pipes on a degraded blanket bog. Moors for the Future Partnership, Edale, UK.

MoorLIFE 2020 Final Report:
Action D3

The design and effect of blocking deep, mineral-based peat pipes on a degraded blanket bog

Dec 2022

Prepared by:

MOORS FOR THE FUTURE PARTNERSHIP

Mike Pilkington and Ade West-Samuel
Moors for the Future Partnership
The Moorland Centre, Edale, Hope Valley, Derbyshire, S33 7ZA, UK

T: 01629 816510
M: 07972 734077
W: www.moorsforthefuture.org.uk

Contents

List of Figures

List of Tables

Abstract

1. Sub-surface water flow through peat pipes on upland blanket peat can evade current land management practices which are designed to slow surface overland flow, and is likely to aggravate flood risk, erosion rates and loss of fluvial carbon while also potentially lowering water tables, reducing diversity and increasing gaseous carbon emissions. But there is a lack of information on these effects and on methods for their mitigation.
2. This trial aimed to (i) design a method for blocking sub-surface water flow through deep, large-diameter pipes running along the interface between the mineral base layer and the overlying peat layer, and (ii) quantify the effect of the blocking on key attributes of "favourable" blanket bog functioning.
3. BACI-designed monitoring was installed to assess the effect of the blocking on open water storage, water table, water flow and DOC concentrations.
4. Three types of blocks were designed, each using a different core material (peat, stone or heather bale) and constructed to maximise surface contact with the mineral substratum.
5. Blocking locations, identified at the downstream end of collapsed sections or beneath vent holes, were first mechanically excavated to provide a clear substratum and to expose the pipe tunnel.
6. The results showed that all three block types created open water storage pools and caused water tables to rise, but with significantly greater effects in blocks constructed from peat cores, during high rainfall months, and in winter. Significant reductions in the depth to water table were found at least 5 m from the blocking location, with maximal effects at 2–3 m. Blocking significantly increased the lag time of peak flows (by 44 minutes) and significantly decreased peak stage.
7. DOC concentrations from pipe effluent were typically high for Bleaklow sites and varied closely with season, but there was no effect of blocking.
8. It was concluded that this block design (and especially where peat was used as the core material) was highly effective at storing water, raising water tables and also that blocking generally slowed and reduced peak flows in large-diameter, mineral-based peat pipes.

Executive summary

The site

The site was a sloping, south-south-west facing, heather-dominated upland blanket bog with Site of Special Scientific Interest (SSSI) status, but in degraded state and reported as "unfavourable recovering" condition. The site had deep gullies and peat depths ranging from 0.5 – 3 meters. Pipes were identified and located mainly from the presence of exit and entrance tunnels separated by open gully sections which suggested that they were collapsed sections of parallel linear pipes. The pipes had maximum diameters of over one metre, and ran along the interface between the mineral substrate and the peat layer. There were also vertical vent holes leading down to the pipes.

Experimental design

With the assumption that a series of collapsed sections and vent holes running roughly in a line downhill were indicative of single pipe, nine roughly parallel pipes were identified and assumed to run independently of each other, although cross-connections were possible. A Before-After-Control-Intervention (BACI) design was chosen with seven pipes allocated for the blocking intervention (containing more than forty blocking locations) and two pipes allocated for the control. Monitoring equipment was installed and active 12 months before blocking occurred and continued for 12 months afterwards.

Designing and installing the blocks

Blocks were designed to maximise surface contact with the mineral substratum and with the core of the block constructed from peat, stone or heather bales. The core of the block was designed to completely cover the pipe tunnel entrance at the downstream end of collapsed sections. The blocking process involved a preparatory stage using a mechanical excavator to remove rocky and vegetative debris, creating a relatively flat mineral surface and exposing the pipe tunnel area, so that it was clearly visible and ready for block construction. The design included a final treatment of peat profiling which extended the area of the block upstream, and also maximised contact with the mineral substratum.

Monitoring

Open water storage was monitored only after blocking, the blocked locations were surveyed fortnightly to assess the degree of open water storage formed using a simple scale from 0 – 4.

Water tables were surveyed at a single blocking location on each of five of the seven treatment pipes and on each of the two control pipes. Seven dipwell clusters were installed (two at peat core blocks, two at stone core blocks, one at heather bale block and two control locations), each consisting of 10 manual dipwells arranged in a linear transect at right angles to the direction of flow (surveyed weekly).

Water flow was measured at the downstream end of all nine pipes using a pressure sensing logger installed directly in open gully sections downstream of all blocking locations, and with a preference for u-shaped channels on rock streambed. The loggers recorded depth every 10 mins and were downloaded every fortnight. "Peak depth" was defined as the maximum depth during rain events and "Lag time" was defined as the duration between the end of a rainfall event and the time of peak depth. Complex hydrographs of peak depth were mainly omitted from analysis.

Dissolved Organic Carbon (DOC) concentrations were measured in water samples collected every fortnight from the water flow logging locations (only if there was active flow) and sent to University of Manchester laboratories for determination of DOC.
Rainfall at the site was measured using a single automatically recording rain gauge, logging total tips every 10 mins and downloaded fortnightly.
There was a baseline period and a post-blocking period, each of 12 months (PRE and POST), and within each 12 month period, equivalent six-month periods were used to distinguish between changes that occurred in winter (Pre1 and Post1) and those that occurred in summer (Pre2 and Post2).
Sources of error were discussed, especially concerning direct assessment of peak depth on irregular and erosive stream beds. All post-blocking results (except open water storage, for which no pre-blocking measurements were possible) were calculated as a change from the equivalent period pre-blocking, and also relative to those in the Control.

Results

The creation of open water storage pools

1. Water storage scores of pools that formed behind the blocks were significantly higher
    a. for pipe blocks constructed with peat cores compared to those constructed from either stone- or heather bale cores
    b. in the winter monitoring period compared to the summer
2. A gradual decrease in average monthly water storage scores during the whole 12-month post-blocking monitoring period was related to decreases in total monthly rainfall – the blocks remained robust and functional for the duration of the trial.
3. There was a positive, linear relation between the number of peat core blocks and the average water storage score along pipes. A negative relationship for all blocks and stone core blocks was due to increasing numbers of non-peat core blocks progressively excluding the number of peat core blocks.
4. There was also a positive linear relationship between rainfall amount and water storage scores

Water table depth

1. There was a strong positive linear relation between average monthly water storage scores and the change in monthly relative water table depth, suggesting that higher storage scores caused a greater rise in water tables towards the surface.
2. There was a strong positive linear relation between total monthly rainfall and average monthly water table depth, both before and after blocking, and for both the control and treatment dipwell clusters. However only the treatment (blocked) clusters showed an increase in the linear gradient in the POST blocking period – suggesting that increases in total monthly rainfall caused water tables of blocked dipwells to rise more steeply than unblocked dipwells
3. The most substantial rise in water table occurred
    a. In winter (+2.3 cm, $P < 0.001$)
    b. Near blocks constructed from peat cores (+2.5 cm, $P < 0.001$)
    c. At a distance of 2 and 3 m from the blocking location (+2 cm and +1.9 cm, respectively, $P < 0.01$)
4. The combination of all the above criteria provided a maximum post blocking change of 6.9 cm (peat core blocks over the Pre-Post1 comparison and at a 3 m distance from the block.

Water flow

1. Complex peaks were mainly omitted from analysis.
2. There were 15 peaks available for analysis in the summer comparison periods (Pre2/Post2) and 37 in the winter periods (Pre1/Post1). Of the 15 summer peaks, 10 were in Pre2, five in Post2. In contrast, of the 37 winter peaks, there were 15 peaks in Pre1 and 22 peaks in Post1. When summer and winter periods were combined, there were 25 peaks in the 12 month PRE period and 27 peaks in the POST period.
3. Lag time was substantially and significantly increased after blocking (average of +44 min), with significant increases seen in 6 out of the 7 individual blocked pipes.
4. Peak stage was also significantly decreased after blocking, with significant individual decreases seen in 5 out of the 7 blocked pipes.

Dissolved Organic Carbon (DOC)

1. There was a pronounced and clear seasonal variation in DOC concentrations with late summer maxima (September) and winter minima (February).
2. There were no significant effects of blocking on DOC concentrations
3. There were some weak linear relations suggesting that pipes with more blocks (above about 5) had more negative change in DOC and vice versa and also that pipes with higher post blocking water storage scores (above about 1.5) had more positive increases in DOC, and vice versa. These tendencies could be translated to mean that pipes with more peat blocks were linked with higher water storage scores and were also linked with higher DOC concentrations – perhaps due to the pipe flow being forced up and out of pipes and along the surface, where DOC concentrations are greatest.

Conclusions

Blocking using all three types of core material resulted in the creation of open water storage pools and a rise in water tables that was maximal at 2–3 m distance, but extended at least as far as 5 m away from the block, at right angles to the direction of flow. The effect was significantly greater for blocks constructed from peat, during high rainfall and in winter. Blocking significantly and substantially slowed and reduced peak flow and had no significant effect on DOC concentrations, although forcing water out of pipes and along the surface may have contributed to a linear relation with increasing DOC, especially for the more impermeable peat blocks.

In conclusion, this design for blocking mineral-based pipes was highly beneficial for key attributes of "good" bog functioning; especially in creating open water shortage pools and raising water tables which would have a strong likelihood of increasing diversity towards blanket bog indicator species richness, including Sphagnum growth and thus Favourable Condition. In addition, the results showed that beneficial changes in lag time and peak stage would contribute towards for a downstream reduction in flood risk while having minimal effect on increasing DOC concentrations.

1. Introduction

Peat pipes are sub-surface conduits commonly found in British blanket bogs, and especially those that are degraded (Jones et al., 1997; Holden and Burt, 2002b; Holden et al., 2002; Holden, 2004). Their origins may be traced to desiccation cracking at the peat surface during dry periods (Jones, 1971); subsequent rain events leading to rapid infiltration of water tending towards the development of a branching network of pipes on shallow slopes or more parallel and singular pipes on steeper slopes (Holden, 2005a). Pipes may be particularly prevalent on steepest top slope sections, and also in gripped (artificially drained) systems (and especially in older gripped systems), in areas of bare peat or *Calluna* cover, and possibly also in *Sphagnum*-dominated sites (Holden 2005b). Pipe exit points found near the sides of gully systems on a degraded site on Bleaklow were found to be particularly prevalent on south and south-westerly facing banks, and situated nearer the surface at head-ward retreat positions, but deeper in the peat layer when exiting onto straight gully sides (Regensburg et al., 2020). However, deeper peat pipes found at the interface between the mineral bedrock layer and the overlying peat are often of much larger diameter, can have extensive collapsed and collapsing sections, and may have once been part of the original stream network prior to the formation of peat (J. Holden, 2018: personal communication) Although rapid sub-surface flow can occur in pipes with pipe flow responding quickly to rainfall events (Jones, 1971, Gilman and Newson, 1980, Bryan and Yair, 1982), declining post-event pipe flow can be more drawn out than other run-off production processes. Thus it is likely that that low flows in streams are maintained for longer by pipe flow during inter-storm periods (Holden and Burt, 2002b; Smart et al., 2013). In general however, the presence of pipes is a cause of concern for restoration practitioners on blanket bogs:
Firstly, headwater peatlands are often the source of flooding for communities at risk in the south Pennines (Acreman and Holden, 2013; Allott et al., 2019) and degraded blanket bogs in particular have been targeted for monitored restoration actions that reduced peak flows and extended lag times (Shuttleworth et al., 2018). However to date there has not been the same focus on the role of piping and sub-surface pipeflows in these systems, which can contribute up to 49% of stream flow (Jones, 1982; Jones and Crane, 1984), but which can also evade surface restoration actions.
Secondly, piping is also strongly associated with erosion (Bernatek-Jakiel and Poesen, 2018), especially when roof collapse leads to wash-out of peat particles and gully formation (Wilson, 2011; Xu et al., 2020). Furthermore, the route taken by a pipe can undulate vertically through the peat layer, and substantial amounts of both mineral and organic material, may be transported (Bryan and Jones, 1997), contributing to stream concentrations of both dissolved and particulate organic carbon (DOC and POC) as well as nutrient and toxic pollutants of water (Tipping et al., 2003; Rothwell et al., 2007), collectively causing problems for water treatment (Xu et al., 2020). DOC can be associated with lead (Shuttleworth et al., 2014), precursors of trihalomethanes (THM) which can be carcinogenic and mutagenic (Chow et al., 2003), brown colouration which can alter taste and odour, and cause microorganism blooms (Lofgren et al., 2003). Subsequent oxidation of fluvial carbon compounds to carbon dioxide (CO_2) adds to greenhouse gas emissions and climate change (Evans et al., 2015). Regensburg et al (2021b) found strong seasonal variations in DOC concentrations but no discernible effect of blocking, although blocking was not considered feasible for these gully-edge pipes.
Thirdly, the presence of peat pipes is also likely to lower water tables: Regensburg et al. (2021) found that water tables were deeper in the vicinity of peat layer pipes close to pipe outlets and this effect is likely to be more pronounced for large dimeter mineral layer pipes. Consequential drawdown effects on water table are likely to favour vegetation more suited

to drier conditions, reducing the diversity of blanket bog indicator species and contributing to oxidative losses of carbon.

There is a lack of clear understanding regarding the individual effects of revegetation and gully-blocking on the benefits of Natural Flood Management (NFM), and especially on the delay and reduction of storm flow (lag time and peak discharge). Modelling by Goudarzi et al. (2021) suggested that during the largest storms these benefits were primarily due to surface roughness of vegetation slowing overland flow (kinematic storage) – an effect which recent research suggests is magnified by an abundance of *Sphagnum* (Allott et al., 2022). However the models of Goudzari et al. predicted that the impact of gully blocking would be similar in magnitude: indeed during smaller events, the effects of interception and surface ponding could be more important (static storage), although in this latter case, the volumes of open water pools required would have to be on a similar scale to the rainfall amounts associated with flood-relevant events. To this end Jackson et al. (2021) have calculated storage potential associated with large-scale bunding and blocking. These findings are particularly relevant to the development of restoration methods aimed at reducing flow within pipes. While the work by Regensburg et al. (2021) found that blocking shallow gully-edge pipes at their exit points on gully sides resulted in leakage and may even have exacerbated pipe formation, the blocking of collapsed sections of deep, large-diameter and mineral-based pipes is essentially a type of gully-blocking with which many practitioners are already well-practiced (Buckler et al., 2013) and which also creates open water pools (Jackson et al., 2021).

This present study therefore aims to provide a robust design for blocking these type of pipes at the downstream end of collapsed “gully” sections, forcing water up and out of the pipes, and onto the vegetated surface to be slowed by kinematic storage, thereby enhancing NFM benefits and reducing erosive export of particles and DOC. It also aims to show their effectiveness in creating open water storage pools and in raising water tables.

2. Methods

2.1. Site location

The trial site (Fig. 1) was located on an upland bog with south-south-west aspect lying within the Dark Peak Site of Special Scientific Interest (Robinson's Moss (049), unit ID 1014932, grid reference SE 037 002) at an altitude between 480 and 510 m above sea level (NE 2022). The site was incised by parallel running gullies, frequently eroded down to the mineral layer. Dominant vegetation comprised heather, bilberry, crowberry and cotton grass with *Sphagnum* present in wetter flushes and vegetated gullies (NE 2022). Many of the gullies appeared to be the collapsed sections of mineral-based linear pipes with tunnel exits at the upstream end and tunnel entrances at the downstream ends. Peat depth was observed to vary from about 0.5 m to 3 m. There were also vertical vent holes leading down to pipes. The course of the pipes did not always correspond with those of the gullies – for instance pipes were sometimes observed to run alongside the gully, within the interfluvial "hagg", and then opening out into the side of the gully. The site was managed with minimal sheep grazing by the Royal Society for the Protection of Birds. The habitat was described as being in an "unfavourable recovering" condition in the last recorded assessment (in 2011), and suitable for curlew, snipe and golden plover with hunting habitat for merlin and short-eared owl (NE 2022).

