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Effects of rainfall, overland flow and their interactions on peatland interrill erosion processes

Changjia Li*, Joseph Holden and Richard Grayson

water@leeds, School of Geography, University of Leeds, Leeds, LS2 9JT, UK.

*Correspondence to: Changjia Li, School of Geography, University of Leeds, Leeds, LS2 9JT, UK. E-mail: gycl@leeds.ac.uk; changjia.li@hotmail.com

Highlights

1. Raindrop impact increased peat surface erosion rate by 47%.
2. Raindrop impact increased flow resistance which reduced overland flow velocities by 80–92%.
3. Interaction between rainfall and flow reduced erosion by 73–85% through increasing flow resistance and reducing stream power.

Abstract

Interrill erosion processes on gentle slopes are affected by mechanisms of raindrop impact, overland flow and their interaction. However, limited experimental work has been conducted to understand how important each of the mechanisms are and how they interact, in particular for peat soil. Laboratory simulation experiments were conducted on peat blocks under two slopes (2.5° and 7.5°) and three treatments : Rainfall, where rainfall with an intensity of 12 mm hr^{-1} was simulated; Inflow, where upslope overland flow at a rate of 12 mm hr^{-1} was applied; and Rainfall + Inflow which combined both Rainfall and Inflow. Overland flow, sediment loss and overland flow velocity data were collected and splash cups were used to measure the mass of sediment detached by raindrops. Raindrop impact was found to reduce overland flow by 10–13%, due to increased infiltration, and reduce erosion by 47% on average for both slope gradients. Raindrop impact also reduced flow velocity (80–92%) and increased roughness (72–78%). The interaction between rainfall and flow was found to significantly reduce sediment concentrations (73–85%). Slope gradient had only a minor effect on overland flow and sediment yield. Significantly higher flow velocities and sediment yields were observed under the Rainfall + Inflow treatment compared to the Rainfall treatment. On average, upslope inflow was found to increase erosion by 36%. These results indicate that overland flow and erosion processes on peat hillslopes are affected by upslope inflow. There was no significant relationship between interrill erosion and overland flow, whereas stream power had a strong relationship with erosion. These findings help improve our understanding of the importance of interrill erosion processes on peat.

KEYWORDS: overland flow; erosion; flow hydraulics; raindrop impact; peat

Introduction

During rainfall events, soil erosion processes mainly include mechanisms of soil detachment, sediment transport by raindrop impact and surface flow and sediment deposition. For interrill erosion, the dominant processes are detachment by raindrop impact and transport by raindrop-impacted sheet flow (Kinnell, 2005). Raindrop impact affects interrill erosion processes in two ways. First, raindrops provide the primary force to initiate soil particle detachment and the importance of raindrop impact on sediment detachment has been shown under both laboratory and field conditions (Salles et al., 2000). The effect of raindrop impact on detachment capacity is highly related to rainfall properties such as rainfall intensity, drop size, velocity and kinetic energy (Salles and Poesen, 2000), soil type (Quansah, 1981) and slope gradient that affects the impact gradient of falling drops (Singer and Blackard, 1982; Torri and Poesen, 1992). In addition, raindrop impact is important in affecting flow hydraulics and sediment transport as overland flow depths are typically shallow, in the order of a few millimetres (Beuselinck et al., 2002; Holden et al., 2008). The impact of raindrops on a thin water layer is highly related to the ratio of flow depth to raindrop diameter and an extensive body of literature has been published on the subject (see Gabet and Dunne (2003) for a concise review). However, little information is available on how raindrop impact affects overland flow hydraulics (Beuselinck et al., 2002) or the quantified contribution of raindrop impact to erosion rates (Vaezi et al., 2017). Knowledge about mechanisms of raindrop impact is helpful for improving interrill erosion models and equations and developing efficient landscape restoration strategies to prevent erosion.

For interrill erosion areas, soil detachment and sediment transport are simultaneously influenced by rainfall-driven and flow-driven erosion processes and their interaction. However, rather limited attention has been given to the importance of the interaction between rainfall- and flow-driven processes (Rouhipour et al., 2006; Asadi et al., 2007). In modelling the interrill processes, physically-based erosion models such as WEPP (Nearing et al., 1989) assume that rainfall-driven erosion is the only process occurring in interrill areas, and any interaction between rainfall and flow is ignored. One possible reason for this is that the interaction is complex and requires extensive data for parameterization and validation. However, the interaction has been found to be important in affecting interrill erosion, showing both positive and negative effects (Rouhipour et al., 2006; Asadi et al., 2007). Asadi et al. (2007) investigated the interaction between erosion processes driven by rainfall and flow, and found that the interaction was generally positive for the three different soil types studied. Rouhipour et al. (2006) found a negative interaction for a loamy sand, and a positive interaction for a silty loam on gentle slopes (< 1°) with no rills present under laboratory conditions. Tian et al. (2017) conducted field experiments on plots on a steep loess hillslope (26°), applying upslope overland flow simulation with and without rainfall impact. They found that the interaction between rainfall and flow had a negative impact on erosion under low inflow conditions, decreasing total soil loss by 20%. These studies demonstrate that the interaction between interrill erosion processes driven by rainfall and flow should not be neglected, especially on low slopes and under low energy flows.

Most soil erosion work has been conducted on mineral soils, with much less known about erosion of organic soils which hold large amounts of the world's terrestrial carbon. Peatlands, where organic-rich peat slowly accumulates (Charman, 2002), cover approximately 2.84% of the world's land area (Xu et al., 2018) and are important terrestrial carbon sinks that store one-third to half of the world's soil carbon (Yu et al., 2012). The physical and chemical characteristics of peat can be quite different to those of mineral soils (Hobbs, 1986). Of particular concern in terms of erosion are rain-fed blanket peatlands which cover 105000 km^2 of the Earth's surface (Li et al., 2017a) and can occur on sloping terrain, with slope angles as high as 15°. As such, blanket pe atlands could be more vulnerable to water erosion than other types of peatlands which may occur in landscapes with very little surface gradient. Many blanket peatlands in the Northern Hemisphere have experienced severe erosion and are under increasing erosion risk from future climate change (Li et al., 2016a; 2017a), which will lead to enhanced losses of terrestrial carbon in many regions. The main blanket peat erosion processes include sediment supply processes (e.g., freeze-thaw and desiccation), sediment transfer from hillslopes (e.g., interrill erosion, rill erosion and gully erosion), bank failures and mass movement (Evans and Warburton, 2007). Blanket peat erosion has adverse impacts on landscapes (Holden et al., 2007), reservoir sedimentation (Labadz et al., 1991), water quality (Rothwell et al., 2005) and carbon dynamics (Holden, 2005). Although peatland erosion has been studied for almost sixty years some of the processes remain poorly understood (Bower, 1960; Evans and Warburton, 2007; Li et al., 2016 a, b; 2017 a, b). The prevention of peat erosion relies on selecting appropriate conservation strategies which in turn requires a thorough understanding of the peat erosion processes.

Most previous studies examining the effect of raindrops on shallow overland flow were conducted in arid or semi-arid environments. However, little attention has been given to northern peatlands which have very different rainfall characteristics being dominated by high frequency, low intensity rainfall. Kløve (1998) used indirect evidence of the positive hysteresis in the overland flow and sediment concentration relationship to suggest that raindrop detachment tended to decrease with increasing wetting of the peat surface. However, the effectiveness of the raindrop detachment might have been overestimated based on the extremely high intensity rainfall (35-240 mm hr^{-1}) applied (Kløve, 1998). High intensity rainfall is rare in many blanket peatlands where low intensity rainfall with small drop diameter is more common. Holden and Burt (2002) applied rainfall simulation with more realistic intensities ranging from 3 to 12 mm hr^{-1} on bare peat blocks. They found that raindrop detachment is important in supplying available sediment for overland flow transport, especially in the early stage of the rainfall simulation test. These findings suggest that rainsplash is important in sediment supply. However, current understanding is underpinned by very little quantitative research which makes it difficult to understand the mechanisms of raindrop impact on flow hydraulics and erosion processes.

Overland flow and erosion processes on hillslopes are scale dependent as soil properties, hydrology and sedimentation processes vary with slope position (Kirkby, 1978; Kirkby, 1985; Cerdà, 1998). Holden and Burt (2003b) used networks of crest-stage tubes to monitor overland flow production on peatland hillslopes during storm events, and revealed the importance of spatial variation and flow accumulation in overland flow generation. Overland flow and erosion rates in downslope positions are affected by accumulated flow and sediment transported from upper slope positions. However, to date, no experimental studies have been performed to investigate the effect of accumulation of flow on erosion processes and overland flow hydraulics in peatlands.

There are three key issues to be addressed for soil erosion which also apply directly to peatland interill erosion: (1) the effects of raindrop impact on sediment detachment, overland flow hydraulics and sediment transport processes; (2) the interaction of rainfall and shallow overland flow on interrill overland flow and erosion processes; and (3) the impact of slope gradient and position on interrill erosion processes. This study aims to address all three of these issues using the specific example of organic-rich peatland soil. The specific objectives are:

(1) Assess how rainfall impact affects overland flow hydraulics and erosion processes at shallow overland flow.

