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Impact of natural gullies on groundwater hydrology in the Zoige peatland, China

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ABSTRACT

Study region: The study area was in the upland peatland within the Zoige basin with elevations ranging between 3400 and 3800 m. It is located in the source area of Upper Yellow River that is developed on the Qinghai-Tibet Plateau, China.
Study focus: We examined possible influence of two different types of gullies on groundwater hydrology in this alpine peatland, the gullies whose beds cutting through the peat layer and those whose beds are within the peat layer. We measured saturated hydraulic conductivity, hydraulic head, and water table levels both vertically and horizontally in three representative sites distributed in the study area representing blanket peatland and peats surrounded by two types of the gullies during May 11–23, 2017. Using these data, we showed that different patterns of these parameters in both directions may be clearly observed among the three sites.
New hydrological insights for the region: We have shown for the first time in this region that (1) gullies with the bed cutting through the peat layer may have profound impact on peat groundwater hydrology; (2) groundwater seepage at the bottom of the peat layer may be enhanced by gullies with the bed cutting through the peat layer; and (3) increased groundwater seepage could be an additional cause for peatland degradation during the prolonged dry and cold period of a year.

1. Introduction

The importance of peatlands is highlighted by the fact that they hold about 10% of the world's freshwater and 30% of global soil carbon while only consisting of 3% of the Earth's lands (Ballard et al., 2011; Holden, 2009a; Rubec, 2005). Yet, hydrological properties of peatlands can be profoundly altered by gullies developed through natural erosion processes and artificially excavated drainage ditches (Armstrong et al., 2010; Sikstrom and Hokka, 2016). Much of attention has been paid to how gullies and ditches change overland flow, subsurface flow, and macropore/pipe flow, as well as water table levels. We have known thus far that gullies and ditches may (1) increase or decrease peak discharges of channel flow with the total volume of water produced during one storm event unchanged and increase long-term runoff efficiency at the watershed scale (Archer, 2003; Holden, 2009b; Holden et al., 2006); (2) significantly increase throughflow and baseflow because of raised water table during storm event, catchment dewatering, and soil structure alteration (Daniels et al., 2008; Holden et al., 2007); (3) enhance pipe (or macropore) flow during the dry season (Holden, 2005; Holden et al., 2004; Rossi et al., 2012); and (4) cause the well-known distance decay effect of the water table from a gully

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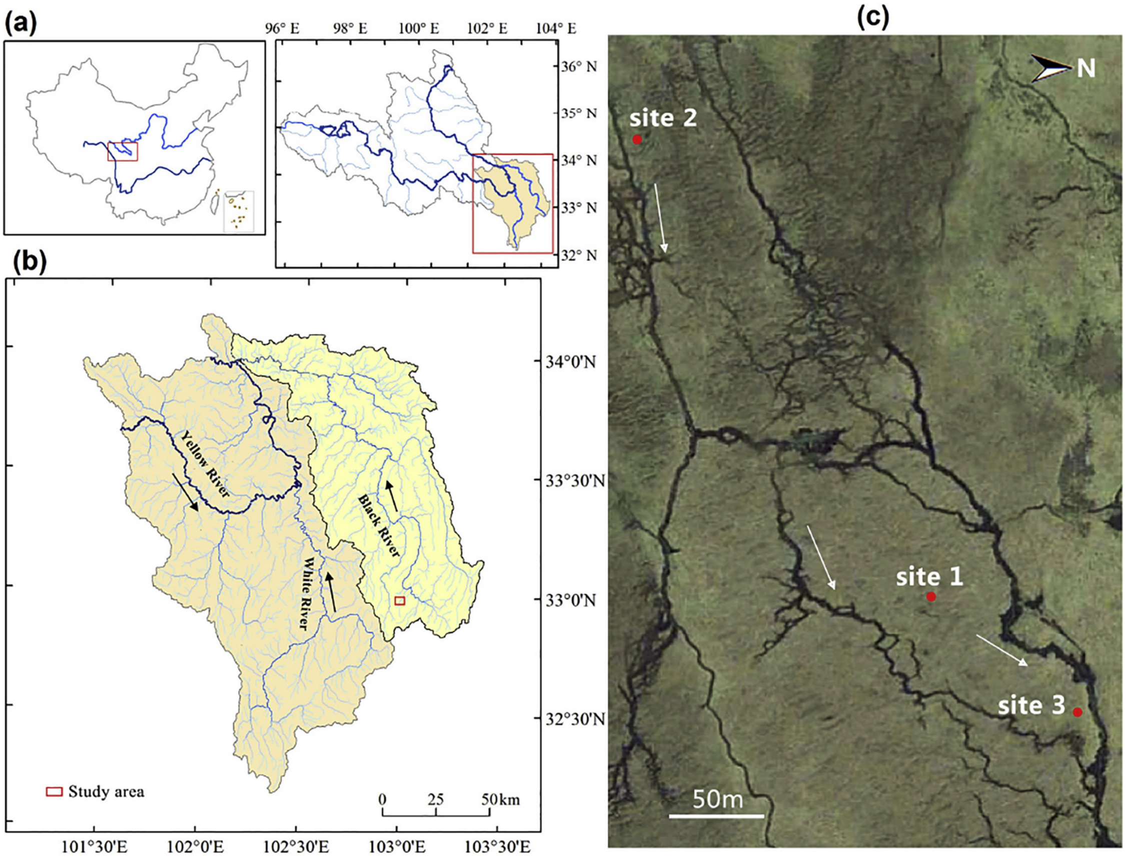