Fig. 1. Map showing the trial site on Arnfield Moor

The trial site on Arnfield Moor (labelled "Work site") is denoted by a collection of multi-coloured dots. Access to the site was on a farm track (thin blue and green lines) leading north east from Arnfield. © Crown Copyright and database rights 2020

2.2. Locating pipes

Peat pipes were identified from the readily observable collapsed sections and were found in almost all cases to be running along the interface between the mineral base and the overlying peat layer. The collapsed sections were either in the form of vertical "vent holes" leading down to the horizontal pipes (Fig. 2, left), or longer and more open gully sections, leading directly to tunnel entrances (Fig. 2, right). The length of the collapsed sections varied between approximately 30 cm diameter for the vertical vent holes, up to more than 20 m length of gully between tunnel exits and entrances. The coordinates of these vertical holes and collapsed gullied sections were mapped and connecting lines were drawn as an assumption of flow path continuity between them (Fig. 3, top).

Fig. 2. Photograph of a vertical vent and a collapsed gully section leading to pipe tunnel

2.3. Experimental design

Nine pipes were identified (P1 – P9), two of which were reserved as control pipes (P4 and P5) (Fig. 3). A BACI design was used, in the context of using a "Before intervention" and "After intervention" comparison with both "Control" and "Intervention" pipes. The intervention pipes consisted of pipes ear-marked for blocking along their length and at the downstream end of each of the collapsed, exposed sections. Control pipes were kept free of blocking. Monitored variables consisted of water flow, water quality and water table depth, along with rainfall, temperature and barometric pressure.

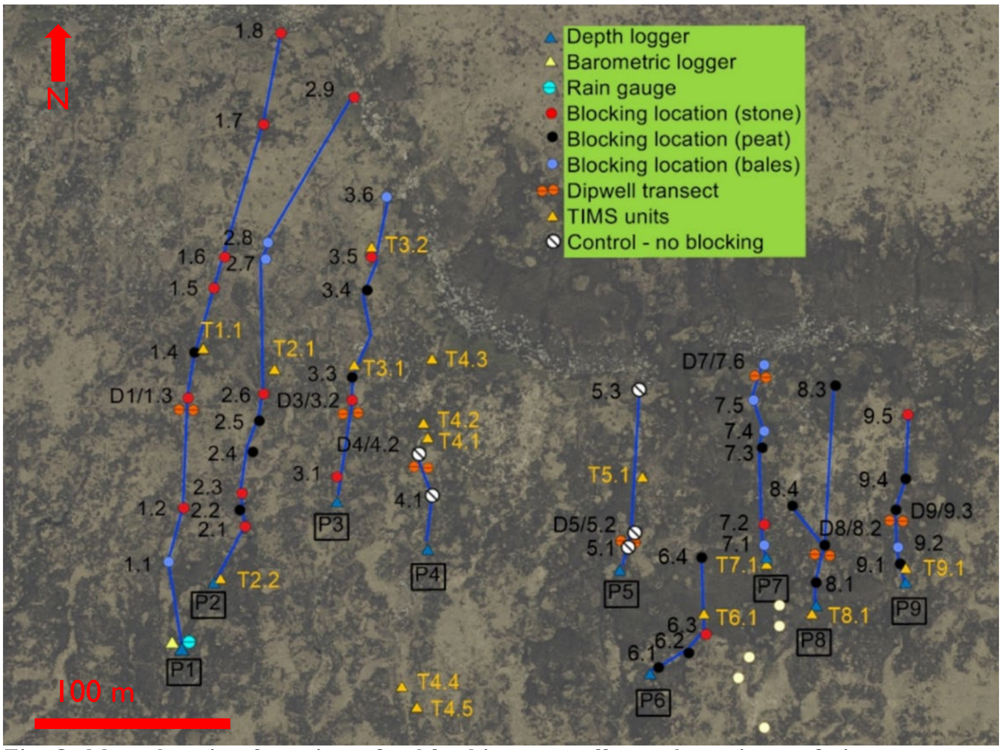


Fig. 3. Map showing locations for blocking on collapsed sections of pipe

The map also shows dipwell transects (orange circles), monitoring equipment (triangles) and assumed flow paths (blue lines). The yellow triangles in the map indicate the location of "TIMS" units – passive collectors for trapping eroding particulate peat.

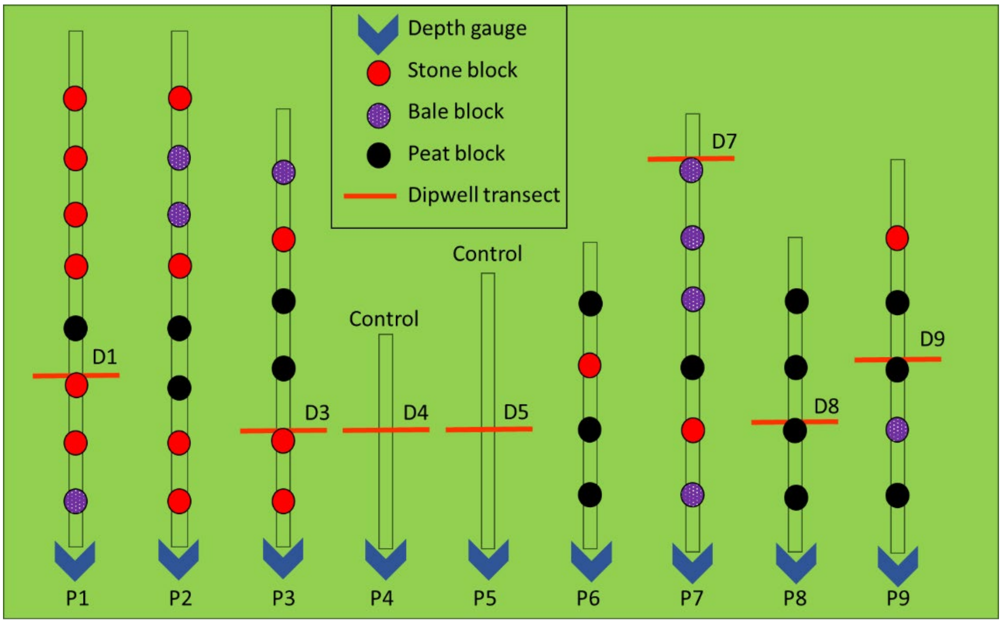


Fig. 4. Schematic of map in Fig. 3, showing locations for blocking and monitoring equipment

Note P4 and P5 were designated as control pipes with no blocking. Dipwell clusters in the form of transects were positioned at two stone dam blocking locations, two peat dam blocking locations but only one heather bale dam blocking location. There was also a rain gauge and barometric logger at the same position as the depth logger in P1

2.4. Pre- and post-blocking comparison periods

The effect of blocking the pipes was evaluated by comparing measurements of variables across equivalent seasonal periods before and after blocking (Fig. 5 and Table 1), and in relation to the control measurements.

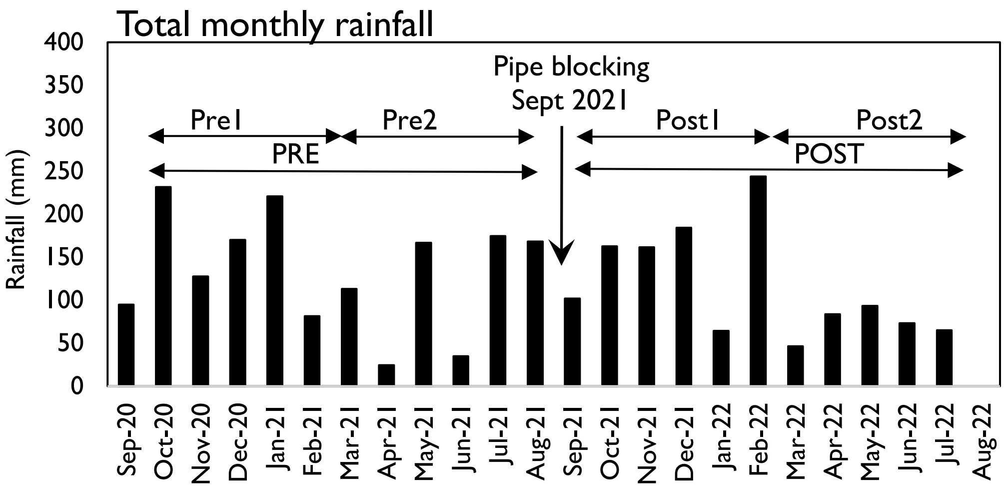


Fig. 5. Pre- and post-blocking comparison periods

Note: Pre1, Pre2, Post1 and Post2 periods were each of six months duration. PRE and POST were each of twelve months duration. Pipe blocking works occurred in September 2021. The graph also shows total monthly rainfall amounts.

Table 1. Details of pre- and post-blocking comparison periods

Period	Duration (months)	Start date	End date
Pre1	6	Sep 2020	Feb 2021
Post1	6	Sep 2021	Feb 2022
Pre2	6	Mar 2021	Aug 2021
Post2	6	Mar 2022	Aug 2022
PRE	12	Sep 2020	Aug 2021
POST	12	Sep 2021	Aug 2022

2.5. Monitored variables and the monitoring regime

2.5.1. Rain and barometric pressure at the site

A tipping bucket rain gauge and a barometric logger for atmospheric compensation of the submerged loggers were additionally installed at P1. Barometric pressure was logged automatically every 10 minutes. Rainfall was logged every 10 minutes as the total number of rain gauge tips in each of the preceding 10 minute periods. Downloads occurred every fortnight.

2.5.2. Water storage (all 41 blocking locations)

After blocking had been installed, the retention of water behind the blocks was assessed by repeated fortnightly estimates of water storage. These "water storage scores" were assigned to each of the 41 blocks and provided a simple indication of the amount of ponding or open water storage. The score was applied to the space immediately upstream of each block, and averaged over the different post-blocking periods. The fortnightly scores were assigned according to five simple categories:
0 = empty of water
1 = less than one quarter full of water
2 = approximately half full of water
3 = more than three quarters full of water
4 = full of water and overtopping

2.5.3. Water table (five blocked and two unblocked locations)

Dipwell clusters were installed 12 months before blocking, each with 10 dipwells installed at 1 m intervals along a transect extending from both sides of the pipe just upstream of the blocking location and at right angles to the direction of flow in the pipe (see Fig. 3, Fig. 4). Dipwell clusters were installed at five of the blocking locations, one location on each of five pipes, as follows: two on peat blocks (D1 and D3), two on stone blocks (D7 and D8) and one on a bale block (D9). Two further dipwell clusters were installed at equivalent locations on each of the two control pipes (D4 and D5), the choice of location in all cases based on relative flatness of the terrain. Water table depths were measured manually every week in the dipwells using blow tubes and noting the depth where audible bubbling occurred. Methods for calculating water table depth relative to control (relative water table depth) and changes in relative water table depth are identical to those provided for water flow variables and described in section 2.5.5.

2.5.4. Water flow (all seven blocked and two unblocked pipes)

V-notch weirs were not installed – a limitation imposed by available resources and also the physical difficulties of installing multiple weirs in rocky, mineral-based substratum, with associated issues of side- and undercutting. Water flow was therefore not calculable as discharge. Alternatively, depth or “stage” was measured using depth loggers installed directly in channels downstream of all blocking locations (see Fig. 3, Fig. 4), at positions along the channel that best fulfilled the following criteria: steep-sided channels, straight channel section immediately upstream of the chosen positon, flat rock bed, vertical rock sides or intact peat channel sides, as well as intact pipe ceiling if positioned close to upstream pipe exit.

The loggers were suspended inside plastic pipe stilling wells which were in turn firmly attached to the cross bars of bolted “Dexion” angle-iron lengths driven deep into the peat and into the underlying mineral layer for stability. Water pressure was logged automatically every 10 minutes and downloaded every fortnight. Logger pressure readings were calibrated to actual depth using fortnightly manual depth verification. The relationship between logger pressure and fortnightly manually verified depth was obtained over the entirety of each of the six-month comparison periods and used to convert each of individual 10 min logger pressure measurements to actual depth.

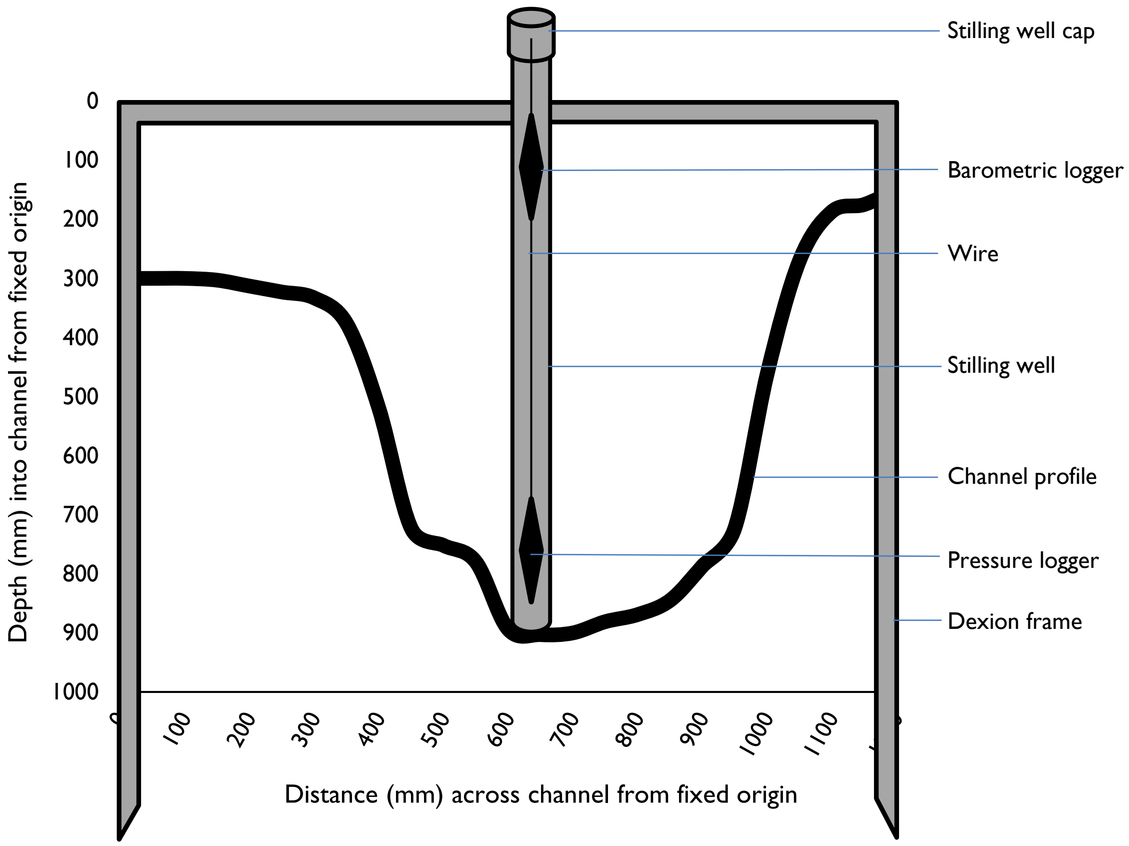


Fig. 6. Cross-sectional channel profile with stilling well and metal “Dexion” frame

2.5.5. Peak “stage” and Lag time (all seven blocked and two unblocked pipes)

Hydrograph peaks for all nine pipes were chosen for analysis if they were visibly discernible as single peaks. In reality, the rain events giving rise to these peaks were rarely single discrete events, often including intermittent showery beginnings and/or ends, or multiple events following on from previous events without time for a return to base flow in between. Two simple water flow variables were calculated;

- Peak stage, defined as the maximum depth (mm) reached during a rain event; and
- Lag time, defined as the duration (mins) between the end of a rain event and the time of the maximum peak stage.