(2) Examine the effects of interactions of rainfall and flow on sediment yield and flow hydraulics.

(3) Investigate the effects of slope gradient and upslope inflow on peat hillslope overland flow and erosion.

These research objectives were addressed by comparing overland flow and sediment yield processes and flow hydraulic characteristics under laboratory experiments of rainfall simulation, upslope inflow simulation and a combination of rainfall and upslope inflow simulation on peat blocks.

Materials and methods

Materials

Bare peat blocks with no vegetation cover were collected from the upper peat layer at Moor House National Nature Reserve (54°41’N, 2°23’W), a blanket peat site in the North Pennines of England. A plastic rectangular gutter (1.0 m long, 0.13 m wide and 0.08 m in depth) was pushed parallel to the peat surface into the peat, and carefully dug out to extract an undisturbed peat block. All samples were tightly sealed using plastic film to minimize peat oxidation and drying before being stored at 4 ℃ prior to laboratory analysis. Basic chemical and physical properties of the peat blocks were determined on subsampled peat (Table 1).

Peat samples were extracted from the experimental blocks and then sent to the laboratory where a Morphologi G3 instrument was used to capture two dimensional images of peat particles and to calculate various size and shape parameters (Table 1). Median particle diameter was 12.27 µm, with the particle-size distribution being shown in Figure 1.

< Table 1 is here please >

< Figure 1 is here please >

A 'drip-type' rainfall simulator was used to simulate representative precipitation. The general set-up and operating principles of the rainfall simulator are illustrated in Bowyer-Bower and Burt (1989). The rainfall simulator (Figure 2) had a height of 1.8 m with a raindrop generator plate of 1.0 m × 0.5 m consisting of 627 drop formers arranged in a 19 × 33 matrix (Holden and Burt, 2002). The drop formers were made from Tygon tubing of 2.3 mm outside diameter (OD) and 0.7 mm inside diameter (ID), through which was threaded 25 mm long, 0.6 mm OD fishing line. A 3 mm ID wire mesh hung 200 mm below the Perspex plate to break up water drops into a distribution of drop sizes closer to that of natural rainfall. Rainwater was supplied from a constant head system comprising two 25 L Mariotte bottles mounted above the Perspex drip-screen. The uniformity coefficient of rainfall (Christiansen, 1942) was determined using an array of twenty 250 mL measuring cylinders. The rainfall uniformity coefficient was 89 ± 2 % under a rainfall intensity of 12 mm hr^{-1}, which indicates a good distribution of rainfall on the plots. Rainwater was supplied with a standard electrical conductivity of 421 ± 1 µs cm^{-1} and a pH of 7.2 ± 0.1, to minimize the effects of changing water quality on the hydrological and erosion response of the peat blocks during rainfall simulation experiments. Rainfall intensity was controlled by a manometer board carefully calibrated to determine a relationship between head difference and rainfall intensity. Mean annual precipitation (records during periods of 1951–1980 and 1991–2006) at Moor House is 2012 mm (Holden and Rose, 2010), but frequency analysis of hourly rainfall intensity showed that rainfall intensities are usually low and rarely exceed an intensity of 12 mm hr^{-1} (Holden and Burt, 2002; 2003b). In this study, an intensity of 12 mm hr^{-1} was selected and calibrated by a tipping bucket rain gauge. The drop-size distribution of the simulated rainfall was measured using the flour-pellet method (Laws and Parsons, 1943), and the median raindrop size (D_{50}) of the rainfall produced by the simulator at 12 mm hr^{-1} was 1.5 mm, which aligns with natural drop-size distributions for this rainfall intensity (Holden and Burt, 2002). The mean kinetic energy was calculated as 0.069 J m^{-2} s^{-1} based on drop-size distribution data (Holden and Burt, 2002).

< Figure 2 is here please >

Experimental design

The experimental set-ups used (Figure 2) included the rainfall simulator described above, a Mariotte bottle located at the upslope plot boundary to provide upslope inflow at a constant rate and a 1.0 m long by 0.13 m wide soil flume. The peat blocks were placed inside separate flumes. The gaps between the peat blocks and the soil flumes were filled with plastic sheets, in order to prevent linkage and enable all overland flow from the peat blocks to be collected. Bower (1960) classified the gully systems in blanket peat environments into two distinct types of dissection (Type 1 and Type 2). Type 1 dissection occurs on the flatter interfluve areas where peat is usually 1.5 – 2 m in depth on slopes less than 5° (Bower, 1960). Peat gullies tend to frequently branch and intersect as an intricate dendritic network (Labadz et al., 1991). Type 2 dissection is characterized by steeper slopes (exceeding 5°), with a system of sparsely branched drainage gullies incised through the peat to bedrock and aligned nearly parallel to each other (Bower, 1960; Labadz et al., 1991). It has been suggested that the transition between Type 1 and Type 2 dissection of gully systems occurs at 5° (Bower, 1960). For our experiment, the slopes were set at 2.5° and 7.5° to represent either side of this transition while also being representative of typical blanket peatland slopes in the Pennine region of England. For each slope gradient, three treatments were conducted on the bare peat blocks (Table 2):

(1) Rainfall events to simulate rainfall-driven erosion processes: Rainfall was applied at an intensity of 12 mm hr^{-1} for a duration ranging from 60 to 120 min.

(2) Inflow events to simulate flow-driven erosion processes: Upslope inflow was applied with a constant rate of 26 mL min^{-1} determined by a volumetric method and which corresponded to 12 mm hr^{-1} rainfall on the studied plots.

(3) Rainfall + Inflow events to simulate the combined impacts of rainfall and flow on erosion processes. Both rainfall (12 mm hr^{-1}) and upslope inflow (26 mL min^{-1}) were applied simultaneously. Near-surface throughflow (typically upper 5 cm) and saturation-excess overland flow are dominant in blanket peatlands (Evans et al., 1999, Holden and Burt, 2002; 2003a). Therefore, in blanket peatlands the Rainfall + Inflow condition can simulate a downslope position affected by accumulated upslope inflow. The simulated upslope overland flow

of 26 mL min^{-1} applied to the studied plot represents a 20 m long upslope contributing area with a rainfall intensity of 12 mm hr^{-1}. Compared with the Rainfall treatment, the Rainfall + Inflow treatment represents a plot 20 m downslope from the hill top.

< Table 2 is here please >

The simulation experiments were firstly conducted with a duration of 120 minutes. Results showed that overland flow rates for those first sets of tests increased with time and then attained equilibrium. Steady-state rates of overland flow were achieved within the first 60 minutes. Suspended sediment concentrations initially increased with increasing overland flow rate, and then declined to an almost constant rate. After this point there was little variation in overland flow generation. Consequently, the duration of the subsequent experiments was shortened to 60 minutes to save time. In addition, this change in experiment duration had no impact on mean overland flow rates and sediment concentrations as once a steady-state overland flow rate was achieved the values of these parameters exhibited little variation with time.

Measurements

During each run the time of overland flow-initiation was recorded, after which each test lasted for between 60 and 120 minutes. Total surface overland flow was sampled at the plot outlet every 5 min. Overland flow volumes (mL) for each sample were determined using a measuring cylinder. Overland flow rates (mL s^{-1}) were subsequently determined by dividing these overland flow volumes by the sampling duration. Samples were then left to settle for 6 hours to allow deposition of the suspended sediment. The clear supernatant was decanted, and the remaining turbid liquid was transferred to rectangular foil container and oven-dried at 65.0 ℃ until a constant weight was achieved. The dry sediment mass (mg) was calculated, and the sediment concentration (mg mL^{-1}) was determined as the ratio of dry sediment mass (mg) to the overland flow volume (mL). The sediment yield rate (mg m^{-2} s^{-1}) was defined as the ratio of dry sediment mass (mg) per unit area (m^2) per sampling duration (s).

Surface overland flow velocities (V_s) were determined using a fluorescein dye tracing method (Smart and Laidlaw, 1977) at 5 min intervals with 3 replicates for each plot. The time required for the leading edge of a fluorescein dye tracer to travel across a marked distance was recorded at a resolution of 0.01 s.

Splash cups were used to measure the mass of detached sediment when exposed to simulated rain (12 mm hr^{-1}) (Morgan, 1981). These comprise PVC cups with a diameter of 6.5 cm and a height of 4.5 cm with a filter at the bottom, which were filled with undisturbed peat material collected from the field; the soil surface was made flush with the rim of the cup by removing excess soil. The splash cups were placed inside an open cylindrical bucket with a diameter of 25 cm and a height of 10 cm to collect the splashed peat particles. A beaker located below the bottom end of the splash cup collected water infiltrated through the paper filter. All splashed peat and water was collected by the bucket. At the end of each run the inner wall of the bucket was carefully cleaned with deionised water in order to collect all splashed peat. The buckets were placed in an oven at 65.0 ℃ until a constant weight was achieved, and the mass of oven-dried splashed peat was determined.