Fig. 1. General settings of the Zoige peatland and locations of the study area and sampling sites. (a) Locations of the Upper Yellow River Watershed and the Zoige basin; (b) The two tributaries and location of the study area within the Zoige basin; (c) Positions of the three sampling sites.

(Allott et al., 2009; Holden et al., 2006, 2011; Luscombe et al., 2016). In addition, studies have revealed that drainage due to ditches (and gullies) could reduce or increase hydraulic conductivity, peat bulk density, and storage capacity, which further leads to lowered water table and the subsequent peatland shrinkage (Glaser et al., 1981; Price et al., 2003; Ramchunder et al., 2009). Nonetheless, it is still unclear how gullies and ditches affect groundwater by altering hydraulic conductivity and head within the peat layer. The objective of this research was to provide evidence that may explain such effect by examining the impacts of natural gullies on saturated hydraulic conductivity, hydraulic head, and water table in an upland peat within Zoige basin, China. We selected a site in a hollow of peatland, and next to a type-I and type-II gully (defined later), respectively. At each site, we measured (1) saturated hydraulic conductivity both along a vertical profile of the peat and at certain representative depths, and (2) hydraulic head at different peat depths. In addition, we measured water table levels along two transects perpendicular to each of the two selected gullies. By comparing the data among the three sites, we showed different hydrological properties of groundwater in peats near the two types of gullies and discussed their implications in understanding the cause for the area reduction of peatland.

2. Methods and materials

2.1. Background of the Zoige basin

The Zoige basin is located on the southeastern side of the Upper Yellow River (UYR) Watershed that sits on the northeastern edge of the Qinghai-Tibet Plateau, China (Fig. 1a). It covers the area of about 22,145 km^2 with elevations ranging between 3400 and 4800 m (Li et al., 2010). The Zoige basin was developed about 13 million years ago by an intense mountain-building uplift and subsequent fast sediment fill, which created a variety of low mountains and hills within the basin (Nicoll et al., 2013). Zoige peatland, whose area currently takes about 17% of the total basin area (Li et al., 2011), was initiated in the early Holocene and fully developed about 3000 BP (Chen et al., 1999; Harkins et al., 2007; Zeng et al., 2017; Zhao et al., 2014). Geological structure of the entire UYR watershed has been controlled by various tectonic movements (e.g., strike-slip faulting), which generated a few knickpoints along the downstream reach of the first bend (with a U-shape planform) (Fig. 1a) in the UYR (Craddock et al., 2010; Perrineau et al., 2011). These knickpoints initiated the erosion process that has been controlling landscape evolution of the Zoige basin. Downstream of the Black River, one of the two main tributaries merging into the UYR in the area (Fig. 1b), the bridge piers are exposed for about 0.5 m, showing the dominance of incision in the river. The knickpoint-controlled erosion has also catalyzed various gully networks developed through a large part of the basin. In the peat areas contributing to the middle and upper reaches of the rivers, gullies have been deeply incised, such that gully beds generally cut through the peat layer and have reached the underlying mineral layer. Moving further upslope, peatlands may contain first- and second-order gullies whose beds remain within the peat layer. Although the boundary between the two types of gullies varies spatially within the Zoige peatland, their morphological distinction may be readily identified in the field. Accompanied with these gullies are networks of artificial ditches created between 1960s and 1980s for transferring peatlands to grasslands for grazing (Li et al., 2015; Yan and Wu, 2005; Zhang et al., 2014). These ditches are typically straight and shallow (i.e., less than 0.5 m), and often are connected to nearby natural gullies or meandering rivers. Because their beds are usually well above the bottom of the peat layer, artificial ditches usually serve as concentrated flow paths allowing surface water to drain out of the peatland fast without initiating significant channel bed and bank erosion and sediment transport. Therefore, they have a similar hydrological role to the second type of natural gullies mentioned above.