Calculating change in relative Peak stage/Lag time:

1. Individual measurements of peak stage/lag time for individual pipes (from hydrograph analysis) were recorded by date order, along with an average for the seven blocked (treatment) pipes and an average for the two unblocked (control) pipes.
2. The average value for the two unblocked control pipes was subtracted from the average for the seven blocked pipes, providing estimates of relative variables for individual blocked pipes and for all blocked pipes:

$$T - C = R$$

   T = Variable associated with the treatment pipes
   C = Variable associated with the control pipes
   R = Treatment variable relative to (corrected by) the control variable
3. These relative values were then assessed for basic descriptive statistics such as mean, median, max, min, etc within the different comparison periods.
4. Finally the median relative values were converted into trajectories of change over time, having been normalised to a common starting value of zero.

2.5.6. Measuring depth instead of flow – sources of error and mitigation

1. The assumption of consistent relationship between water depth and water flow from pre- to post-blocking periods was dependent on the cross-sectional channel profile (at the position of the depth logger) remaining constant and resistant to erosion.
2. To mitigate the effects of potential changes to the profile, the following methods were used (and more fully discussed in Annex 1, Section 1):
   a. Repeated measurements of cross-sectional dimensions (results in Annex 1)
   b. Expressing depth in blocked pipes relative to depth in the control pipes
   c. Presenting results as non-relative to the control where cross sectional channel profile of the control may have exaggerated the “relative” results (details in Annex 1, section 1)
   d. Observing and interpreting imbalances in rainfall between pre- and post- periods (see Fig. 12)
   e. Observing and interpreting imbalances in the number of hydrograph peaks between pre- and post- periods (see Fig. 19)
   f. Mitigating for various scenarios involving hidden cross-connections between control and blocked pipes affecting depth in control and blocked pipes

2.5.7. DOC concentrations (all pipes)

Water samples were collected in 30 ml sample tubes from the water flow locations every fortnight (but only if the stream was flowing). Samples were sent to laboratories at University of Manchester where dissolved organic carbon (DOC) concentration was measured directly, via UV-persulphate oxidation on a Shimadzu TOC analyser.

2.6. Design for blocking

Three types of block were designed for the trial (Fig. 7) and assigned to a blocking location as follows: the largest diameter pipes were generally reserved for blocks constructed from peat, while medium diameter pipes were reserved for stone blocks. This was a consideration prompted by the cost of air lifting stone. The smallest diameter pipes, in some rare cases not based on mineral substrate, were reserved for heather bale blocking, which were mainly installed manually, without the help of an excavator. Thus, along the (assumed) length of any individual pipe, there was a variable number of blocks and a variable combination of block types, depending on the dimensions of the pipe and the number of suitable blocking locations (see Fig. 3, Fig. 4). For the larger pipes destined for either peat or stone blocks and which required pre-excavation in preparation phase (see section 2.7, below), the depth of the pipe base below the surrounding interfluvial surface was measured to ensure that the mineral base could be reached by the excavator (see Fig. 8, photo of extended excavator arm and bucket). Full details in Annex 2.

2.7. Preparation for blocking

Blocking locations were generally at the downstream end of collapsed sections and were often obscured by rocky debris or vegetation partially blocking the entrance to the pipe tunnel. These needed mechanical excavation to clearly expose the pipe entrance and also to create a flat and clear working surface on which to install blocks (Fig. 8). Similarly, blocking locations beneath narrow vertical vent holes had to be widened and elongated by mechanical excavation (Fig. 9). In most cases the underlying mineral layer was composed of malleable clay mixed with soft rock which allowed relatively easy mechanical gouging: only in one or two cases did the presence of large boulders make this impossible. Blocking locations destined to be blocked by heather bales were not required to be excavated mechanically. Full details in Annex 2.

2.8. The block-building process

After the preparation process for the stone and peat blocking locations, stone was airlifted directly onto each of the stone blocking locations, unit by unit, and shaped by hand so that the stone pile completely occluded the pipe tunnel entrance (see Fig. 7). For peat blocks, the excavator constructed peat dams by first removing turves from a borrow pit before using consolidated wet peat to build the block adjacent to the tunnel entrance. For heather bale blocks, the bales were airlifted to the site and moved into their final position by hand. Either whole intact bales or pieces of bales were pushed into or built up at the tunnel entrance. Full details in Annex 2.

2.9. Peat profiling on the blocks

Finally, the excavator used wet consolidated peat from the borrow pit to extend and cover the constructed blocks with a layer of peat that ramped down in an upstream direction from the constructed block (see Fig. 7). This layer helped provide additional surface area in contact with the mineral substratum and thus prevent undercutting. It also provided an escape route for stock falling into storage ponds forming behind the blocks. Retained turves were used to cover and stabilise any bare peat surfaces. Full details in Annex 2.

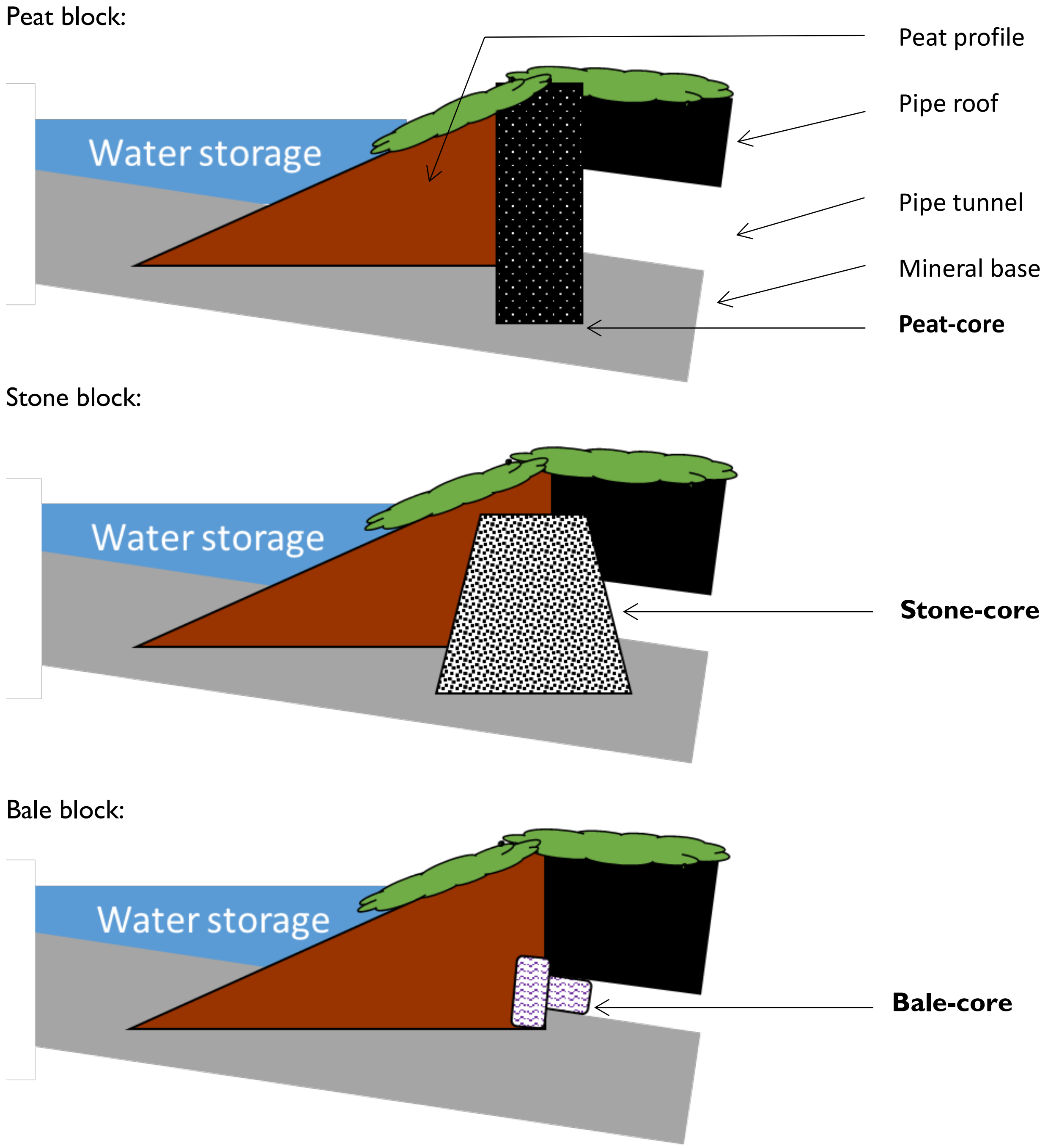


Fig. 7. The three types of peat pipe blocks used in the trial

Note: Three interchangeable core materials were used in the same basic design. Turves (green) that had been first removed were used to finish off the blocks, and stabilise bare peat surfaces.

Fig. 8. Photographs showing preparation for blocking within a collapsed pipe "gully" section

Pipe tunnel at P2.1 obscured (left), being cleared of vegetation and rocky debris (middle) and the location prepared for blocking (right). Note the excavator has gouged down into the mineral layer which is composed of soft clay with some rocky material.

Fig. 9. Photographs showing preparation for blocking within a vertical "vent" hole

Pipe tunnel at P1.3 obscured by vertical vent hole (left), being excavated, enlarged, and cleared of rocky debris (middle) and the location prepared for blocking (right). Note that, as for collapsed gully sections, the excavator has gouged down into the mineral layer which is composed of soft clay with some rocky material.

Fig. 10. Photographs showing the blocking process using a stone core at P2.1

Pipe tunnel at P2.1 having had preparation and air-drop of stone (left), followed by peat profile and turf cover (right). Note that the excavator has finished the right-hand gully side by profiling it to a shallower angle, ready for natural re-vegetation.

Fig. 11. Photographs showing the blocking process using a peat core at P1.4

Pipe tunnel at P1.4 having had preparation and peat dam core installed (left), followed by peat profiling and topping with turves (middle) and full of water several months later (right).

3. Results

3.1. Rainfall in the different Pre-Post comparison periods

Rainfall amounts before and after blocking in the six-month Pre1/Post1 (winter) comparison periods were similar (927 mm and 919 mm, respectively), but they were substantially unbalanced in the six-month Pre2/Post2 (summer) periods (682 mm and 362 mm, respectively). Rainfall amounts were (consequently) also unbalanced in the 12-month PRE/POST comparison (1609 mm and 1281 mm respectively, Fig. 12). This had a significant effect on water storage and relative water tables associated with the blocks (see Fig. 13 and Fig. 17, respectively, below), but there was no significant effect on water table depths of the control clusters (Annex 1, section 2)

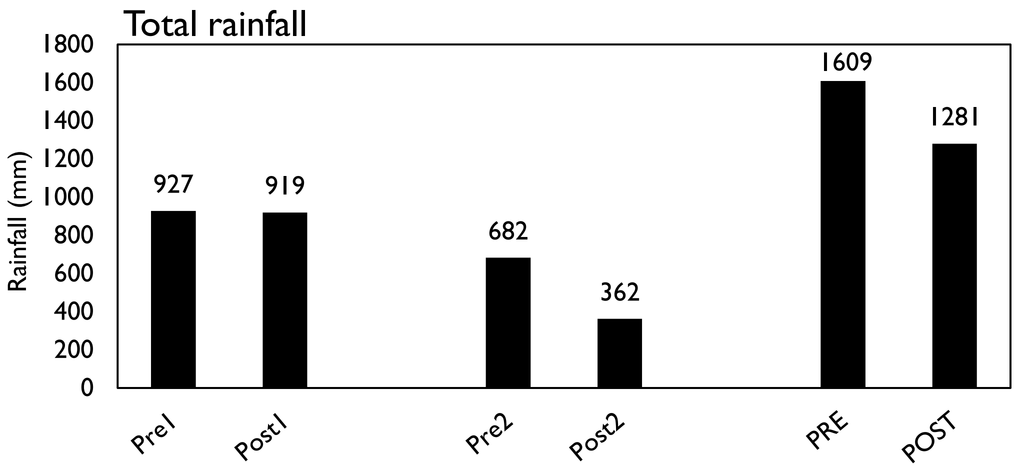


Fig. 12. Total rainfall in the different comparison periods

The six-month comparison periods were Pre1 (Sep 2020 – Feb 2021), Post1 (Sep 2021 – Feb 2022), Pre2 (Mar – Aug 2021), Post2 (Mar – Aug 2022). The 12 month comparison periods were PRE (Sep 2020 – Aug 2021), and POST (Sep 2021 – Aug 2022).

3.2. Water storage

Water storage was scored fortnightly using a scale with categories from 0 to 4, depending on the level of water in the space created just upstream of the block (see section 2.5.2). Mean water storage scores over the entire post-blocking period (POST) ranged from a minimum of 0 to maximum of 3.05 (Fig. 13 top). The ten blocks with the lowest storage scores (ranging from 0 to 0.14) included six constructed of stone and four of heather bales. The ten blocks with the highest storage scores (ranging from 2.38 to 3.05) were all constructed of peat.

Mean water storage scores associated with blocks made from peat cores were significantly higher than those made from stone or bale cores, in all three of the post–blocking comparison periods ($P < 0.01$, Fig. 13 bottom).

Mean water storage scores in Post1 were significantly higher than those in Post2, for all blocks and also for each of the individual block types ($P < 0.01$, Fig. 13 bottom).

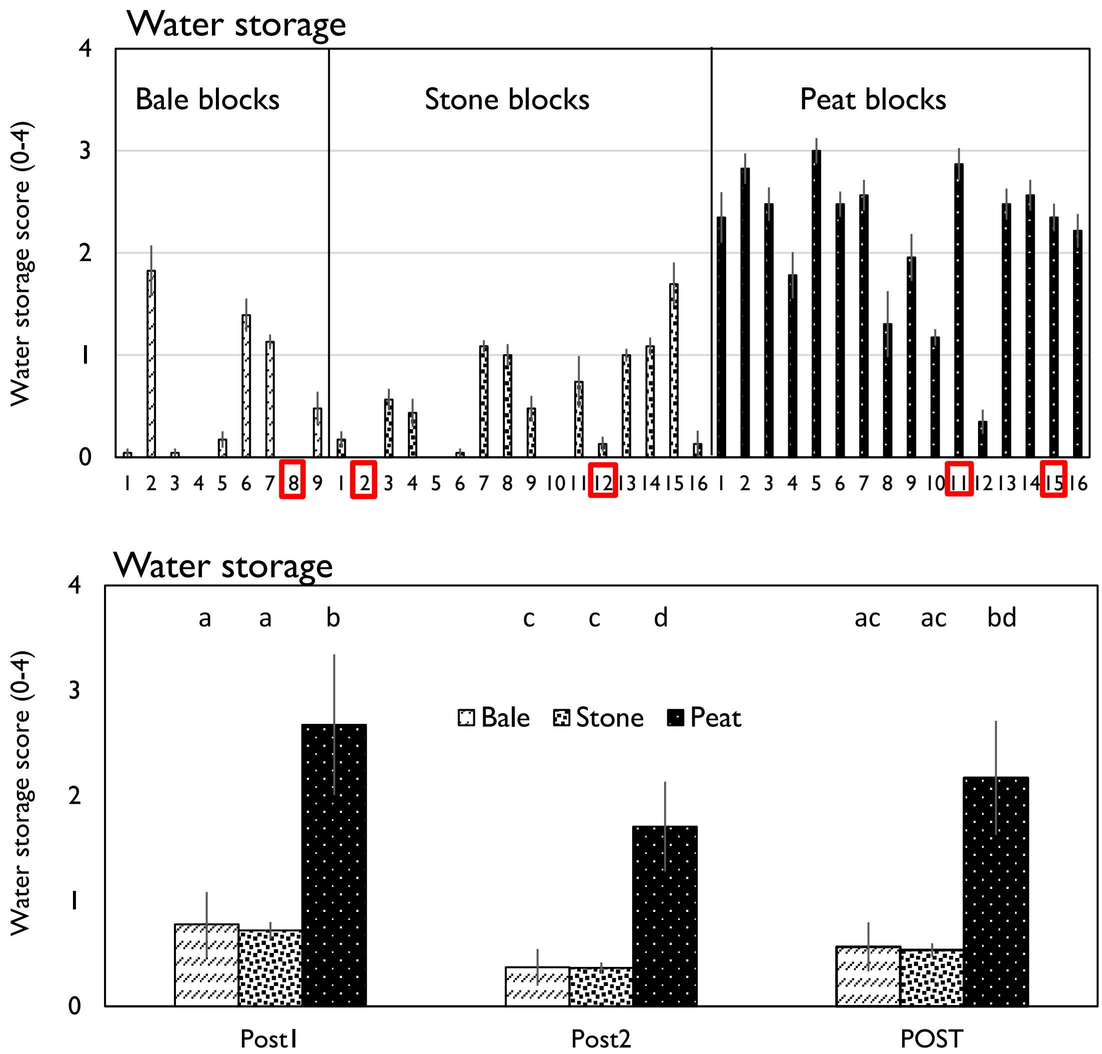


Fig. 13. Water storage scores of individual blocks (top), and as a response to different core material (bottom)

Water storage behind blocks was scored from 0 to 4 according to the proportion of the potential storage space occupied by water (see section 2.5.2); fortnightly scores, (n = 23) were averaged over the different post-treatment monitoring periods (see Fig. 12 *for details). Red borders in top graph indicate blocking locations which were also equipped with dipwell clusters for monitoring water table. Error bars are ± 1 standard error. Statistical testing for differences in bottom graph was performed in Minitab using Mann Whitney U and scores not sharing the same letter are different (P < 0.01).*

In a temporal sequence, monthly average water storage scores and monthly total rainfall appeared to decline gradually throughout the entire POST period, (Fig. 14 top). There was a significant positive linear relationship between total monthly rainfall and water storage scores for blocks with peat cores (P < 0.01), stone cores (P < 0.01) and heather bale cores (P < 0.001) (Fig. 14, middle).
Finally, there was a strong and significant and positive linear relationship between the number of peat core blocks along the length of pipes and the average water storage score of pipes (Fig. 14, bottom) The equivalent relationship for stone core blocks was also significant, but negative.