Data analysis

Infiltration rates were calculated by subtracting the overland flow rates measured at the plot outlet from the inflow rate. The possible influence of evaporation was minor because of the short duration of the experiments and a relatively low room temperature (7.5 ℃) for the experiments and thus was deemed negligible. The instantaneous infiltration rates (f_i) for different experimental treatments were calculated by equations (1)–(3), respectively (Pan and Shangguan, 2006):

Under Rainfall conditions: $$f_i = I\cos\theta - 10\,R_i / S\,t \quad (1)$$

Under Inflow conditions: $$f_i = F - 10\,R_i / S\,t \quad (2)$$

Under Rainfall + Inflow conditions: $$f_i = I\cos\theta + F - 10\,R_i / S\,t \quad (3)$$

where I is the rainfall intensity that equals to 12 mm hr^{-1}; θ is the slope (º); F is the upslope inflow rate that equals to 12 mm hr^{-1}; R_i is the ith overland flow volume collected (mL); S is the plot area (cm^2); t is the time interval between the collection of successive overland flow samples (min) and the factor 10 is the adjusting coefficient.

For a laminar flow profile, the vertical velocity distribution is shown by a quadratic equation, with zero at the bed and a maximum for surface velocity (V_s) (Katz et al. 1995). The profile mean velocity (V) was calculated by equation (4):

$$V = k\,V_s \quad (4)$$

where V is mean flow velocity (cm s^{-1}); V_s is surface flow velocity (cm s^{-1}); k is a coefficient which is 0.33 for shallow flows on bare peat surfaces under gentle slopes (Holden et al., 2008).

The overland flow was presumed to be uniform and the average flow depth was calculated from:

$$h = q / V = Q / (Vbt) \quad (5)$$

where h is mean flow depth for the whole plot (cm); q is the unit discharge ($cm^2\ s^{-1}$); Q is the overland flow volume during t duration (ml); b is the width of water-crossing section (cm).

The Manning's friction coefficient n is determined by (Pan and Shangguan, 2006):

$$n = (h^{2/3} \cdot J^{1/2}) / V \quad (6)$$

where J is the sine of the bed slope ($m\ m^{-1}$).

Flow shear stress τ (Pa) (Foster, 1982) and stream power Ω ($W\ m^{-2}$) (Bagnold, 1966) were calculated by:

$$\tau = \rho g h J \quad (7)$$

$$\Omega = \rho g q J \quad (8)$$

where ρ is the density of water ($kg\ m^{-3}$).

It is assumed that any sediment produced by the Rainfall experiment was the sum of the peat materials detached and transported by both the action of raindrops and flow induced processes whereas any sediment produced by the Inflow experiment resulted from flow induced processes only. The difference in the sediment collected at the exit from the flume between the Rainfall and Inflow events was assumed to be caused by raindrop impact:

$$I_{raindrop}\ (SC) = SC_{Rainfall} - SC_{Inflow} \quad (9)$$

where $I_{raindrop}$ (SC) is the raindrop impact on sediment, $SC_{Rainfall}$ and SC_{Inflow} are the average sediment concentration in Rainfall and Inflow experiments, respectively.

In terms of sediment concentration, the interaction between rainfall- and flow-driven erosion is defined as the difference between the sediment concentration resulting from the combination of rainfall and flow driven erosion (Rainfall + Inflow) and the sum of the concentrations controlled by rainfall driven erosion process (Rainfall) and flow driven erosion processes (Inflow) (Asadi et al., 2007). Thus

$$Interaction\ (SC) = SC_{Rainfall + Flow} - (SC_{Rainfall} + SC_{Inflow}) \quad (10)$$

where $SC_{Rainfall + Flow}$ is the sediment concentration in Rainfall + Flow experiment. Following Asadi et al. (2007), the Interaction (SC) > 0, = 0 and < 0 indicate a positive, zero and negative interaction of rainfall and flow driven erosion, respectively. Similarly, the effects of the interaction on other flow hydraulic parameters can be derived from equations in the same form of equations (10).

Datasets were tested for normality using the Anderson-Darling normality test and then either the Student t-test or the Mann-Whitney U-test were applied to test for a significant difference in the means or the medians of the studied response variables between two treatments. Parametric tests were used when both datasets being considered were normally distributed, and non-parametric tests were used for datasets when at least one of them was not normally distributed. Correlation analysis and stepwise regression analysis were used to find the relationship between overland flow hydraulics and sediment yield rate. Test results were considered significant at $p < 0.05$.

Results

Overland flow and infiltration

Typical overland flow and sediment concentration trends for the tests are shown in Figure 3. Overland flow rates in nineteen out of twenty-two cases under the Rainfall, Inflow and Rainfall + Inflow treatments increased with time before attaining equilibrium. Consequently, two stages were defined within a simulation test; the initial overland flow increase stage and the steady-state overland flow stage. Infiltration rates peaked early in the simulations followed by a decrease to quasi-steady state values (i.e. oscillating around a fairly stable mean value) (Figure 4).

< Figure 3 is here please >

< Figure 4 is here please >

Regardless of slope, mean overland flow rates for the Rainfall treatment with raindrop impact were significantly higher (Student t-test, $p = 0.014$) than those of the Inflow treatment without raindrop impact indicating that raindrop impact increased overland flow rate (Table 3). In comparison with the Inflow treatment, overland flow for the Rainfall treatment increased on average by 10–13% (Figure 5a).

< Table 3 is here please >

< Figure 5 is here please >

The Rainfall treatment produced the lowest mean infiltration rate at 1.68 ± 0.43 mm hr^{-1} and 1.59 ± 0.24 mm hr^{-1} under the 2.5° and 7.5° conditions , respectively (Table 3). Student t-tests showed that the mean infiltration rate produced by Rainfall treatments were significantly lower than those for the Inflow ($p = 0.013$) and Rainfall + Inflow ($p = 0.002$) treatments (Table 3). Compared with the Inflow treatment without raindrop impact, the mean infiltration rate for the Rainfall treatment with raindrop impact was reduced by

44% under the 2.5° slope, and by 41% for the 7.5° slope (Figure 5b). Under steady-state overland flow the average reduction of raindrop impact was 80% and 69% under the 2.5° and 7.5° conditions, respectively (Figure 5b).

Slope angle had no significant impact on overland flow rate (Mann-Whitney U tests, $p = 0.936$) and infiltration rate (Student t-test, $p = 0.687$).

Sediment yield

For both the Rainfall and Rainfall + Inflow treatments with raindrop impact, sediment concentrations increased during the initial stage of overland flow generation to a peak value before gradually declining (Figure 3). In contrast, for the Inflow treatment without raindrop impact, the sediment concentration was almost constant with little variation with overland flow generation.

Peat splash erosion rates measured by splash cups were 0.28 ± 0.11 g and 0.33 ± 0.09 g under the 2.5° and 7.5° slopes, respectively. The mean sediment concentration for the three treatments followed the order: Rainfall > Rainfall + Inflow > Inflow treatment (Table 4). Student t-tests showed that the sediment yield for the Rainfall treatment with raindrop impact was significantly higher than that of the Inflow treatment without raindrop impact ($p = 0.048$). The difference in sediment yield with and without raindrop impact was assumed to reflect the contribution of raindrop impact. On average, raindrop impact contributed to 62% and 31% of mean sediment yield under the 2.5° and 7.5° condition s, respectively (Table 5). The impact of raindrops on sediment increase in the initial overland flow stage was similar to the steady-state overland flow stage (Table 5). Compared with the Rainfall treatment, the Rainfall + Inflow produced sediment yields that were 1.4-1.7 times higher (Table 4). The simulated upslope inflow contributed to increasing sediment yields, with average contributions of 29% and 42% under the 2.5° and 7.5° conditions, respectively (Table 5).

< Table 4 is here please>

< Table 5 is here please>

The mean total amount of peat loss (dry weight) was 0.98, 0.48 and 1.72 g for the Rainfall, Inflow and Rainfall + Inflow treatments, respectively, under the 2.5° condition, and was 0.97, 0.73 and 1.35 g for the Rainfall , Inflow and Rainfall + Inflow treatments, respectively, under the 7.5° condition (Figure 6) . Student t-tests showed that the differences in the total peat loss between the 2.5° and 7.5° were not significant for all the three treatments.

< Figure 6 is here please >

The interaction between rainfall-driven and flow-driven erosion processes defined in equation (10) was negative throughout the whole experimental process (Figure 7), with average values of -73% and -85% under the 2.5° and 7.5° conditions, respectively (Table 5) . The contribution of the interactions to sediment concentration increase was lowest at the start of overland flow generation but increased rapidly and approached an approximately constant value (Figure 7). In comparison with the Rainfall + Inflow treatment, the effects of the interaction on reducing sediment concentration mainly occurred in the initial overland flow stage, with average contributions of 82% and 163% under the 2.5° and 7.5° conditions, respectively. These values were higher than those (50–69%) in the steady-state overland flow stage (Table 5).

< Figure 7 is here please >

Flow hydraulics

The overland flow hydraulic parameters under the 2.5° and 7.5° conditions are shown in Table 6. Median overland flow velocities for the Inflow treatment were 1.8 cm s^{-1} and 2.5 cm s^{-1} under the under the 2.5° and 7.5° conditions , respectively. These were significantly higher (Mann-Whitney U test, $p < 0.001$) than those produced by the Rainfall treatment, which were 1.0 cm s^{-1} under the 2.5° condition, and 1.3 cm s^{-1} under the 7.5° condition . Raindrops impacted on mean flow velocity, with reductions of 80% and 92% under the 2.5° and 7.5°

conditions, respectively, with a median reduction of 86% under both slope gradients (Table 7). Overland flow velocities under the Rainfall + Inflow conditions increased significantly (Mann-Whitney U test, $p < 0.001$) compared to the Rainfall and Inflow conditions (Table 6). For all three treatments flow velocities increased with increasing slopes (Table 6).

< Table 6 is here please >

< Table 7 is here please >

The average flow depth for the Rainfall treatment was significantly higher (Mann-Whitney U test, $p < 0.001$) compared with the Inflow treatment (Table 6). Raindrop impact increased flow depths by 64% and 56% under the 2.5° and 7.5° conditions, respectively (Table 7).

Of the three treatments, the Rainfall treatment produced the highest Manning's friction factor (n) and flow shear stress (τ) (Table 6); and the Rainfall + Inflow treatment produced the largest stream power (Ω). Raindrop impact increased n, τ and Ω by 72-78%, 59-65% and 21-31%, respectively (Table 7).

Relationships between overland flow and sediment

Sediment yield (y) generally increased with increasing overland flow rate (x) (Figure 8). However, for all treatments no significant linear relationship was found between erosion and overland flow. A power law ($y = 1.5986x^{1.276}$, $n = 313$, $R^2 = 0.547$, $p < 0.001$) performed well in describing the relationship between sediment yield and overland flow rate.

< Figure 8 is here please >

Spearman's Rank correlation analysis was used to test for a relationship between erosion and some hydraulic parameters (Table 8). Under both the Rainfall and Inflow conditions, erosion rate was significantly correlated with shear stress and stream power ($p < 0.01$). Under the Rainfall + Inflow conditions, stream power had a significant role in influencing erosion ($p < 0.01$). For all treatments, the crucial hydraulic parameters affecting erosion rate were shear stress and stream power, with stream power having the largest correlation coefficient (0.711). The significantly positive erosion–stream power relation for all the three treatments demonstrated that sediment yield rate increased with an increase in stream power.

< Table 8 is here please >

Discussion

Effects of rainfall on overland flow and sediment yield

Overland flow rate was significantly higher for the Rainfall treatment with raindrop impact than that for the Inflow treatment without raindrop impact. This result may be associated with peat surface sealing and crusting caused by raindrops striking the peat surface through the shallow overland flow (Burt and Slattery, 1996), leading to a decreased peat infiltration rate. In the initial stage of overland flow generation the peat infiltration capacity was high. The gradual sealing of the peat surface and increase in soil moisture contributed to reduced infiltration during the steady-state overland flow stage.

Raindrop impact significantly reduced the surface flow velocity on the gentler slope gradient. When raindrop impact was eliminated, average flow velocity increased greatly as raindrops increase surface roughness as represented by Manning's n friction factor. This is in agreement with Savat (1977) and Beuselinck et al. (2002) who reported that raindrop impact played a key role in disturbing overland flow and retarding flow velocity for gentle slopes and shallow overland flow conditions.

Raindrop impact significantly increased sediment yields, with an average increase of 47% for both slope gradients. The observed difference in erosion between the Rainfall and Inflow treatments primarily resulted from the effects of raindrops. For the Rainfall treatment, the sediment concentration rate peaked early in the rainfall simulation and then decreased to a final constant rate. The peak corresponded to the period when peat aggregates previously weathered by processes such as freeze–thaw and desiccation (Francis, 1990; Labadz et al., 1991; Shuttleworth et al., 2017) were detached and splashed by raindrop impact, and the peat soil shear strength decreased with saturation. As overland flow increased in the first few minutes, loose sediments on the surface were mobilised and exported (Figure 3). The erosion pattern appeared to be transport-limited in the initial stage of runoff generation. Continued raindrop impact increased the flow depth and resistance to detachment, as a result erosion rates dropped to an equilibrium level marking the balance between the erosive forces of splash and rain-impacted flow detachment and the resistance of the soil surface. The peat loss rate in the steady-state overland flow stage was generally lower compared with the initial peak rate, despite the increase in the overland flow rate and the associated transport capacity. This demonstrates that the erosion rate experienced a switch from a transported-limited to a detachment-limited system when steady state overland flow was achieved. For the Inflow treatment, the continuous low erosion rates with little temporal change indicated a detachment-limited system. Under the low flow velocity conditions, the impact of sheet flow without the impact of rainfall has limited effect on peat erosion as peat is fiber-rich and highly resistant to water erosion, requiring a high flow velocity before continuous erosion of peat material occurs (Carling et al., 1997).

Our study highlights the important role that raindrop impact plays in detaching peat materials for flow transport. However, the observed average contribution of raindrop impact (47%) was smaller than that reported by Guy et al. (1986) who found that the contribution exceeded 85%. The discrepancy may reflect the lower rainfall intensity used in our study. Raindrop impact has been demonstrated to play a key role in affecting overland flow, flow hydraulics and soil loss under lower rainfall intensity conditions. More significant effects could be expected with higher kinetic energy levels closer to those experienced where natural rainfall is driven by strong wind. Windy conditions are typical of many upland environments and during a drought period dry peat with a low density has a high potential susceptibility to transport by wind (Foulds and Warburton, 2007b). Under wet and windy conditions, wind-driven rain is important in peat surface erosion through the detachment and transport of peat particles (Warburton, 2003; Foulds and Warburton, 2007a). Future work could examine overland flow interactions with wind-driven rainsplash erosion and its contribution to total erosion as rainfall on blanket peatlands is often associated with strong winds (Evans and Warburton, 2007).

Effects of the interaction between rainfall and inflow on soil erosion

For rainfall-driven erosion events (Rainfall and Rainfall + Inflow treatments), raindrop impact significantly impacted soil detachment and resulted in higher sediment yields (Table 4). However, the effect of shallow overland flow in the absence of rainfall on peat erosion was low.

The interaction between rainfall-driven and flow-driven erosion processes was defined as positive where the total sediment concentration produced by the Rainfall + Inflow treatment exceeded the sum of those generated by the Rainfall and Inflow treatments; and as negative where the total sediment concentration for the Rainfall + Inflow treatment was lower than the sum of those for the Rainfall and Inflow treatments. A negative interaction was observed under both the 2.5º and 7.5º slopes. Interaction was found to substantially reduce sediment concentration. This primarily results from significantly increased flow resistance caused by the retardation effect of raindrops on shallow overland flow (Table 7). In addition, interaction resulted in a decrease in stream power by -0.03 × 10^{-2} W m^{-2} and -0.06 × 10^{-2} W m^{-2} under the 2.5° and 7.5° slopes, respectively. This decrease was responsible for a decrease in sediment concentration as erosion was found to be positively correlated with the stream power. Rouhipour et al. (2006) and Asadi et al. (2007) found negative interaction existed in the initial stage of overland flow generation under gentle slopes and shallow overland flow conditions on silt loamy and sandy soils. However, our results contradict the positive and minor interaction effect (< 20%) reported by Tian et al. (2017) who used higher flow depths and much steeper slopes in their study of loess soil. Our results showed that the interaction between rainfall and flow driven erosion processes are important in affecting flow hydraulics and sediment, in particular under gentle slopes and shallow overland flow conditions. Consequently, to improve process-based interrill erosion modelling such as WEEP (Nearing et al., 1989) the interaction between rainfall and flow driven erosion processes should be considered. However, further work is required to acquire an extensive dataset for parameterization across different soils and slope conditions.

Effects of slope gradient and upslope inflow on overland flow and erosion processes

The effect of slope gradient on overland flow and infiltration was not found to be statistically significant. Considering values normal to the surface, for both the Rainfall and Rainfall + Inflow conditions, there was a small difference (<1 %) in the raindrop energy flux density between the 7.5° and 2.5° slopes. This was insufficient to cause a significant difference in porosity near the surface resulting from compaction under raindrop impact, a factor which can be important in affecting infiltration (Mualem et al., 1990). In addition, no significant differences were found in the peat splash rate for the two slopes.

Due to the effect of upslope inflow, the average sediment yield under the Rainfall + Inflow condition was significantly higher than under the Rainfall condition. The average contribution of upslope inflow to increasing erosion was 36%. Compared with the Rainfall treatment, the Rainfall + Inflow treatment showed significantly higher flow velocity and stream power but lower Manning's n. These results indicate that accumulated overland flow from the upper slope positions contributes to erosion on the lower slope positions, through increasing flow velocity and stream power and decreasing surface roughness (Table 6). Similar findings have been reported by previous studies on semi-arid soils

(Gilley et al., 1985; Parsons et al., 1994). However, the contribution of upslope inflow in our study was minor as upslope inflow rate was lower for peat detachment.