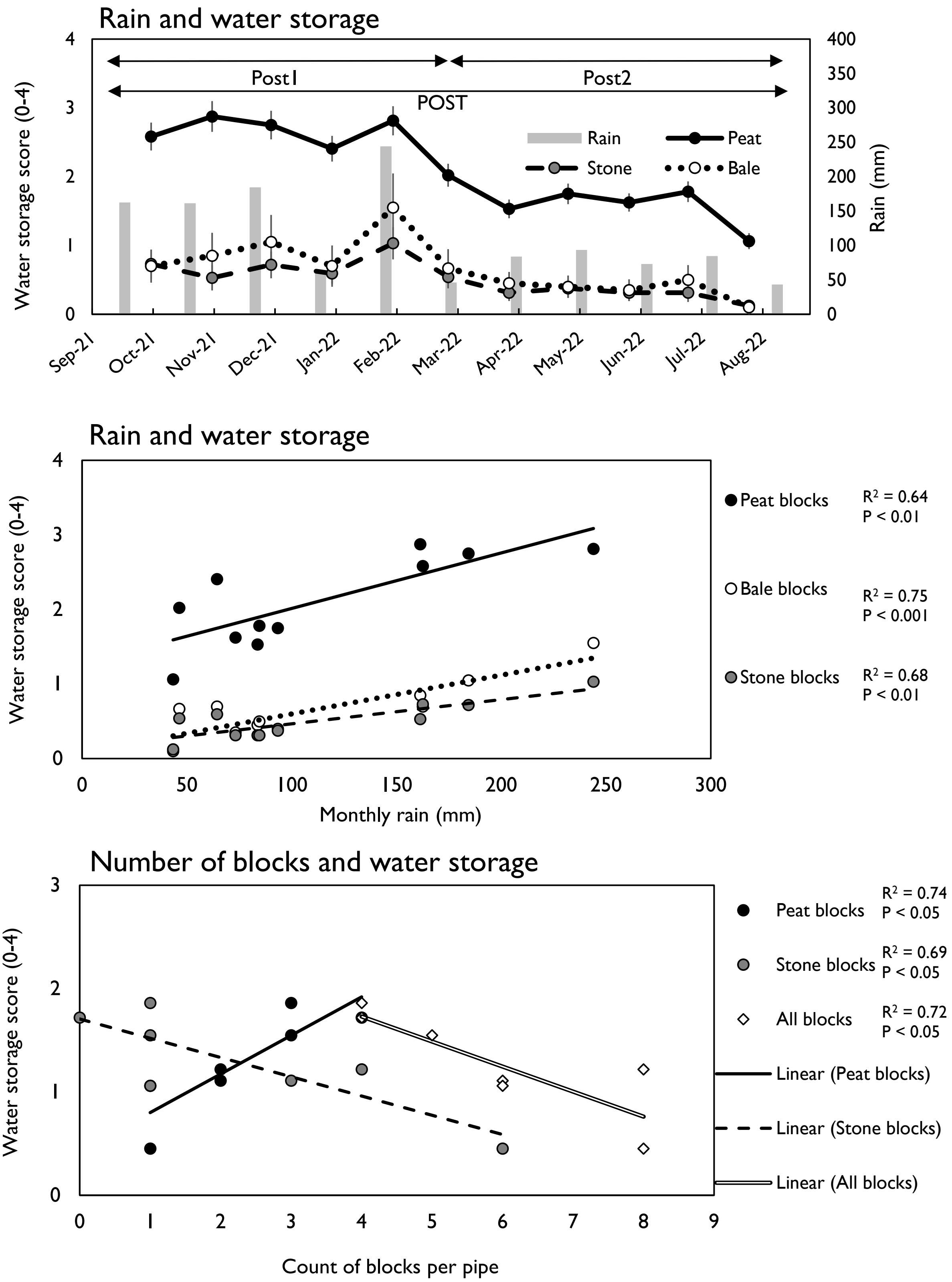


Fig. 14. Relationships between rain, the number and type of blocks and water storage

Water storage was scored fortnightly (see section 2.5.2), and here averaged over calendar months in the POST period (see Fig. 12 *for details). Rain was logged over 10 min periods and summed to give monthly total rain. Significant positive linear relationships (P < 0.01) were found between monthly total rainfall and monthly average water storage scores (middle) and between the count of peat blocks in pipes and the average water storage scores of the pipes (bottom). A negative relationship was found for all blocks and stone blocks (P < 0.05) and there was no significance for those with bale core (not shown).*

3.3. Water table depth (WTD)

3.3.1. Relationship with rain

There was a strong and significant negative linear relationship between total monthly rainfall amount and the depth to the water table in the control and the treatment dipwell clusters (i.e. with increases in rain there were decreases in depth – meaning water tables were rising to the surface, Fig. 15, top). This relationship was found both before blocking in the 12 month PRE monitoring period and also after blocking in the 12 month POST period – note that in Fig. 15 (top), the gradient of the POST treatment (blocking) relationship was steeper than the PRE treatment relationship, but unchanged for the control relationship.

3.3.2. Relationship with water storage

Water storage was measured at each of the 41 blocking locations, water table depth was measured at only five blocking locations (see x-axis of Fig. 13 top, and rationale in section 2.5.3). There was a positive linear relationship between water storage capacity behind blocks and the change in relative water table depth behind the same blocks (Fig. 15, top).

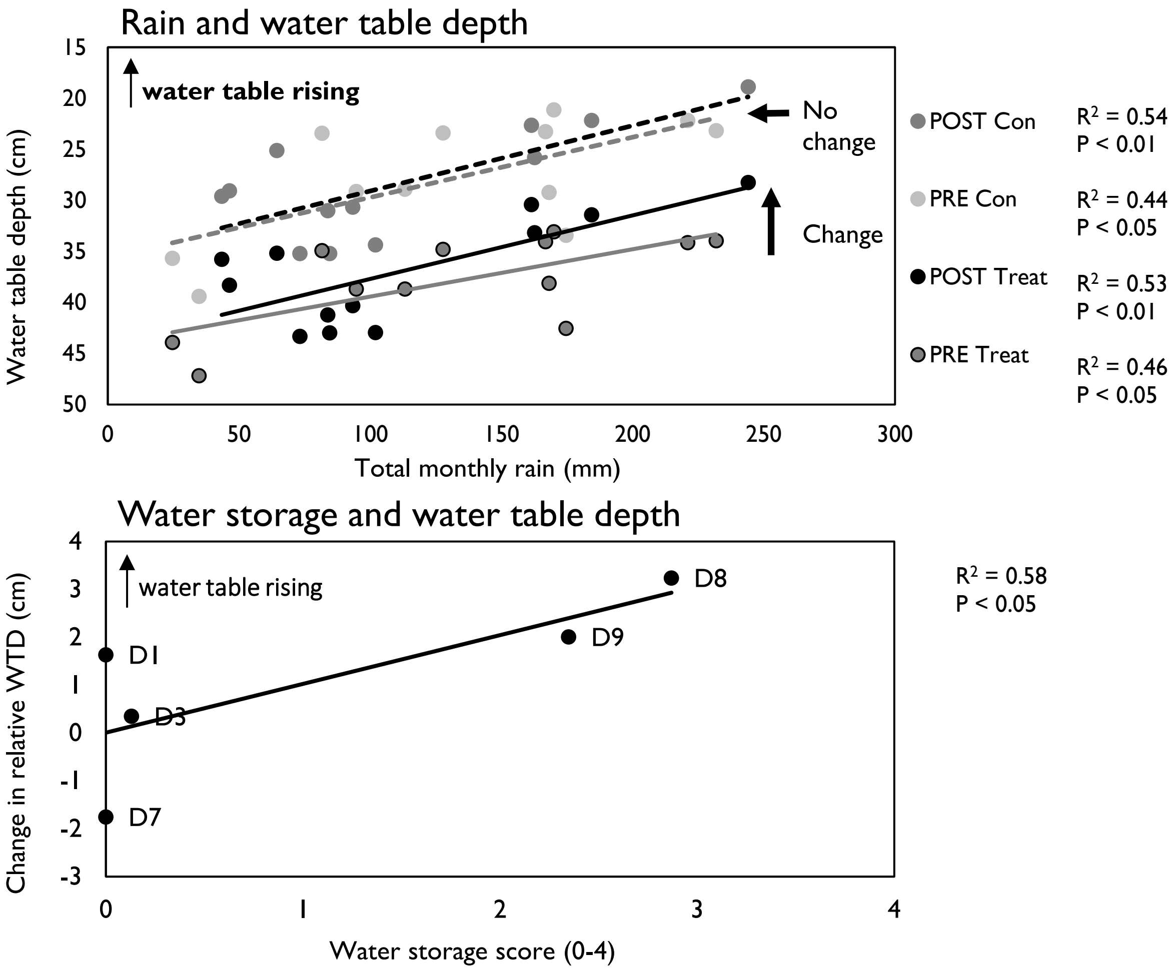


Fig. 15. Relationships between water storage scores, rainfall and water table depth

Water table depth (WTD) and rain were averaged per calendar month over the PRE and POST annual periods (n = 12, top). Change in relative water table depth and water storage were averaged for each of the five dipwell clusters (n = 5, bottom). The change in relative water table depths was derived from the PRE-POST comparison (see Fig. 12 *for details of PRE/POST monitoring periods). Significant linear relationships (P < 0.05) were found in all cases.*

3.3.3. Variations of water table depth through time

Water table depths at the site varied widely between dipwell clusters according to the prevailing topography, and also exhibited seasonal variations with summer maxima and winter minima (Fig. 16). As an example, the water table of one of the two control clusters (D4) was closest to the surface with a mean depth of 18 cm, while the other control cluster (D5) had a mean depth of 39 cm, and that of the D7 cluster was furthest from the surface at 58 cm.

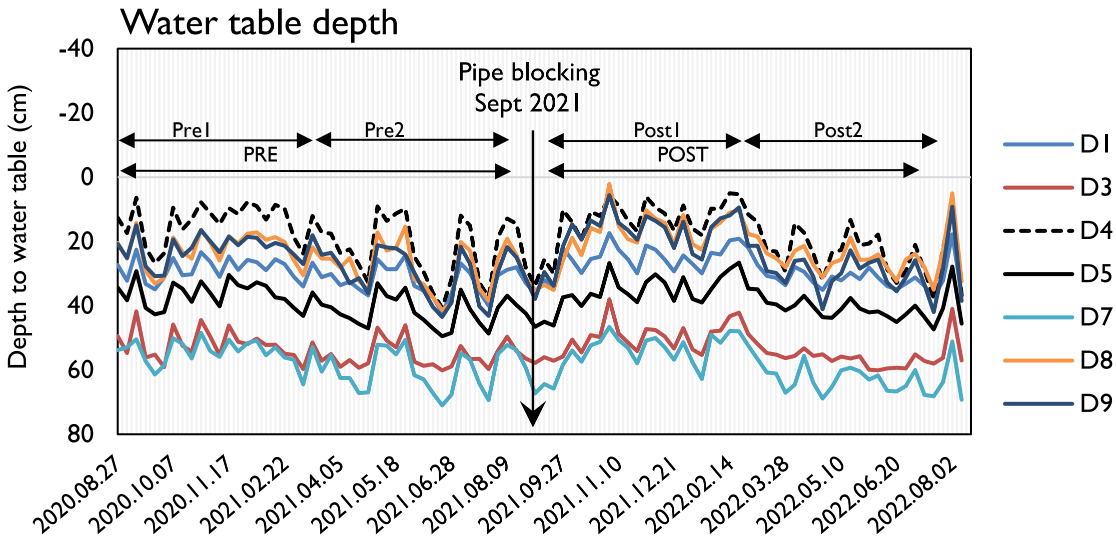


Fig. 16. Depths to water table in different dipwell clusters through time

The dipwell clusters were arranged as linear transects with 10 dipwells in each transect. Values at each date were expressed as means across all dipwells along transect (n= 10). Pre1/Pre2 and Post1/Post2 were consecutive six monthly periods pre- and post-blocking, respectively. PRE and POST were consecutive twelve monthly periods pre- and post-blocking (see Fig. 12 *for details). Dipwell clusters acting as controls (D4 and D5) were positioned on the control pipes (P4 and P5). Not all pipes had dipwell clusters. Error bars are not shown for clarity.*

3.3.4. Effect of blocking on relative water table depth

Full supporting statistics and other details in Annex 1, Section 3)

Season (comparison period)

The strongest effect on median relative water table depths occurred in the six-month Pre1-Post1 "winter" comparison (September to February) with a significant decrease in depth (raising of water table) by 2.3 cm after blocking ($P < 0.001$). There was no significant change in the six-month Pre2-Post2 "summer" comparison (March to August, Fig. 17, top, and Annex 1, Section 3, Fig. 3). Combining these results annual median water tables were raised by 1.1 cm in the 12 month PRE-POST comparison ($P < 0.01$).

Block type

Blocks constructed from peat showed the greatest effect on median relative water table depths, significantly decreasing the depth by 2.5 cm after blocking ($P < 0.001$) – blocks made from stone decreased the depth by 1.3 cm (marginal effect of blocking at $P < 0.1$), while the single block made from heather bale material caused a significant *increase* in water table depth after blocking (water tables falling away from the surface by 1.7 cm, $P < 0.01$, Fig. 17, middle, but see section 4.2 below, and also Annex 1, section 1.3)

Distance from block

Over all block types and over the 12 month PRE-POST comparison periods, the greatest change to median relative water tables occurred at 2 and 3 m distance from the blocking location, with water table rising by 2 cm and 1.9 cm, respectively ($P < 0.001$ and 0.01, respectively, Fig. 17, bottom).