The relationship between overland flow and soil erosion

For the Rainfall and Rainfall + Inflow treatments, sediment concentrations typically demonstrated an initial sharp increase followed by a gradual decrease to constant level. In the early stage of the rainfall event, erosion processes were transport-limited as shown by Figure 3 and we observed that this raindrop detachment followed by a raindrop-induced flow transport system as suggested by Kinnell (2005). Peak sediment concentration usually occurred on the rising limb of the hydrograph. With increased overland flow generation, there was a shift in erosion from a transport-limited to supply-limited regime. We found that peak sediment concentration occurred during the rising limb of overland flow graphs (Figure 3) and this was also reported by Kløve (1998) and Holden and Burt (2002). Hence, sediment exhaustion is important in eroding blanket peat. A bare blanket peat surface requires a period of sediment ‘preparation’ or weathering processes to produce a friable and easily erodible surface layer (Francis, 1990; Labadz et al., 1991; Shuttleworth et al., 2017). We found that rainsplash plays an important role in detaching peat particles for flow transport. However, antecedent conditions such as prior freeze–thaw or desiccation activity are very important in controlling peat erodibility and thus erosional response to a given rainfall event. Consequently, further exploration about the combined effects of rainsplash and weathering processes such as freeze–thaw and desiccation could be undertaken in future studies to reveal the relative importance of these controls.

Limitations

Bounded plots with rainfall and inflow simulation techniques were used in this study in order to produce quantifiable results with good levels of experimental control. The plot size (1m × 0.13m) is small but was necessary in order to obtain undisturbed peat blocks and to allow careful collection, transport and storage in the laboratory. In this study, the main active erosion process on the surface of the peat blocks was interrill erosion due to the fact that the supplied water input was insufficient for the peat surface to develop into a rill. Future work could look at rill development and also wind assisted splash effects.

It is also important to emphasize that given that accumulated inflow from upper slope positions may be loaded with sediment, more exploration with sediment-loaded inflow tests could be done in future studies to further our understanding of the effects of accumulated inflow on overland flow and erosion processes.

Conclusions

Raindrop impact was found to play an important role in affecting peat overland flow and erosion processes for gentle slopes and shallow overland flow conditions. Raindrop impact contributed significantly to increasing the sediment yield by 47% on average for both slope gradients. Compared with mineral soils peat soils were more resistant to raindrop impact forces. Raindrop impact was found to increase roughness by 72–78%, resulting in decrease in overland flow velocity by 80–92%. From a restoration perspective covering gently sloping bare peat surfaces by vegetation, brash or stabilizing geo-textiles (Parry et al., 2014) should help reduce erosion under typical rainfall intensities by weakening the impact of rainsplash.

The interaction effect of rainsplash and overland flow on sediment concentration was negative throughout the whole experimental process, with a 73–85% reduction in sediment concentration. This reduction occurred due to significantly increased flow resistance and decreased stream power. This study demonstrated that the interaction between rainfall and flow driven erosion processes was important in affecting overland flow hydraulics and sediment production on gentle peat hillslopes.

Overland flow and erosion processes on peat hillslopes are affected by slope position. The Rainfall + Inflow treatment produced significantly higher flow velocities and sediment yields than the Rainfall treatment. Sediment yield generally increased with overland flow rate but sediment exhaustion and the detachment-limited interrill erosion pattern meant no linear relationship was found. Instead, stream power was found to be a good predictor of peat erosion.

Spatially distributed models of blanket peatlands that predict stream power and which can incorporate rainsplash – flow interactions would be useful for predicting future slope development in blanket peatlands. Recent modelling projections have suggested that many blanket peatlands in the Northern Hemisphere will be more susceptible to erosion under climate change and land management practices (Li et al., 2017a). However such models do not yet incorporate processes covered in this paper and so by feeding in our process-based understanding into peat erosion models it may be possible to improve future projections.

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Tables

Table 1. Some basic physical and chemical characteristics of the tested peat soils.

Basic physical and chemical characteristics		Median values	Standard deviation
Bulk density (g cm^{-3})		0.19	0.01
Porosity (%)		86.5	1.0
Moisture (%)		87.2	0.9
pH		3.7	0.1
Size and shape parameters of peat particles	Length (µm)	18.4	8.9
	Width (µm)	10.8	4.6
	Perimeter (µm)	49.3	23.2
	Circularity	0.83	0.06
	Convexity	0.97	0.02
	Solidity	0.94	0.03
	Aspect Ratio	0.69	0.01
	Elongation	0.31	0.01

Circularity (0–1) quantifies how close the peat particles are to perfect circles; Convexity (0–1) measures the surface roughness of peat particles.

Table 2. Summary of the experimental design and treatments.

Slope	Treatment	Replicate	Total Water Supply (mm hr^{-1})	Rainfall Intensity (mm hr^{-1})	Upslope Inflow Rate (mL s^{-1})	Duration* (min)
2.5°	Rainfall	1	12	12	0	120
		2	12	12	0	120
		3	12	12	0	60
	Inflow	1	12	0	26	120
		2	12	0	26	120
		3	12	0	26	60
	Rainfall + Inflow	1	24	12	26	120
		2	24	12	26	120
		3	24	12	26	60
7.5°	Rainfall	1	12	12	0	120
		2	12	12	0	120
		3	12	12	0	120
		4	12	12	0	60
		5	12	12	0	60
	Inflow	1	12	0	26	120
		2	12	0	26	120
		3	12	0	26	120
	Rainfall + Inflow	1	24	12	26	120
		2	24	12	26	120
		3	24	12	26	120
		4	24	12	26	60
		5	24	12	26	60

* Duration indicates time since overland flow generation (min).

Table 3. Median overland flow and infiltration rates for the three treatments (Rainfall, Inflow and Rainfall + Inflow).

Slopes		Experimental stages	Rainfall	Inflow	Rainfall + Inflow
2.5°	Overland flow (mm hr^{-1})	Initial stage	8.64 ± 0.97 b	8.28 ± 0.52 b	20.75 ± 0.88 a
		Steady-state overland flow stage	11.45 ± 0.35 b	9.30 ± 1.50 c	21.61 ± 0.09 a
		Whole stage	10.31 ± 0.43 b	9.00 ± 1.21 c	21.16 ± 0.36 a
	Infiltration (mm hr^{-1})	Initial stage	3.35 ± 0.97 c	3.72 ± 0.52 b	4.27 ± 0.92 a
		Steady-state overland flow stage	0.54 ± 0.35 b	2.70 ± 1.50 a	2.38 ± 0.09 a
		Whole stage	1.68 ± 0.43 b	3.00 ± 1.21 a	2.83 ± 0.36 a
7.5°	Overland flow (mm hr^{-1})	Initial stage	9.36 ± 0.49 b	8.62 ± 1.32 c	19.25 ± 1.12 a
		Steady-state overland flow stage	11.09 ± 0.56 b	9.49 ± 0.23 c	22.45 ± 0.77 a
		Whole stage	10.35 ± 0.28 b	9.29 ± 0.43 c	21.50 ± 0.26 a
	Infiltration (mm hr^{-1})	Initial stage	2.54 ± 0.49 c	3.38 ± 1.32 b	4.65 ± 1.12 a
		Steady-state overland flow stage	0.77 ± 0.56 c	2.51 ± 0.23 a	1.45 ± 0.77 b
		Whole stage	1.59 ± 0.24 b	2.71 ± 0.43 a	2.40 ± 0.26 a

The same letter within a row (a is highest and c is lowest) indicates no significant difference based on Mann-Whitney U tests at $p = 0.05$.

Table 4. Summary of the measured sediment concentration and sediment yield rate for the three treatments (Rainfall, Inflow and Rainfall + Inflow) in the initial and steady-state overland flow stage.

Slope	Treatment	Replicate	Sediment Concentration (mg L⁻¹)			Sediment Yield Rate (mg m⁻² min⁻¹)		
			IS*	SSRS**	WS***	IS	SSRS	WS
2.5°	Rainfall	1	1159.3	856.6	1058.4	261.7	252.0	258.5
		2	314.1	262.4	273.2	84.0	105.9	101.3
		3	454.0	416.7	435.3	79.9	90.2	85.1
		Mean	642.5	511.9	589.0	141.9	149.4	148.3
	Inflow	1	215.8	204.9	208.6	28.4	28.6	28.6
		2	336.4	266.1	286.6	85.9	85.0	85.3
		3	461.3	280.6	295.7	70.6	53.7	55.1
		Mean	337.8	250.5	263.6	61.6	55.8	56.3
	Rainfall + Inflow	1	327.1	303.9	308.8	168.4	150.2	153.1
		2	677.2	575.5	626.4	228.2	256.2	242.2
		3	613.9	475.6	544.8	249.2	207.8	228.5
		Mean	539.4	451.7	493.3	215.3	204.7	207.9
7.5°	Rainfall	1	507.5	316.0	435.1	182.7	116.4	159.5
		2	506.7	355.0	392.9	87.5	80.3	82.1
		3	748.8	390.1	494.7	172.9	94.5	117.4
		4	464.9	363.6	422.7	77.7	91.7	83.6
		5	579.2	515.3	552.6	95.3	100.8	97.6
		Mean	561.4	388.0	459.6	123.2	96.8	108.0
	Inflow	1	374.6	322.7	333.5	51.0	59.6	57.8
		2	332.4	277.2	295.6	64.4	57.2	59.6
		3	384.7	301.1	325.5	130.6	99.2	106.4
		Mean	363.9	300.3	318.2	82.0	72.0	74.6
	Rainfall + Inflow	1	177.8	275.1	246.8	54.4	109.1	93.1
		2	296.1	210.1	235.5	123.0	111.2	112.7
		3	323.2	784.5	590.3	117.2	370.9	264.1
		4	388.6	343.8	366.2	158.9	178.4	168.7

Slope	Treatment	Replicate	Sediment Concentration (mg L^{-1})			Sediment Yield Rate (mg m^{-2} min^{-1})		
			IS*	SSRS**	WS***	IS	SSRS	WS
		5	575.2	688.7	660.3	248.1	316.3	299.2
		Mean	352.2	460.4	419.8	140.3	217.2	187.6

IS*, SSRS** and WS*** indicate the initial overland flow stage, steady-state overland flow stage and the whole experimental stage, respectively.

Table 5. Changes in sediment concentration and sediment yield due to raindrop impact, inflow impact and interaction in different stages of the experimental process.

Slopes		Stages	Raindrop Impact		Inflow Impact		Interaction	
			In rate	In percentage (%)	In rate	In percentage (%)	In rate	In percentage (%)
2.5°	SC	IS*	304.7	47	-103.1	-19	-440.9	-82
		SSRS**	261.4	51	-60.2	-13	-310.7	-69
		WS***	325.4	55	-95.7	-19	-359.3	-73
	SY	IS*	80.3	57	73.4	34	11.8	5
		SSRS**	93.6	63	55.3	27	-0.5	0
		WS***	92	62	59.6	29	3.3	2
7.5°	SC	IS*	197.5	35	-209.2	-59	-573.1	-163
		SSRS**	87.7	23	72.4	16	-227.9	-50
		WS***	141.4	31	-39.8	-9	-358	-85
	SY	IS*	41.2	33	17.1	12	-64.9	-46
		SSRS**	24.8	26	120.4	55	48.4	22
		WS***	33.4	31	79.6	42	5	3

Notes: SC and SY are sediment concentration (mg L^{-1}) and sediment yield rate (mg m^{-2} min^{-1}), respectively; IS*, SSRS** and WS*** indicate the initial overland flow stage, steady-state overland flow stage and the whole experimental stage, respectively; '–' indicates reduction; Raindrop impact, inflow impact and interaction are determined by 'Rainfall' – 'Inflow', 'Rainfall + Inflow' – 'Rainfall' and 'Rainfall + Inflow' – 'Rainfall' – 'Inflow', respectively.

Table 6. Median overland flow hydraulic parameters for the three treatments (Rainfall, Inflow and Rainfall + Inflow) in different experimental stages.

Slopes	Treatment	Experimental stages	V (cm s^{-1})	h (mm)	n (10^{-2})	τ	Ω (10^{-2})
2.5°	Rainfall	Initial stage	0.7	1.4	190	0.58	0.11
		Steady-state overland flow stage	1.1	1.0	63	0.42	0.14
		Whole stage	1.0	1.1	93	0.46	0.13
	Inflow	Initial stage	1.4	0.4	25	0.17	0.08
		Steady-state overland flow stage	1.9	0.4	18	0.15	0.09
		Whole stage	1.8	0.4	20	0.16	0.09
	Rainfall + Inflow	Initial stage	3.3	0.6	25	0.24	0.18
		Steady-state overland flow stage	2.1	0.7	30	0.32	0.20
		Whole stage	2.6	0.7	28	0.29	0.19
7.5°	Rainfall	Initial stage	1.0	1.1	106	0.49	0.12
		Steady-state overland flow stage	1.4	0.8	40	0.32	0.14
		Whole stage	1.3	0.9	60	0.37	0.14
	Inflow	Initial stage	2.5	0.4	19	0.16	0.11
		Steady-state overland flow stage	2.6	0.4	16	0.15	0.11
		Whole stage	2.5	0.4	17	0.15	0.11
	Rainfall + Inflow	Initial stage	3.7	0.4	15	0.18	0.16
		Steady-state overland flow stage	4.6	0.4	13	0.18	0.20
		Whole stage	4.3	0.4	13	0.18	0.19

Table 7. Effects of raindrop and interaction on increasing the overland flow hydraulic parameters in different experimental stages.

Slopes	Experimental stages	V (cm s^{-1})	h (mm)	n (10^{-2})	τ	Ω (10^{-2})
Raindrop impact						
	Initial stage	-0.7 (-100%)	1.0 (71%)	165 (87%)	0.41 (71%)	0.03 (27%)
2.5°	Steady-state overland flow stage	-0.8 (-73%)	0.6 (60%)	45 (71%)	0.27 (64%)	0.05 (36%)
	Whole stage	-0.8 (-80%)	0.7 (64%)	73 (78%)	0.30 (65%)	0.04 (31%)
	Initial stage	-1.5 (-150%)	0.7 (64%)	87 (82%)	0.33 (67%)	0.01 (8%)
7.5°	Steady-state overland flow stage	-1.2 (-86%)	0.4 (50%)	24 (60%)	0.17 (53%)	0.03 (21%)
	Whole stage	-1.2 (-92%)	0.5 (56%)	43 (72%)	0.22 (59%)	0.03 (21%)
Interaction						
	Initial stage	1.2 (36%)	-1.2 (-200%)	-190 (-760%)	-0.51 (-213%)	-0.01 (-6%)
2.5°	Steady-state overland flow stage	-0.9 (-43%)	-0.7 (-100%)	-51 (-170%)	-0.25 (-78%)	-0.03 (-15%)
	Whole stage	-0.2 (-8%)	-0.8 (-114%)	-85 (-304%)	-0.33 (-114%)	-0.03 (-16%)
	Initial stage	0.2 (5%)	-1.1 (-275%)	-110 (-733%)	-0.47 (-261%)	-0.07 (-44%)
7.5°	Steady-state overland flow stage	0.6 (13%)	-0.8 (-200%)	-43 (-331%)	-0.29 (-161%)	-0.05 (-25%)
	Whole stage	0.5 (12%)	-0.9 (-225%)	-64 (-492%)	-0.34 (-189%)	-0.06 (-32%)

Table 8. Correlation matrix between erosion rate (mg m^{-2} min^{-1}) and different hydraulic parameters, including flow velocity (cm s^{-1}), shear stress (Pa) and stream power (W m^{-2}).

Parameters	Erosion rate	Flow velocity	Shear stress	Stream power
Rainfall treatment (n = 80)				
Erosion rate	1.000			
Flow velocity	-0.359**	1.000		
Shear stress	0.472**	-0.929**	1.000	
Stream power	0.391**	0.097	-0.167	1.000
Inflow treatment (n = 117)				
Erosion rate	1.000			
Flow velocity	0.032	1.000		
Shear stress	0.545**	-0.695**	1.000	
Stream power	0.705**	0.442**	0.230*	1.000
Rainfall + Inflow treatment (n = 115)				
Erosion rate	1.000			
Flow velocity	0.070	1.000		
Shear stress	-0.019	-0.953**	1.000	
Stream power	0.258**	0.383**	-0.152	1.000
All treatments (n = 312)				
Erosion rate	1.000			
Flow velocity	0.066	1.000		
Shear stress	0.358**	-0.809**	1.000	
Stream power	0.711**	0.331**	0.196**	1.000

* and ** indicate that correlation is significant at the 0.05 level and 0.01 level (2-tailed), respectively.

Figures

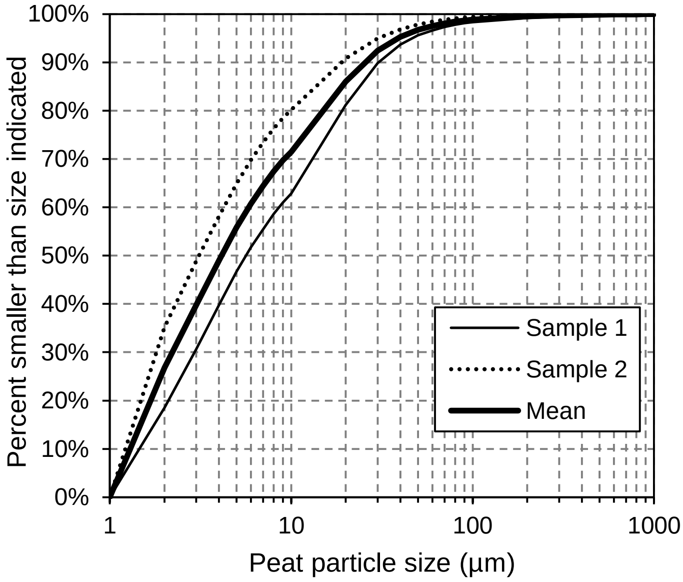

Figure 1. Particle-size distribution curves of the studied peat. The mean peat particle sizes were 16 µm and 8 µm for sample 1 (n = 43, 372) and sample 2 (n = 534, 485), respectively. Bold line shows the mean values of sample 1 and 2.