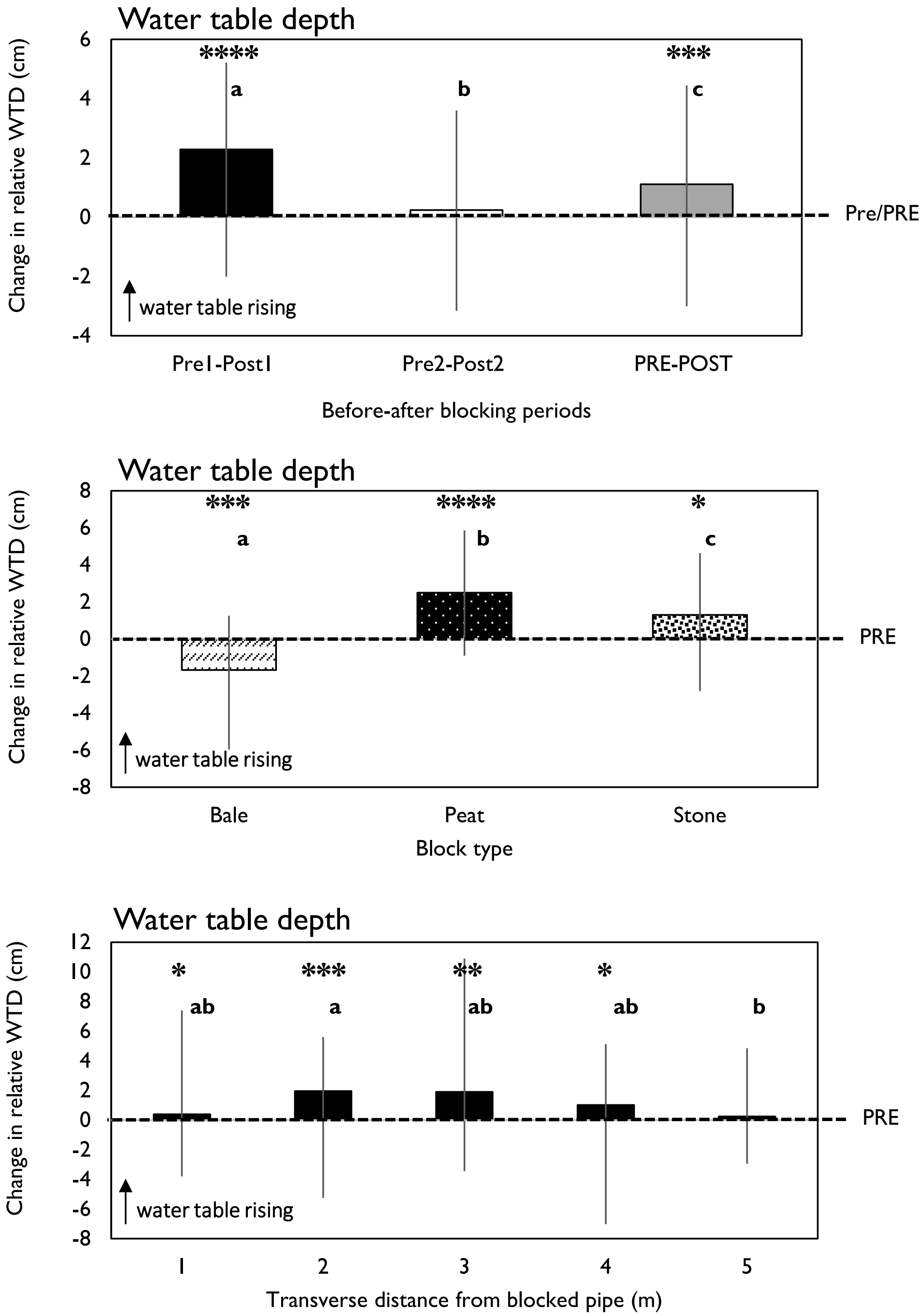


Fig. 17. Effect of season (top), block type (middle) and distance from block (bottom) on change in relative water table after blocking.

*The line marking zero change is the median relative water table depth in the period before blocking occurred, (pre1, pre2, or PRE, in each case normalised to zero). Statistical testing for post-blocking change in relative WTD was performed in Minitab using Mann Whitney U. Error bars were maximum-median (plus) and median-minimum (minus). Responses due to block types were different (P < 0.05) when not sharing the same letter, whereas asterisks marked a significant change from the pre-blocking response, as follows: * = p < 0.1; ** = p < 0.05; *** = p < 0.01; **** = p < 0.001.* See Fig. 12 *for details of pre/post monitoring periods*

Maximum effect
The maximum effect on post-blocking relative water table occurred using blocks constructed of peat, in the Pre1-Post1 comparison, and at 3 m distance from the blocking location (Fig. 18). Where all of these conditions were met the change in relative water tables was 6.9 cm ($P < 0.001$), but there were also significant changes at 1m, 2m, 4m and 5m distance, with water table rising by 2.9 cm, 3.0 cm, 4.0 cm and 2.9 cm, respectively ($P < 0.05$, $P < 0.01$, $P < 0.001$ and $P < 0.001$, respectively).

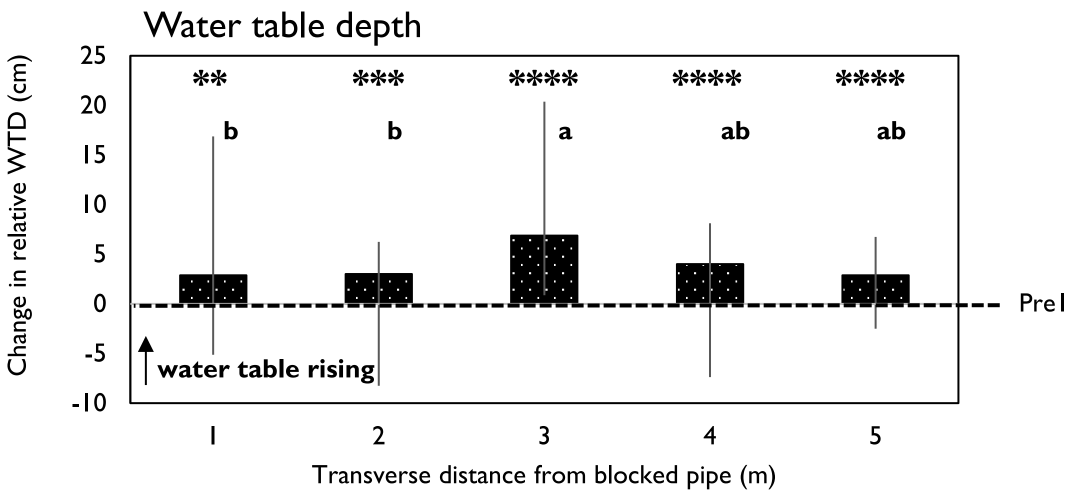


Fig. 18. Maximum effect on change in relative water table depth

Maximum change occurred using peat blocks, in the Pre1-Post1 (winter) comparison period and at 3 m distance from the block. Other details and symbols were provided and explained in Fig. 12 *and* Fig. 17.

3.4. Water flow

3.4.1. Count of hydrological peaks suitable for analysis
Over the different comparison periods, there were relatively large variations in the number of hydrological peaks that were deemed suitable for analysis (Fig. 19). Variation was driven by season and also by random spacing of rain events that sometimes caused multiple closely-packed rain events, often leading to complex and overlapping hydrological peaks, a feature that prevented their suitability and inclusion for hydrograph peak analysis.
The six-month "winter" Pre1 and Post1 periods, between September and February, yielded 15 and 22 suitable events respectively, while the six-month "summer" Pre2 and Post2 periods, between March and August, yielded 10 and 5 suitable events, respectively.
The period with the lowest number of peaks (Post2), occurred during the summer of 2022, during which the month of July was described as being the driest July for England since 1935 with average maximum temperatures for July sitting in the top ten for England (Met Office 2022).
The 12 month PRE-POST periods were more evenly matched in terms of counts of peaks suitable for analysis, with 25 and 27 peaks, respectively.

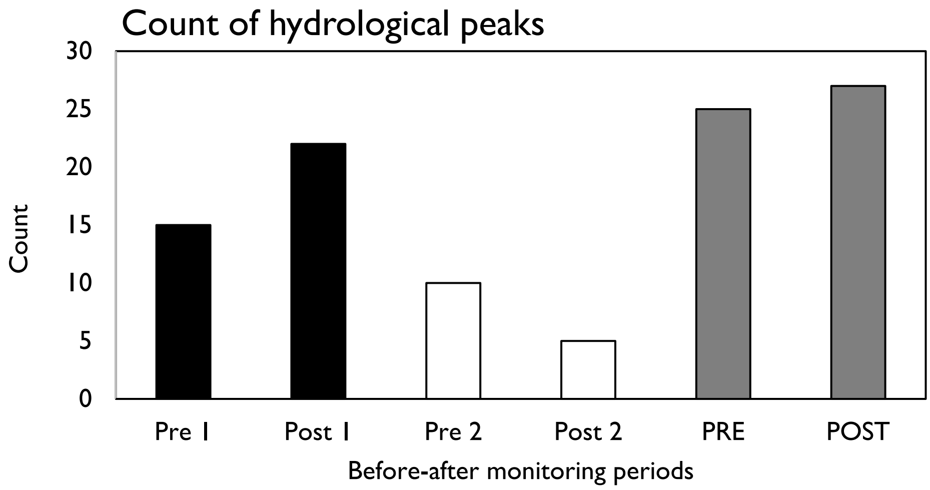


Fig. 19. Count of hydrological peaks suitable for analysis

See Fig. 12 *for details of pre/post monitoring periods*

3.4.2. Lag times

Variations though time

Lag times varied between different pipes (Fig. 20, top), and there were no obvious seasonal variations. In the 12 month period before blocking (PRE), median lag-time was 133 min in the control pipes and 125 min in the pipes destined for blocking (94% of that in the control, (details in Annex 1 section 4, Table 4). In the year after blocking (POST) that of the control had increased to 165 min while that of the blocked pipes had increased to 201 min (122% of the control. This represented an increase of median lag time in the control by 33 min and an increase of the blocked pipes by 76 min.

There was an observable increase in the amplitude of the variations of lag time in the 12 month post-blocking period (POST) relative to those in the PRE blocking period (Fig. 20, top) and especially in the Pre2 – Post2 comparison periods, where rainfall amounts were found to be substantially reduced in the Post2 period (see Fig. 12). When summarised as treatment and control lag times (Fig. 20, middle), there was an observable increase in the treatment lag times relative to those of the control.

Effect of blocking on lag time

The change in median relative lag times between the two six-month comparison periods Pre1 and Post1, and also between the two 12 month periods PRE and POST (Fig. 20, bottom) were substantial and highly significant (+44 mins or an increase of 28 percentage points in the blocked pipes relative to the control; $p < 0.0001$ in both cases). As a result of the relatively small sample number of hydrological peaks suitable for analysis in Post 2, the rise in median relative lag times between Pre2 and Post2 although similar in magnitude (+38 mins) was not significant (see Annex 1, section 4, Table 5).

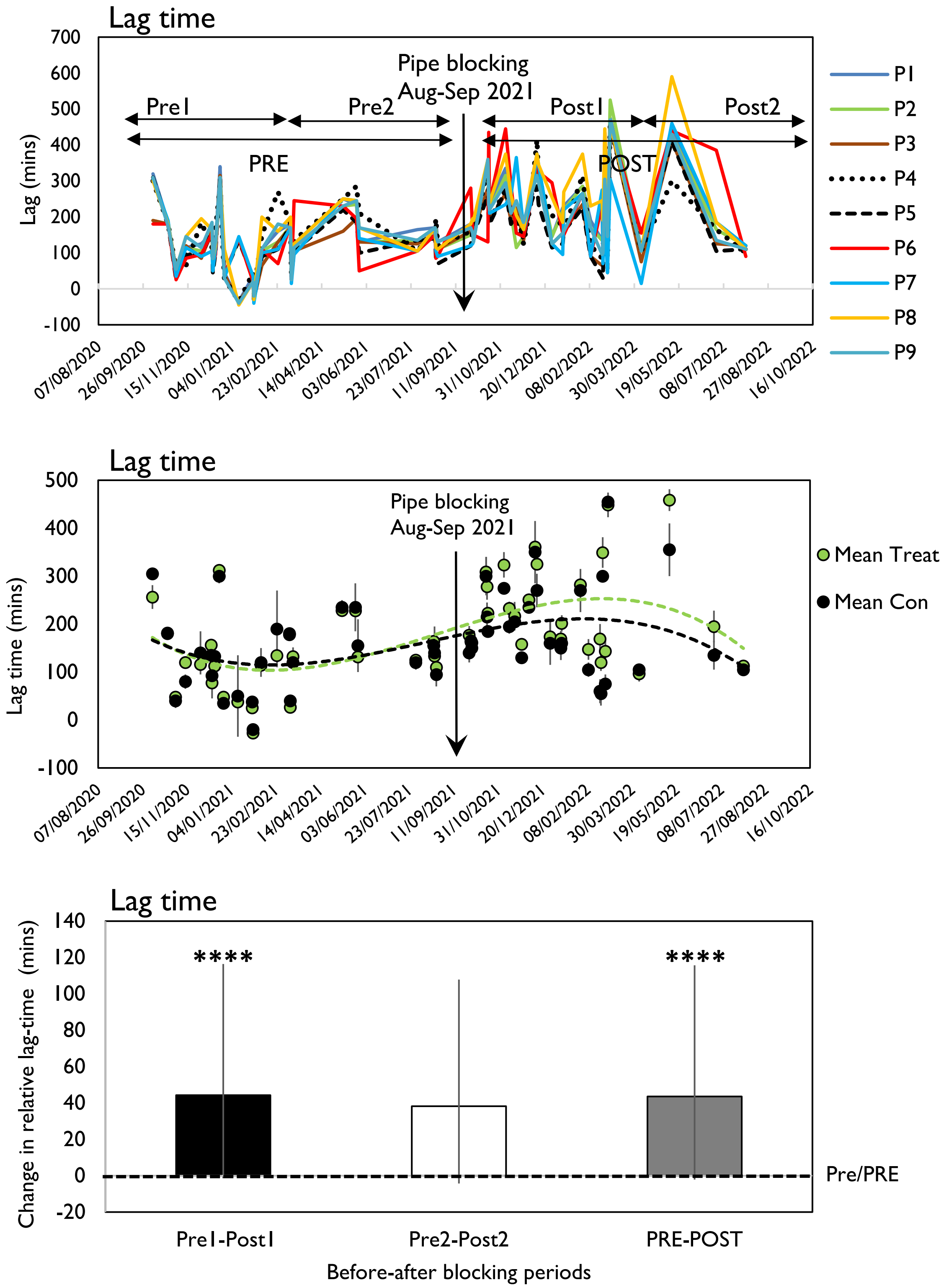


Fig. 20. Lag times – temporal sequence and effect of blocking

*Lag times were given for the nine individual pipes (top). These values were averaged across the control pipes (P4 and P5) and across the treatment pipes (P1-P3 and P6-P9 (middle)), with error bars ± 1 standard error. The line marking zero change (bottom) was the normalised median relative lag time in the period before blocking occurred, (pre1, pre2, or PRE), and error bars were maximum-median (plus) and median-minimum (minus). Statistical testing of medians between equivalent periods before and after blocking was performed in Minitab using Mann Whitney U. Probabilities were denoted by asterisks: * (P < 0.1), ** (P< 0.05), *** (P < 0.01), **** (P < 0.001). There were no differences in the extent of the change between the different comparison periods. See* Fig. 12 *for details of pre/post monitoring periods.*

Effect of blocking on lag time in individual pipes

For individual pipes, increases in lag times after blocking (PRE-POST) were found to be mostly significant (at $P < 0.05$), with the exception of P7 (Fig. 21).