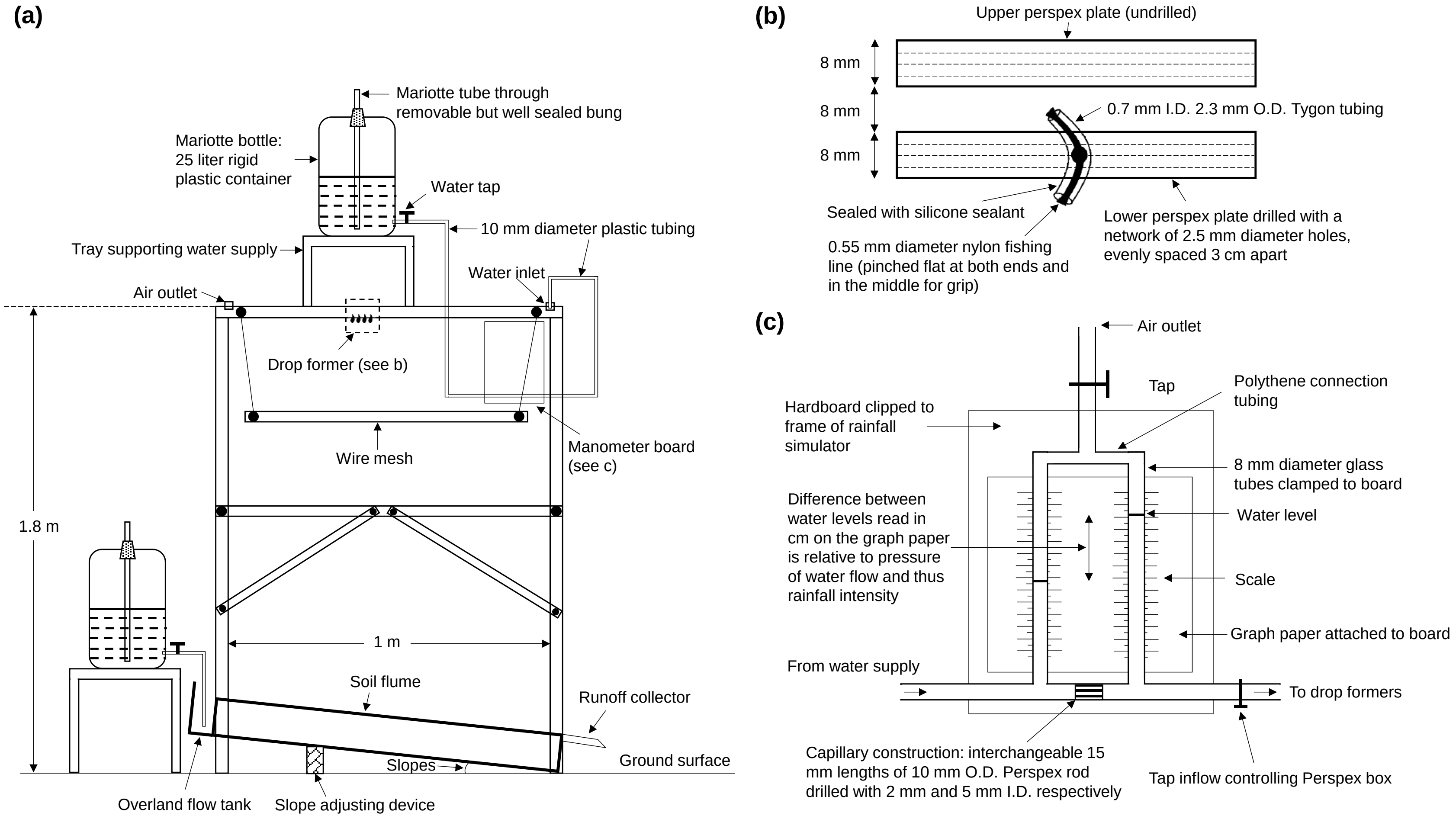

Figure 2. Experimental set-ups used in this study including: (a) rainfall simulator and upslope inflow simulation device; (b) drop former and (c) manometer for control of rainfall intensity. Modified from Bowyer-Bower and Burt (1989) and Holden and Burt (2002).

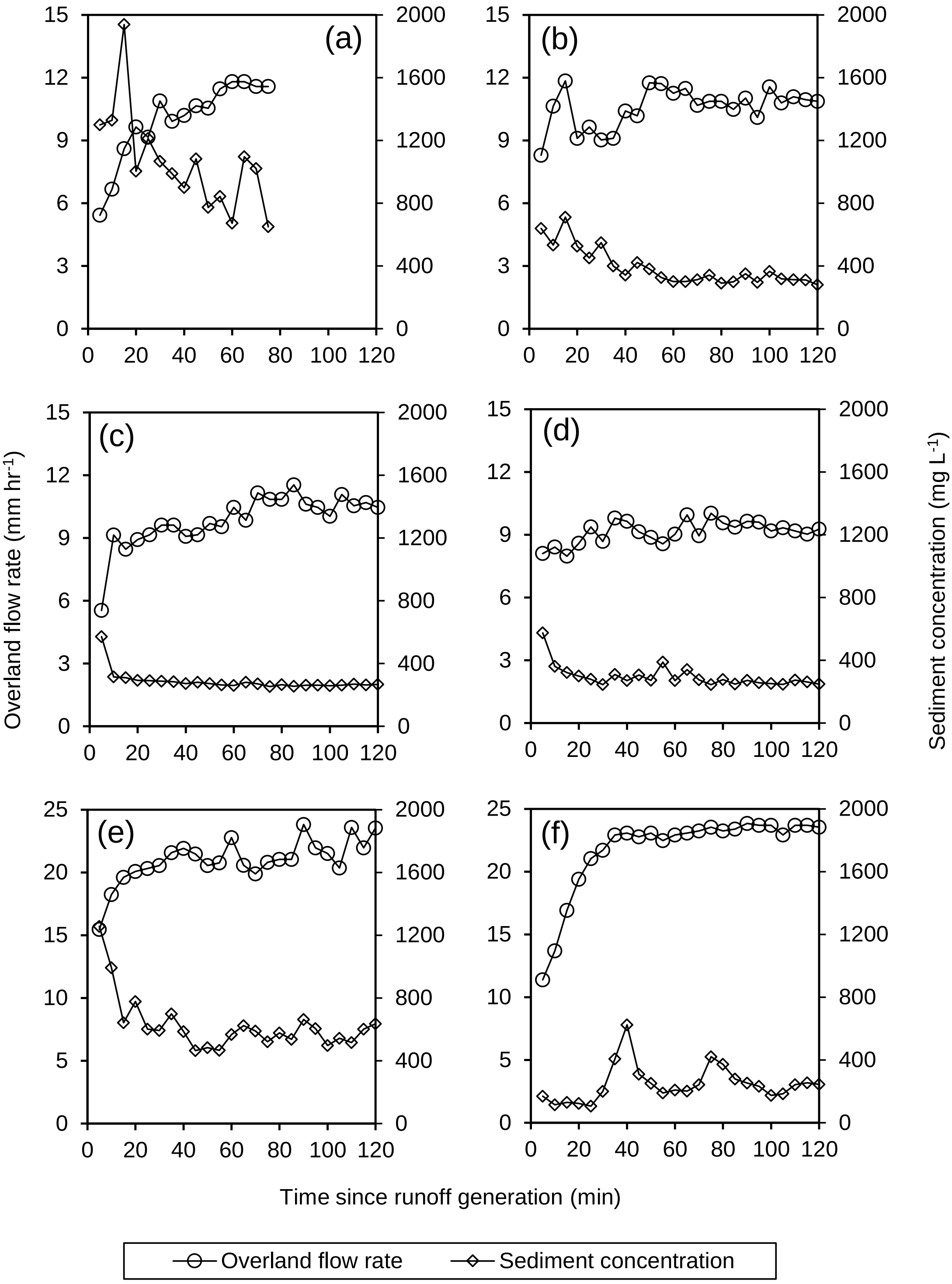

Figure 3. Overland flow and sediment concentration rate for representative replicates with different treatments (Rainfall, Inflow and Rainfall+ Inflow): (a) Rainfall, 2.5°; (b) Rainfall, 7.5° ; (c) Inflow, 2.5°; (d) Inflow, 7.5°; (e) Rainfall+ Inflow, 2.5°; (f) Rainfall+ Inflow, 7.5°.

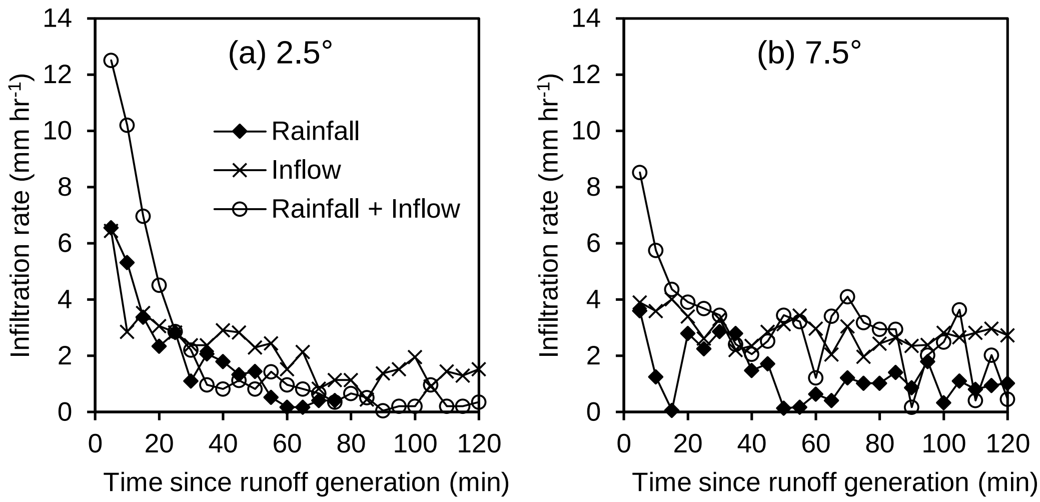

Figure 4. Infiltration rate for representative replicates with different treatments (Rainfall, Inflow and Rainfall+ Inflow) under (a) 2.5° and (b) 7.5° conditions, respectively.

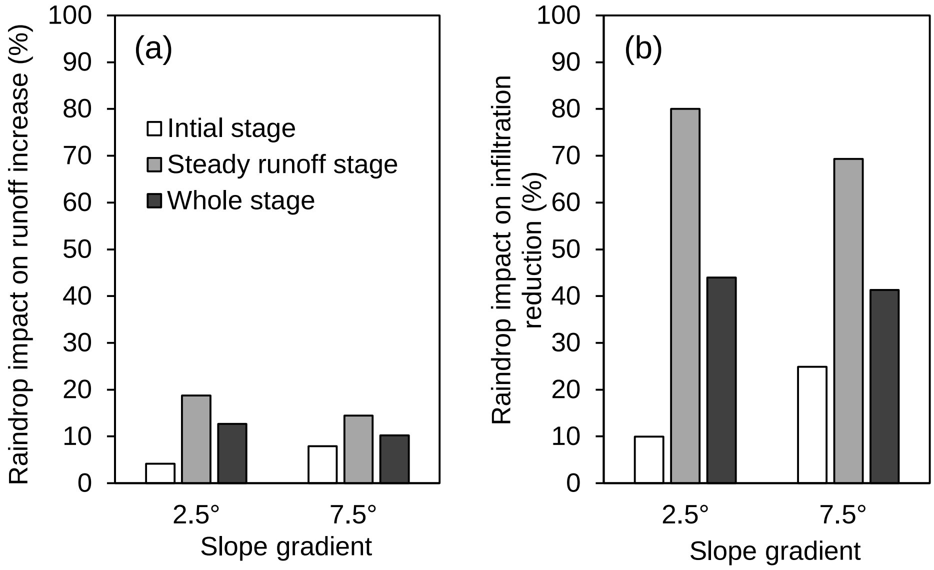

Figure 5. The impact of raindrops on (a) overland flow rate and (b) infiltration, during different experimental stages.

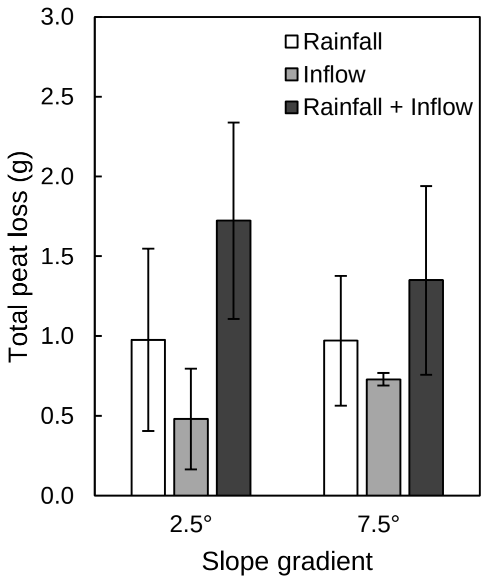

Figure 6. Total peat loss with different treatments (Rainfall, Inflow and Rainfall+ Inflow).

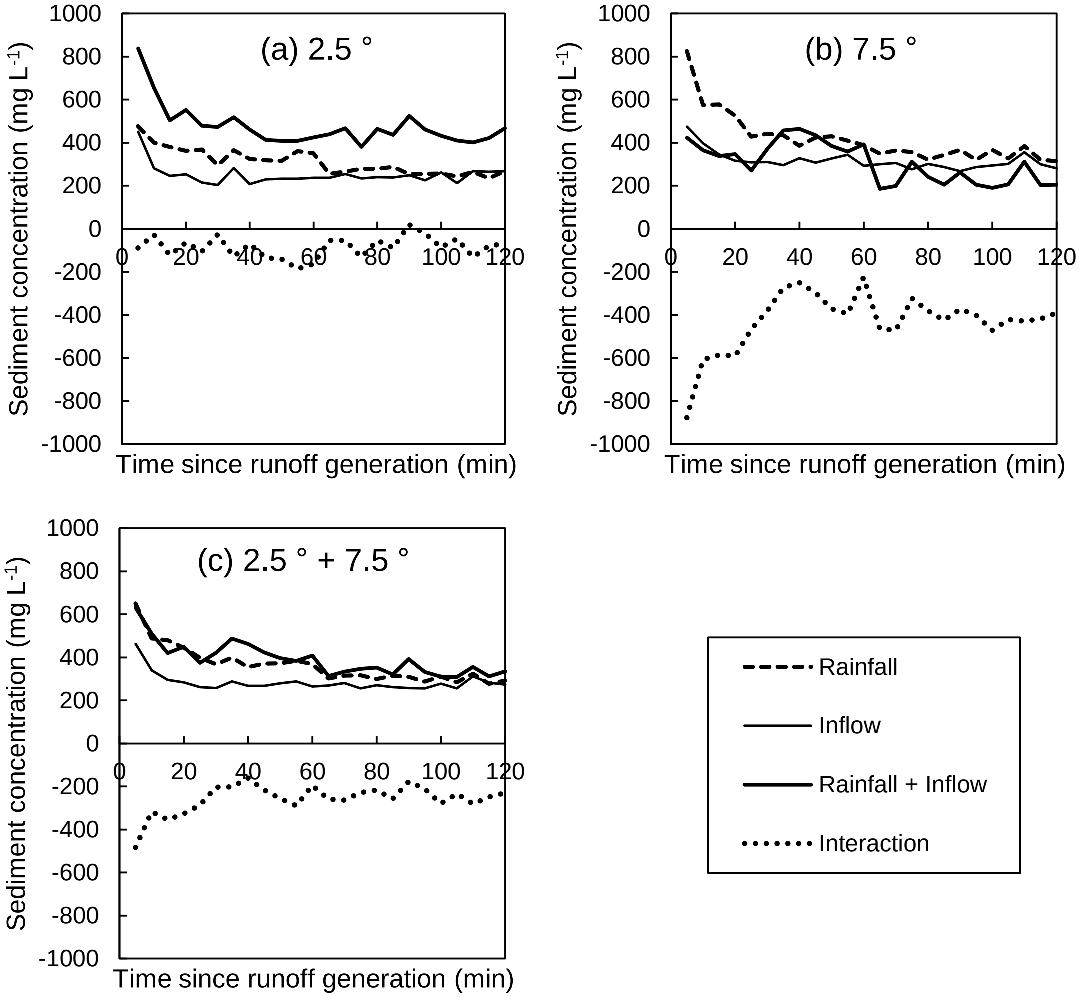

Figure 7. Changes with time in measured sediment concentration for each experimental treatment (Rainfall, Inflow and Rainfall + Inflow) and calculated interaction under (a) 2.5°, (b) 7.5° and (c) 2.5° + 7.5° conditions, respectively.

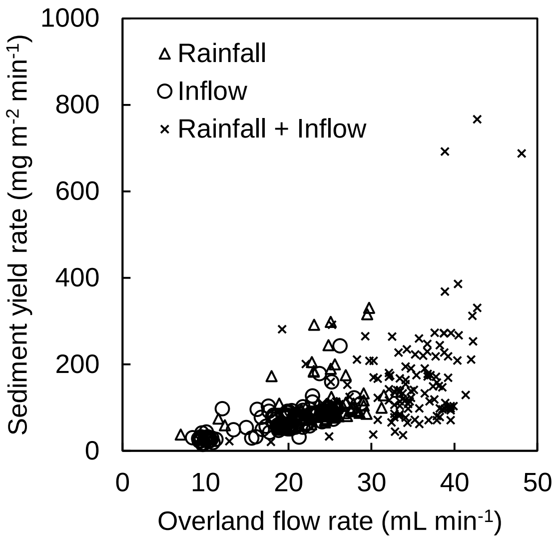

Figure 8. The relationship between sediment yield and overland flow.