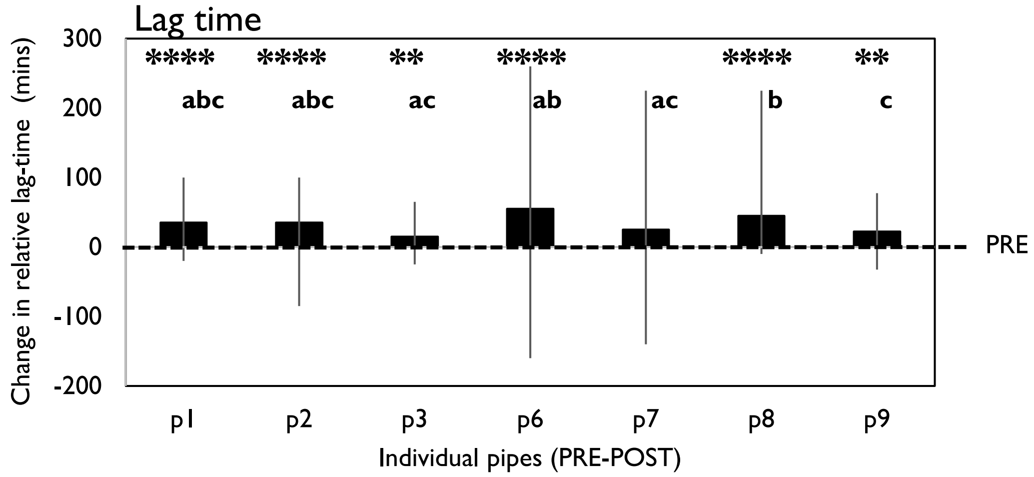


Fig. 21. Lag-time – effect of blocking in individual pipes

The line marking zero change was the normalised median relative lag time in the period before blocking occurred (PRE, see Fig. 12 *for details). Error bars were maximum-median (plus) and median-minimum (minus). Statistical testing of differences was performed in Minitab using Mann Whitney U. Responses due to individual pipes were different (P < 0.05) when not sharing the same letter, whereas asterisks marked a significant change from the pre-blocking response, as follows: * = p < 0.1; ** = p < 0.05; *** = p < 0.01; **** = p < 0.001.*

Increases in lag time for P6 and P8 were relatively high (Fig. 21); a situation that was also consistently found in each of the six-month comparison periods. Both of these pipes were treated with a relatively high number of peat blocks which led to a relatively high water storage score after blocking (see Fig. 14, top). However, although the strongest relationship between a number of different pipe characteristics and change in lag times (Annex 1, section 4, Table 6) did indeed concern the number of peat blocks (Fig. 22), the relationship was not significant ($R^2 = 0.34$, $P = 0.17$).

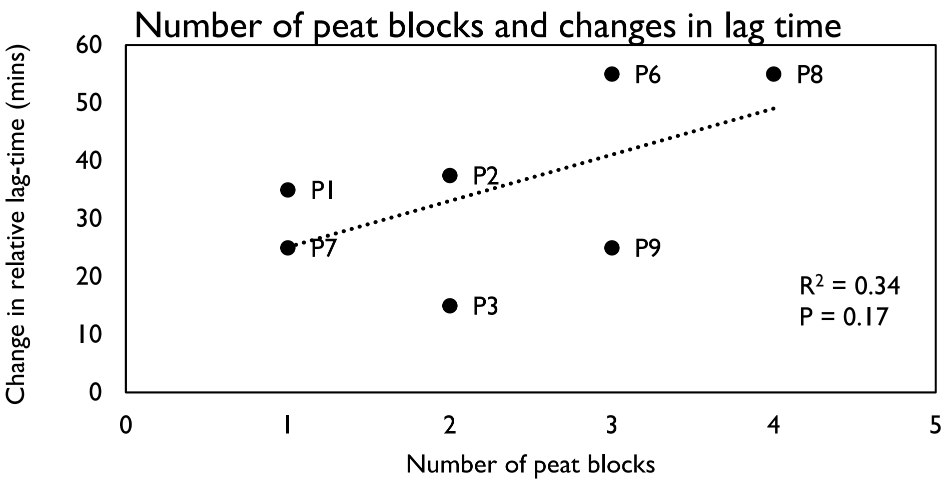


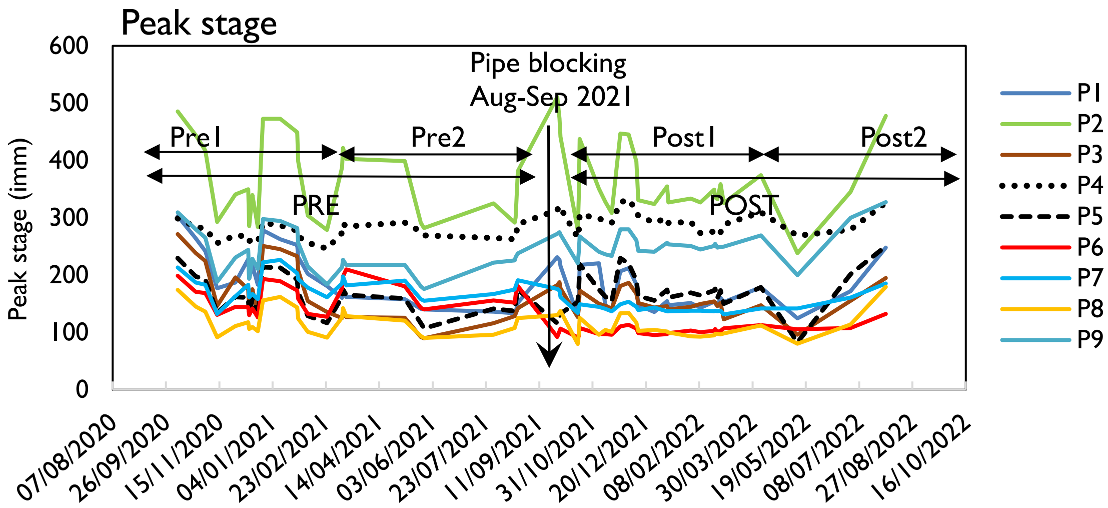
Fig. 22. Correlation between the number of peat blocks and change of lag time

Note: Changes in relative lag-time were shown for the Pre1-Post1 comparison (see Fig. 12 *for details). R^2 = Coefficient of regression in fitted line plot (Statistical testing of differences was performed in Minitab using Mann Whitney U).*

3.4.3. Peak stage

Variations though time

Peak stage varied between different pipes (Fig. 23, top), and there were no obvious seasonal variations. When summarised as treatment and control lag times (Fig. 22, bottom), there was an observable decrease in the treatment peak stage relative to those of the control.



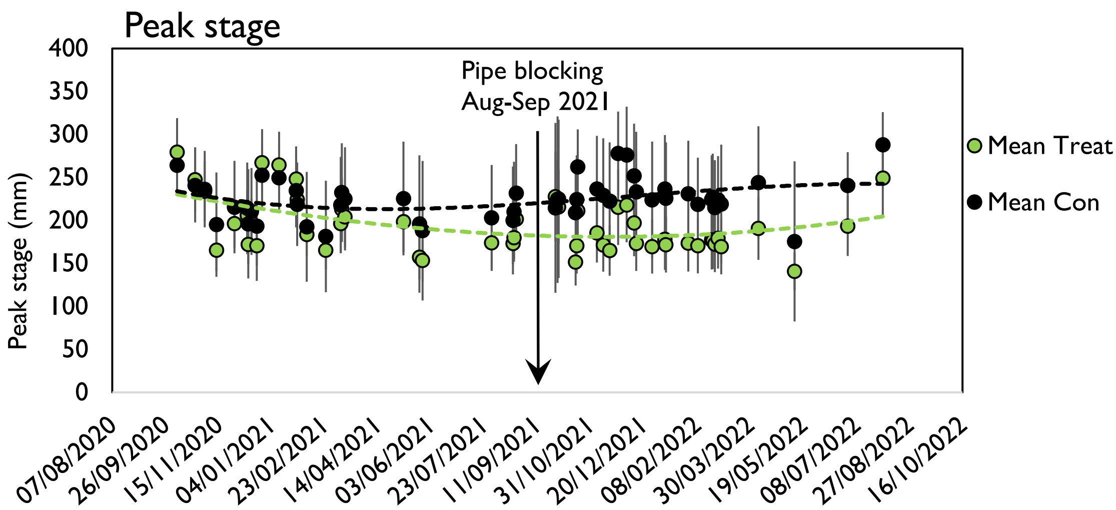


Fig. 23. Peak stage through time

Details and symbols as for Fig. 20 *(top and middle)*

Effect of blocking on peak stage

In the 12 month period before blocking (PRE), median peak stage was 216 mm in the control pipes and 197 mm in the pipes destined for blocking (91% of that in the control, details in Annex 1 section 5, Table 7). In the year after blocking (POST) those of the control had increased to 226 mm while those of the blocked pipes had decreased to 177 mm (79% of that in the control). This represented an increase of median peak stage in the control by 10 mm and a decrease of that in the blocked pipes by 20 mm.

The resulting overall decrease in peak stage between the 12 month comparison periods PRE and POST, was 32 mm or a decrease of 13 percentage points ($P < 0.001$). The greatest decrease in peak stage occurred in the Pre1-Post1 winter comparisons (43 mm, Fig. 24, $P < 0.001$). In spite of the relatively small sample number of hydrological peaks suitable for analysis in the Post2 period, the fall in relative peak stage between Pre2 and Post2 (15 mm,

Fig. 24) was also significant (P < 0.01, and see Annex 1, Section 5, Table 8). See also note on corrections due to sources of error, Annex 1, Section 1.2.

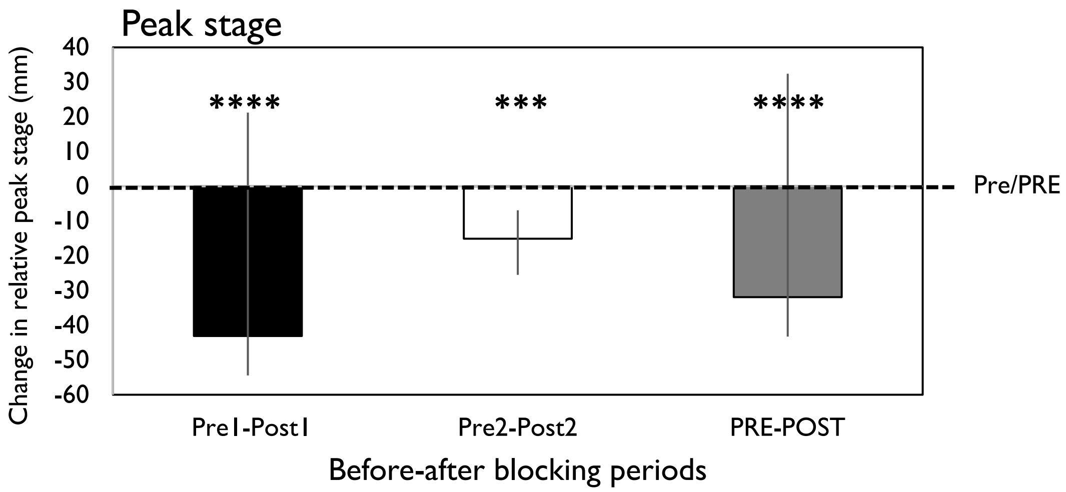


Fig. 24. Changes to relative peak stage after blocking

Details and symbols as for Fig. 20 *(bottom).*

Effect of blocking on peak stage in individual pipes

In the individual pipes, decreases in peak stage after blocking were also found to be highly significant (P < 0.001) in almost all cases, and ranging in magnitude from 31mm in P8 to 67 mm in P6. Changes to peak stage after blocking were not significant for P2 (-22 mm), and P9 (negligible change).

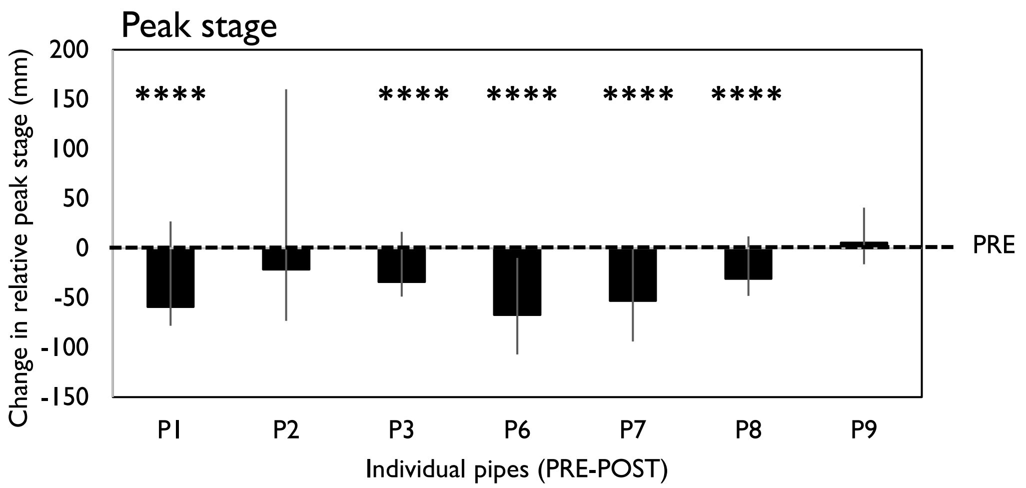


Fig. 25. Changes to relative peak stage after blocking in individual pipes

Details and symbols as for Fig. 21

There were no clear candidates to explain these observed variations in peak stage changes amongst individual pipes (Annex 1, Section 5, Table 9). Those that were available included the numbers of blocks, the numbers of different type of block, the cumulative score for water storage on all blocks associated with each pipe and the diameter of the pipe. As found for lag times, the strongest relationship was found to be with the number of peat blocks, and was confined to the Pre1-Post1 comparison, suggesting that with increasing numbers of peat blocks there was a decreasing magnitude of change in peak stage, but the relationship was relatively weak and not significant ($R^2 = 0.21$, $p = 0.3$). Again, and as mentioned above for lag times, the lack of a strong significant effect relationship for any of these listed factors suggested that peak stage may have been influenced by a multitude of factors that were not easily measurable.

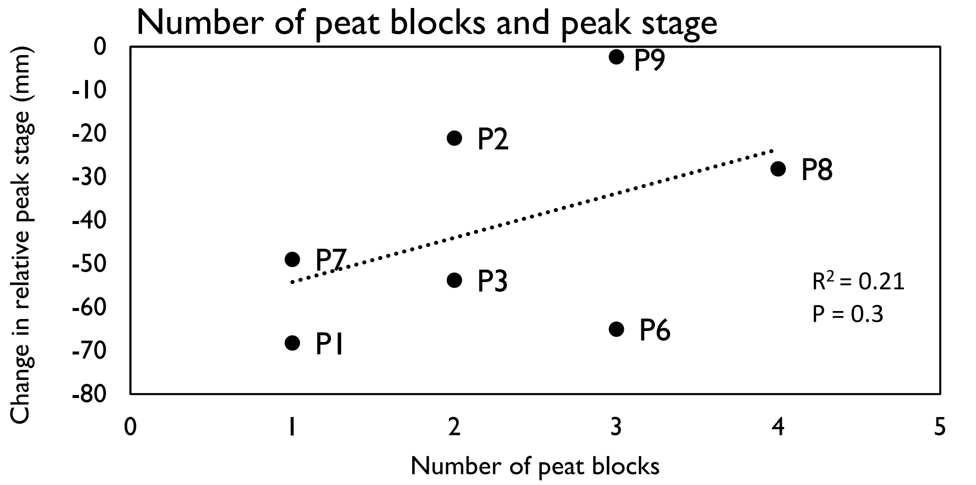


Fig. 26. The relationship between number of peat blocks and changes in peak stage

Note Changes in peak stage were shown for the Pre-Post1 comparison (see Fig. 12 *for details). R^2 = Coefficient of regression in fitted line plot.*

3.5. Dissolved organic carbon (DOC)

3.5.1. Variations though time

Concentrations of DOC in the streams flowing from the different pipes (downstream of blocking locations and at equivalent positions in the control pipes) varied between different pipes and there were also clear and pronounced seasonal variations, with summer maxima and winter minima (Fig. 27). There was no observable change in behaviour after blocking, either as DOC concentrations in individual pipes or as DOC concentrations summarised as treatment and control pipes (Fig. 27, bottom). Maximum concentrations were found immediately after the blocking process in the blocked pipes, and in the late summer/autumn of 2021. Most of the ensuing samples had concentrations that conformed to expectations. Mean concentrations in the year before blocking (PRE) were approximately 35 mg l-1, ranging from a minimum of 21 to maximum of 52 mg l-1 (see Annex 1, Section 6, Table 10).

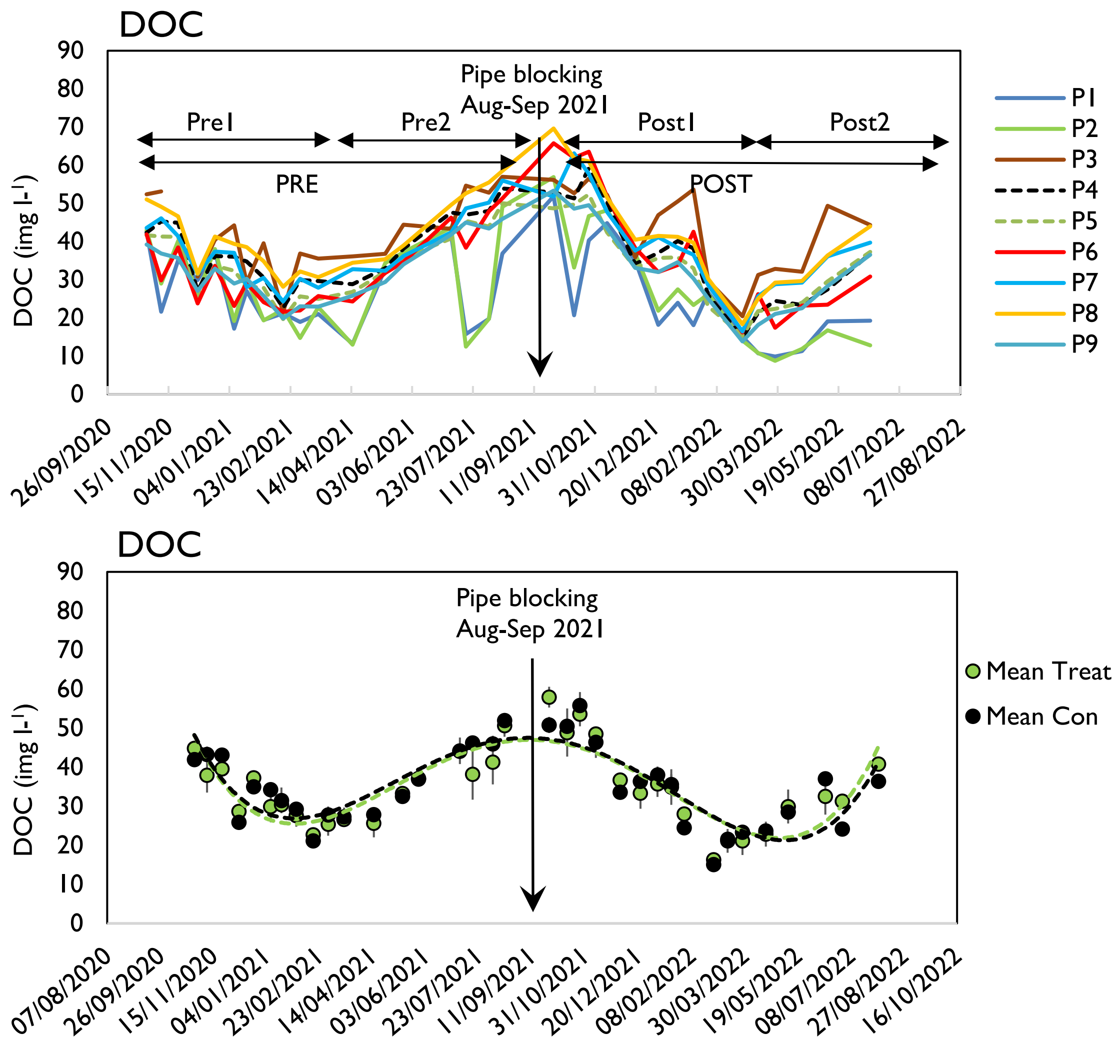


Fig. 27. Dissolved organic carbon (DOC) concentrations through time

Details and symbols as for Fig. 20 *(top and middle)*

3.5.2. Effect of blocking on DOC concentration

There were negligible and non-significant increases in overall relative median DOC concentrations (relative to the control) after blocking in both the six-month Post1 period (+1.4 mg l^{-1}) and the six-month Post2 period (0.9 mg l^{-1}), leading to a similar negligible and non-significant increase (0.75 mg l^{-1}) in the 12-month POST period after blocking (Fig. 28). (Annex 1, Section 6, Table 11).

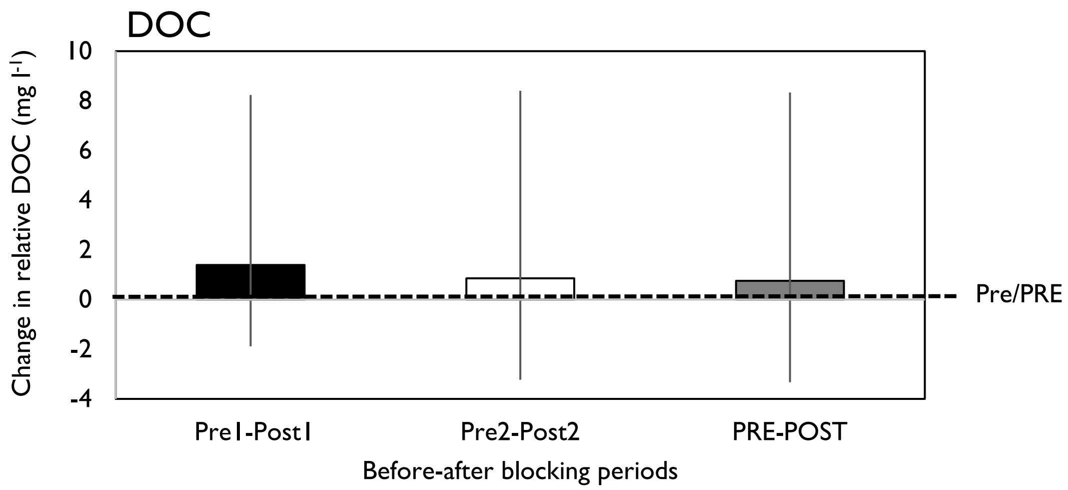


Fig. 28. Changes in relative DOC concentration after blocking

Details and symbols as for Fig. 20 *(bottom)*

3.5.3. Effect of blocking on DOC concentration in individual pipes

Amongst individual pipes, there were both increases and decreases in concentration (Fig. 29). The concentration of DOC increased significantly in P6 (+6.9 mg l-1), P7 (+1.7 mg l-1) and P9 (+1.6 mg l-1). Changes to DOC concentration after blocking were not significant for P1, P2, P3, or P8.

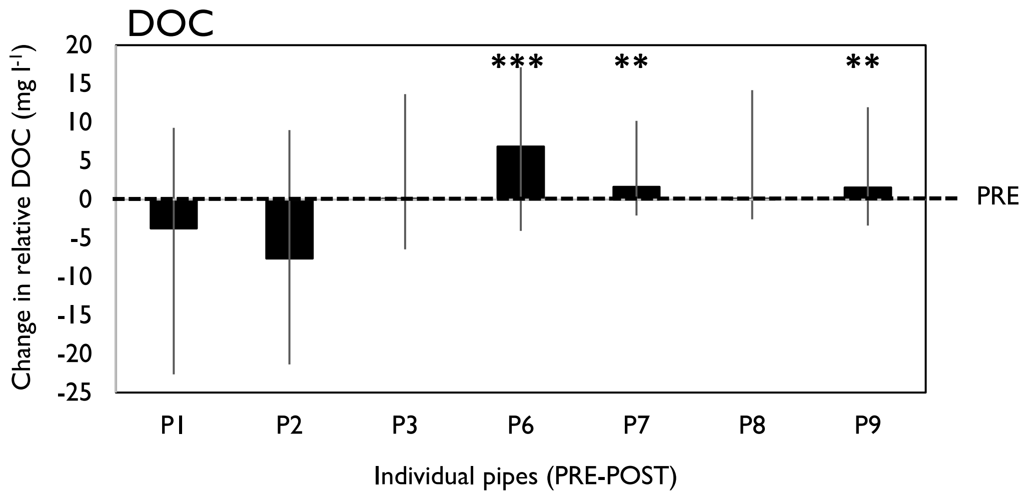


Fig. 29. Changes to relative DOC concentration after blocking in individual pipes

Details and symbols as for Fig. 21

There was a significant negative correlation between the total number of blocks along the length of a pipe and the change in relative median DOC concentration after blocking, such that with increasing numbers of blocks above six blocks, there were decreasing DOC concentrations – and with decreasing numbers of blocks below six blocks, there were increasing DOC concentrations (Fig. 30, top and Annex 1, Section 6, Table 12)

There was a semi-significant positive correlation between the average water storage score of a pipe and the change in relative median DOC concentration after blocking, such that with increasing water storage score above 1.5, there were increasing DOC concentrations

– and with decreasing water storage scores below 1.5 there were decreasing DOC concentrations (Fig. 30, bottom).

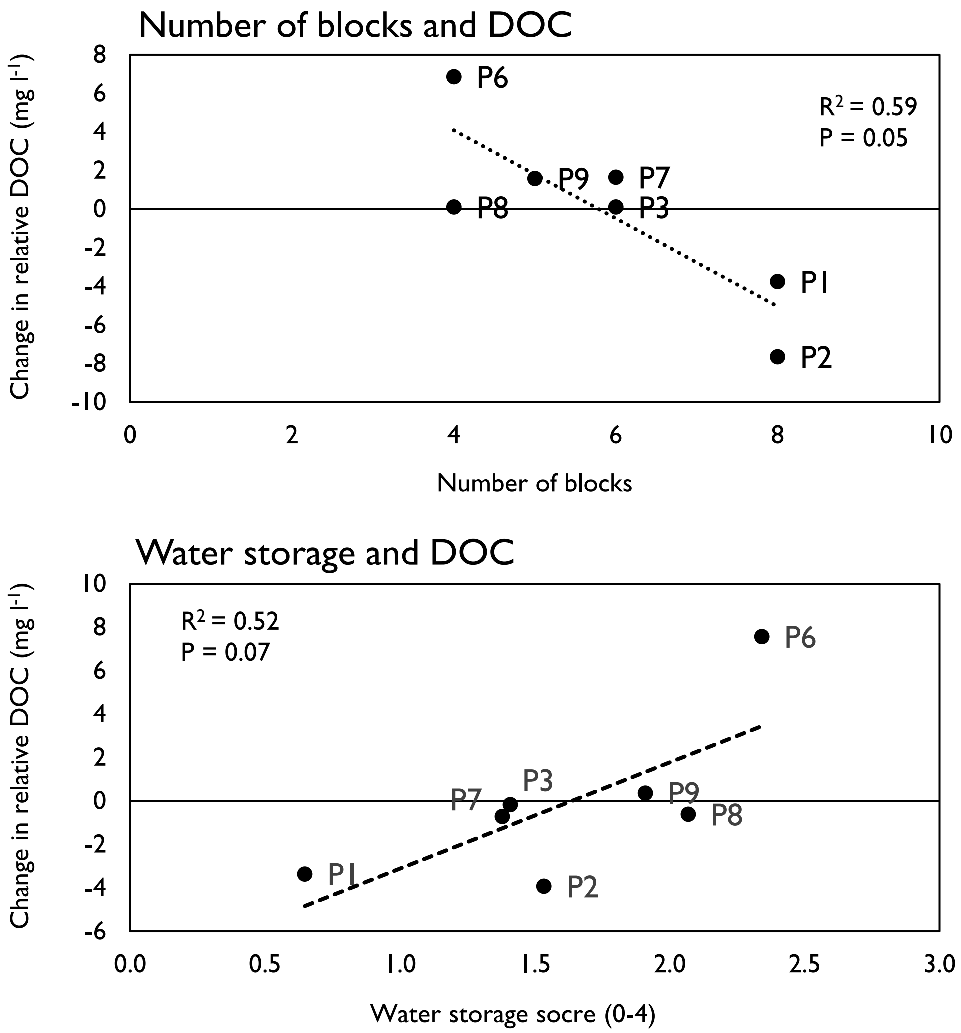


Fig. 30. The relationship between pipe blocking characteristics (top: number of blocks, bottom: water storage score) and changes in DOC concentrations after blocking

Note that changes in DOC concentration were shown for the Pre1-Post1 comparison (see Fig. 12 *for details). R^2 = Coefficient of regression in fitted line plot.*

4. Discussion

Changes that occurred after blocking, unless otherwise stated, were expressed and discussed on the understanding that these changes were statistically significant, relative to the control, relative to the pre-blocking condition, and also normalised to zero for valid comparison of the amount of change between summer and winter periods, block types etc. Thus "increases in water table" actually meant "significant increases in relative water table". And similarly for lag times, peak stage and DOC concentrations. Water storage data were only available post-blocking (no blocks – no storage), so discussions on water storage scores were confined to difference between block types and between winter and summer periods. These changes were also discussed in the light of mitigation of any potential errors using the methods and checks described in the Methods section.

4.1. Water storage

Blocks constructed with peat cores were highly effective at creating open water storage pools – substantially and significantly more so than those with stone or heather bales cores. This was almost certainly a result of the greater impermeably of peat as well as the greater surface area and volume of peat in contact with the mineral base in these types of block. For blocks constructed with stone or heather bale cores there was also a drying effect on the thinner peat profiling layer that was applied, originating from the air contained within these materials. During dry spells especially, when water levels were low, drying of the peat profile would have been more pronounced when coating stone or heather bales, leading to greater permeability.

Lower rainfall amounts in the summer comparison periods had a significantly lowering effect on water storage associated with the blocks. Predictably, monthly water storage behind blocks increased linearly with the amount of monthly rainfall, indicating both the responsiveness of pipe flow to rainfall as well as the effectiveness of blocking, particularly blocks constructed from peat, in creating water storage. Consequently, water storage averaged for individual pipes increased linearly with the number of blocks along the length of pipes that were constructed with a peat core. An equivalent linear *decrease* in water storage per pipe with increasing number of blocks along its length (or with blocks constructed with a stone core) was a symptom of the progressive exclusion of peat core blocks reducing the potential for storage.

4.2. Water table

Lower rainfall amounts in the summer comparison periods had a significantly lowering effect on relative water tables associated with the blocks but there was no significant effect on water table depths of the control clusters. The results also suggested that linear increases in rainfall caused linear increases in water storage behind blocks and also caused linear increases in water table levels in both unblocked and blocked locations. However, the steeper linear relationship after blocking than before blocking (between rainfall and water tables), strongly suggested that, in the presence of blocking, increasing rainfall effected an increasingly greater rise of water table. This has positive implications for more intense rainfall events forecasted under climate change scenarios, although there appeared to be little or no benefit at lower rainfall levels.

The linear relation between water storage and rising water tables strongly suggested direct causation; greater rises in water table across the winter comparison periods than the summer, no doubt reflecting higher water storage scores driven by a combination of observed higher rainfall amounts and the lower evapotranspiration rates consistent with lower winter temperatures.

This direct causation between water storage and water table is further supported by the finding that peat blocks achieved both the highest storage scores as well as the highest rises of water table.
The lack of a positive effect of heather bale blocks on water table change was a random effect of having the dipwell cluster positioned on a heather bale block where water storage consistently scored as zero; and the negative effect on water table no doubt influenced by the preparatory phase of excavating peat and inevitably widening the gully proximal to the dipwells, leading to evaporative drying and falling water table levels. In contrast, water storage scores, which were available for all 41 blocks, showed that bale blocks behaved similarly to stone blocks in creating water retaining pools – a finding also observed by colleagues in the field (K. Thorpe, personal communication, Dec 2022).
Perhaps more surprisingly was the finding that rises in water table were greatest at a distance of 2–3 m distance away from the gully edge of the blocking location, rather than immediately alongside. As discussed above, this can be explained by preparatory excavation of the blocking location causing a widening of the gully and subjecting this part of the peat layer to increased evaporative losses, consistent with gully edge draw-down effects (of water table) reported by Allott et al (2009). At a distance of 2–3 metres, water tables were more protected from such edge draw-down effects during dry periods while also being close enough to benefit from water table rises due to water storage during wetter periods.
A maximal water table rise of almost 7 cm in the first year after blocking with peat core blocks, in winter and at a distance of 2–3 m., compares with rises of 0.7 cm yr^{-1} over a period of 17 years following a wide range of restoration techniques on previously bare peat sites and mainly involving re-vegetation and gully blocking (Allott et al., 2022)

4.3. Water flow (lag times and peak stage)

Lag-times were substantially increased after blocking – for both the six-month winter comparisons and also for the twelve-month annual comparison – by approx. 40 min (median lag times relative to control, or an increase of 28 percentage points). This compared closely with a step-change increase of 20 min and 50 min in the year following re-vegetation and revegetation + blocking, respectively, of bare peat sites (Allott et al., 2022) and more recently (and five years later than above) an annual increase of about 20 min yr^{-1} over 5 years in the latter treatment (revegetation + blocking – but with additional abundant *Sphagnum* growth in flow pathways (Allott et al., 2022)), both found for lag times of peak flows leaving mini-catchments of approximately 1 ha and equipped with v-notch weirs.
Peak stage was substantially decreased after blocking – for both the six-month winter comparisons and also for the twelve-month annual comparison – in the latter case by 13 percentage points (median peak stage in the treatment pipes as a percentage of those in the control pipes. This cannot be compared directly with the peak *discharge* reductions of 45 percentage points reported in Allott et al (2022), further complications no doubt reflecting the complexity of the relationship between depth and flow in the present study.
For both lag time and peak stage of individual pipes, the number of peat core blocks was the strongest controlling variable , but the overall lack of any significant relationship out of several measured variables (Annex 1, Tables 6 and 9) suggested that, as for lag times, peak stage also varied with a multitude of factors.

4.4. Dissolved Organic Carbon

Mean concentrations of DOC in the year before blocking (approximately 35 mg l^{-1}, ranging from a minimum of 21 to maximum of 52 mg l^{-1}) conformed reasonably well to those found in shallow gully-edge pipe water by Regensburg et al (2021b), with 28, 8 and 69 mg l^{-1} as mean, minimum and maximum concentrations, respectively, on a nearby and similarly degraded site on the Peak District's Bleaklow plateau. As discussed by Regensburg et al., these concentrations were also similar to those reported by Holden et al. (2012) for pipe water at Cottage Hill Sike in the northern Pennines. As found by Regensburg et al (2021b), and despite the considerable disturbance involved in the installation of the blocks in the present study, there was no change in concentrations after blocking.

However the results showed an increasing number of blocks was associated with a growing ***negative*** change in post-blocking DOC concentration and, vice versa – a decreasing numbers of blocks was associated with a growing positive change in DOC concentrations. Along with this the results showed that with increasing post-blocking water storage score there was a tendency towards a growing ***positive*** change in post-blocking DOC concentrations, and, as above, the opposite effect for decreasing post-blocking water storage scores.

This appeared contradictory, mainly because we might associate more blocks with more water storage, so that the effect of increasing numbers of blocks and increasing water storage should have similar effects on DOC – but they appear to have opposite effects. However, our observations showed that with increasing ***total*** numbers of blocks, water storage actually declined, almost certainly due to progressively fewer peat blocks (peat blocks being the main block type associated with storage). Thus both increasing numbers of peat blocks (fewer total blocks) and increasing water storage were both associated with increasing DOC concentration. A plausible explanation for this might involve water overflowing peat blocks and along the surface of both vegetated and bare peat before re-joining stream and pipe flow and on to the sampling points downstream. Indeed Clark et al. (2008) found strong correlations in DOC concentrations between peat-surface (between 1 and 5 cm deep) and stream water.

5. Conclusions

The design and installation of the trialled blocks, using maximised surface-area contact with a pre-excavated and "cleaned" mineral surface, created stable structures (at least over the first year of monitoring) and water storage pools which were positively associated with rising water tables. Both water storage creation and rising water tables were most substantial and significant using blocks constructed with a peat core, over which a peat profile layer was used to increase surface area contact. There were also positive effects on water storage associated with blocks constructed from stone cores and heather bale cores, over which a peat profile layer was also added. The blocks were also effective at increasing peak flow lag times and reducing peak flow depth, and stream concentrations of DOC were not affected.
It was concluded that the blocks, and especially those constructed from peat cores, were highly effective at benefitting many of the key functional attributes of blanket bogs, including the creation of water storage pools, raising of water tables and reducing flood risk.

6. Acknowledgements

Thanks to members of the Moors for the Future Partnership "Conservation and Land Management" team for their time and advice on the practical concerns of blocking and using excavators on boggy terrain, notably Phil Straton, Gareth Roberts, Dewi Jackson and especially Jamie Freestone who managed the excavator works.

Thanks to members of the Moors for the Future Partnership "Science team" for their support, field visits and comments, especially Dave Chandler, Tom Spencer, Joe Margetts and latterly Steve Maynard for helping to push it over the line.

Thanks to Susannah Green of Natural England for patiently and painstakingly reconciling the contrasting demands of preserving strict adherence to Habitat Regulations while also allowing for the trialling of new techniques and the gathering of evidence.

Special thanks to the many volunteers who helped to collect field data in often challenging conditions, especially Steven Delderfield, Giles Parsons, Tom Helliwell, Sally Hunter and Sue Sharkie-Hurrell.

Finally a big thank you to Diarmuid Crehan for his supportive project management and unfailing cheer through thick and thin.

7. References

Acreman, M., &Holden, J.(2013). How wetlands affect floods. *Wetlands*, **33**(5), 773–786. https://doi.org/10.1007/s13157-013-0473-2

Allott, T., Auñón, J., Dunn, C., Evans, M., Labadz, J., Lunt, P., MacDonald, M., Nisbet, T., Owen, R., Pilkington, M, Proctor, S., Shuttleworth, E., Walker, J. (2019). Peatland Catchments and Natural Flood Management. Report to the IUCN UK Peatland Programme's Commission of Inquiry on Peatlands Update.

Allott, T.E.H., Blundell, A., Chandler, D., Evans, M.G, Margetts, J.J., Moody, C.S., Pilkington, M.G., Rees, J., Ritson, J.P, Shuttleworth, E.L, Spencer T. (2022). Chapter 1: Summary in Allott, T.E.H. et al. (2022) Monitoring the biodiversity and ecosystem service impacts of restoration of degraded blanket bog sites. Final report of the MoorLIFE 2020 project Action D2: Moors for the Future Partnership, Edale.

Allott, T.E.H., Evans, M.G., Lindsay, J.B., Agnew, C.T., Freer, J.E., Jones, A. & Parnell, M. (2009). Water Tables in Peak District Blanket Peatlands. Moors for the Future Report No 17. Available at: https://www.research.manchester.ac.uk/portal/files/38525401/FULL_TEXT.pdf Google Scholar

Bernatek-Jakiel, A., Poesen, J., (2018). Subsurface erosion by soil piping: significance and research needs. Earth-Science Reviews, 185, 1107-1128.

Bryan, R., &Yair, A. (1982). *Badland geomorphology and piping*. Geo Books. Google Scholar

Bryan, R.B., Jones, J.A.A. (1997). The significance of soil piping processes: inventory and prospect. Geomorphology, 20, 209-218.

Buckler, M., Proctor, S., Walker, J.S., Wittram, B., Straton, P. and Maskill, R. (2013). Moors for the Future Partnerships restorations methods for restoring bare peat in the South Pennines SAC: evidence-based recommendations. Moors for the Future Partnership: Edale.

Chow AT, Tanji KK, Gao S. (2003). Production of dissolved organic carbon (DOC) and trihalomethane precursor (THM) from peat soils. Water Res 37: 4475–85.

Clark, J.M., Lane, N., Chapman, P.J. and Adamson, J.K. (2008). Link between DOC in near surface peat and stream water in an upland catchment. Science of The Total Environment 404, Issues 2–3, Pages 308-315. https://doi.org/10.1016/j.scitotenv.2007.11.002

Evans, M., Stimson, A., Allott, T., Pilkington, M., Shuttleworth, E., Holland, N., Spencer, T., Walker, J. (2015). Annex 4: *Dissolved Organic Carbon concentrations*. In Pilkington M.G. *et al*. (2015) Restoration of Blanket bogs; flood risk reduction and other ecosystem benefits. Final report of the Making Space for Water project: Moors for the Future Partnership, Edale.

Gilman, K., & Newson, M. (1980). *Soil pipes and pipeflow: A hydrological study in upland Wales*. Geo Abstracts. Google Scholar

Goudarzi, S., Milledge, D. G., Holden, J., Evans, M. G., Allott, T. E. H., Shuttleworth, E. L., et al. (2021). Blanket peat restoration: Numerical study of the underlying processes delivering natural flood management benefits. *Water Resources Research*, *57*, e2020WR029209. https://doi.org/10.1029/2020WR029209

Holden, J. (2005a). Controls of soil pipe frequency in upland blanket peat. *Journal of Geophysical Research: Earth Surface, 110*, Artn F01002. doi: http://dx.doi.org/10.1029/2004fj000143

Holden, J. (2005b). Peatland hydrology and carbon release: why small-scale process matters. *Philosophical Transactions of the Royal Society. A Mathematical, Physical and Engineering Sciences, 363*(1837), 2891-2913. doi: https://doi.org/10.1098/rsta.2005.1671

Holden, J., & Burt, T. P. (2002). Piping and pipeflow in a deep peat catchment. *CATENA, 48*(3), 163-
199. doi: http://dx.doi.org/10.1016/S0341-8162(01)00189-8
Holden, J., 2004. Hydrological connectivity of soil pipes determined by ground-penetrating radar tracer detection. Earth Surface Processes and Landforms, 29, 437-442.
Holden, J., Burt, T. P., & Vilas, M. (2002). Application of ground-penetrating radar to the identification of subsurface piping in blanket peat. *Earth Surface Processes and Landforms*, **27**(3), 235– 249. https://doi.org/10.1002/esp.316
Jackson, D., Auñón, J., and Crehan, D. (2021). Environment Agency Greater Manchester Natural Flood Management Opportunity Mapping Project Report. MFFP Report
Jones, J. A. A. (1971). Soil piping and stream channel initiation. *Water Resources Research*, **7**(3), 602– 610. https://doi.org/10.1029/WR007i003p00602
Jones, J. A. A. (1982). Experimental studies of pipe hydrology. In R. B. Bryan & A. Yair (Eds.), *Badlands geomorphology and piping* (pp. 355– 370). GeoBooks.
Jones, J. A. A., & Crane, F. G. (1984). Pipeflow and pipe erosion in the Maesnant experimental catchment. In T. P. Butt & D. E. Walling (Eds.), *Catchment experiments in fluvial geomorphology* (pp. 55– 72). GeoBooks.
Jones, J. A. A., Richardson, J. M., & Jacob, H. J. (1997). Factors controlling the distribution of piping in Britain: a reconnaissance. *Geomorphology, 20*(3-4), 289-306. doi: https://doi.org/10.1016/S0169-555X(97)00030-5
Löfgren S, Andersen T, Forsius M. (2003). The color of water: climate induced water color increase in Nordic lakes and streams due to humus. Nordic Council of Ministry brochure; 2003. 12 pp The colour of water (slu.se) accessed January 2023
Met Office (2022). Website of the Met Office, accessed December 2022: Driest July in England since 1935 - Met Office
NE (2022). Designated Sites View of Dark Peak SSSI Robinson's Moss Accessed December 2022: Unit detail (naturalengland.org.uk)
Pilkington, M. (2021). Arnfield pipe blocking trial _WorksSpecification_May 2021. MFFP report
Regensburg, TH, Chapman, PJ, Pilkington, MG, Chandler, DM, Evans, MG & Holden, J., (2020). "Controls on the spatial distribution of natural pipe outlets in heavily degraded blanket peat", *Geomorphology*, vol. 367, pp. 107322. https://doi.org/10.1016/j.geomorph.2020.107322
Regensburg, TH, Chapman, PJ, Pilkington, MG, Chandler, DM, Evans, MG & Holden, J., (2021a). "Effects of pipe outlet blocking on hydrological functioning in a degraded blanket peatland", *Hydrological Processes*, vol. 35, no. 3, e14102. https://doi.org/10.1002/hyp.14102
Regensburg, TH, Holden, J, Pilkington, M, Evans, MG, Chandler, D & Chapman, PJ. (2021b). "Aquatic carbon concentrations and fluxes in a degraded blanket peatland with piping and pipe outlet blocking", *Earth Surface Processes and Landforms.* https://doi.org/10.1002/esp.5290
Rothwell, J.J., Evans, M.G., Allott, T.E.H. (2007). Lead contamination of fluvial sediments in an eroding blanket peat catchment. Applied Geochemistry, 22(2), 446-459.
Shuttleworth, E, Evans, MG, Hutchinson, S.M., Rothwell, J.J. (2014). Peatland restoration: controls on sediment production and reductions in carbon and pollutant export. Earth Processes and Landforms, 40(4), 459-472.
Shuttleworth, E, Evans, MG, Pilkington, M, Spencer, T, Walker, J, Milledge, D & Allott, TEH. (2019). "Restoration of blanket peat moorland delays stormflow from hillslopes and reduces peak discharge", *Journal of Hydrology X*, vol. 2, 100006. https://doi.org/10.1016/j.hydroa.2018.100006

Smart, R. P., Holden, J., Dinsmore, K. J., Baird, A. J., Billett, M. F., Chapman, P. J., & Grayson, R. (2013). The dynamics of natural pipe hydrological behaviour in blanket peat. *Hydrological Processes*, **27**(11), 1523– 1534. https://doi.org/10.1002/hyp.9242

Tipping, E., Rieuwerts, J., Pan, G., Ashmore, M.R., Lofts, S., Hill, M.T.R., Farago, M.E., Thornton, I. (2003). The solid–solution partitioning of heavy metals (Cu, Zn, Cd, Pb) in upland soils of England and Wales. Environmental Pollution, 125(2), 213-225.

Wilson, G. (2011). Understanding soil-pipe flow and its role in ephemeral gully erosion. *Hydrological Processes*, **25**(15), 2354– 2364. https://doi.org/10.1002/hyp.7998

Xu, X., Wilson, G. V., Zheng, F., & Tang, Q. (2020).The role of soil pipe and pipeflow in headcut migration processes in loessic soils. *Earth Surface Processes and Landforms*, **45**(8), 1749 – 1763.

Funded by the EU LIFE programme and co-financed by Severn Trent Water, Yorkshire Water and United Utilities. With advice and regulation from Natural England and the Environment Agency, and local advice from landowners.

Moors for the Future Partnership
The Moorland Centre, Edale, Hope Valley, Derbyshire, S33 7ZA
E: moors@peakdistrict.gov.uk
W: www.moorsforthefuture.org.uk