Over the past six decades, the Zoige surface peat coverage has been degraded to the grass coverage by about 52% in area from its original 4600 km^2 (determined using remote sensing data). The prevailing explanation states that this area reduction should be mainly ascribed to the increasing trend of annual mean summer temperatures in this region, which resulted in the increased evaporation rates (Li et al., 2014; Yan and Wu, 2005; Zhang et al., 2016). This argument implicitly assumed that higher evaporation rates could result in reduced water supply to the peatland. Yet, it failed to consider the important role of precipitation. Although from 1960s to 2010s, annual average precipitation followed a weak declining trend (Li et al., 2015), comparing the change of mean annual evapotranspiration (*ET*) with mean precipitation (*P*) showed that *ET* increased from 485 to 498 mm, while *P* decreased from 684 to 659 mm for the same period (*Li et al.*, 2015). The *P/ET* ratio only changed from 1.41 to 1.32 in the past half century. Therefore, it is unlikely that climate change in this time period would be the only culprit of the peatland shrinkage. What remains might be the impact of gullies on the hydrological properties of peatland. The above-mentioned hydrological changes caused by gullies were mostly for surface runoff and subsurface flow due to storm events. During inter-storm periods, most (if not all) of these fast flows are gone and peat hydrology is more controlled by groundwater flow. However, little is known thus far about the effect of gullies on groundwater flow due to the general lack of field-based hydrological data. Therefore, this study focused on investigating hydrological properties of groundwater in the Zoige peatland under the influence of natural gullies.

According to a widely used gully classification in peatland (Allott et al., 2009), the Zoige peatland generally has class-2 gullies, which have a relatively straight form with a lower drainage density and are often located on sloping lands. To better understand the altered hydrological properties of groundwater, we divide gullies in the Zoige peatland into two types from a different perspective: type-I have beds lying above the bottom of the peat depth, whereas type-II have beds cutting through the peat layer and reaching the underlined mineral soils.

2.2. Study area and sampling sites

The Zoige basin has a continental monsoon climate that involves a long, dry, and cold season from October to April and a short, wet, and warm season from May to September. Annual precipitation varies around 650 mm and the wettest summer months (June-August) take about 60% of the annual precipitation. Precipitation from November to March occurs in the form of snow because of low temperature and the accumulated snow melts gradually from April to May. The basin features widely and gently inclined valleys separated by low mountain ridges. Highly sinuous rivers and gullies extend across the valleys, guiding flows running from southeast to northwest (Fig. 1b). The Zoige peatland belongs to ombrogenous mires whose status is mainly controlled by rainfall (Wheeler, 1995). Peat depth typically varies between 0.8 and 3 m with some exception that could reach as deep as 10 m (observed from a profile of a huge gully wall). The main plant community includes Carex mulieensis, Kobresia, Carex and Tibet Artemisia (Li et al., 2015; Yang et al., 2017). Our study area was located in the peatland near the south ridge of the Black River Watershed (Fig. 1b). The slope of the peat surface is gentle and varies from 0.048 to 0.070.

Three characteristic sites were carefully selected to represent three distinct physical settings of the study area. Site 1 (32° 59′ 11.720″ N, 102° 59′ 23.500″ E) was located on the peat between a first-order type-I (south) and second-order type-II (north) gullies extending from the southwest to northeast direction (Figs. 1c and 2 a). It is a geomorphological hollow, whose elevations are lower than those of the surrounding hummocks. Thus site 1 may be easily saturated during rainfall. The distance from this site to the edges of the type-I and type-II gullies was about 32 and 40 m, respectively. Therefore, groundwater under site 1 is ecohydrologically intact. Site 2 (32° 59′ 06.858″ N, 102° 59′ 13.290″ E) was close to the left side of the first-order type-I gully (about 0.5 m) whose bed was about 35 cm below the peat surface (Figs. 1c and 2b). This gully was shallow and had not been subject to discernable bed incision and bank erosion. So, groundwater under this site is not ecohydrologically intact. Site 3 (32° 59′ 14.151″ N, 102° 59′ 25.592″ E) stayed on the near right of a second-order type-II gully (about 0.5 m) (Figs. 1c and 2c). The gully bed was about 40 cm below the bottom of the peat layer and gully banks collapsed not long before the sampling, indicating very active bank erosion along this gully. Thus, groundwater in the neighboring peat is most possibly disturbed. By measuring the exposed vertical profile of the right bank at site 3, we determined that the peat thickness was about 125 cm deep. Although not measuring it directly, we learned through installing piezometers at sites 1 and 3 that their peat thickness should be at least 125 cm deep. Field measurement began in the middle of May when the daily maximum temperature may be as high as 18 °C. Thus, snow covering the study area in the dry season (i.e., from October to April) had already melted completely. During this period, light rain occurred on some nights and daytime was generally dry. So, our measurements were not directly affected by snowmelt or rainfall.

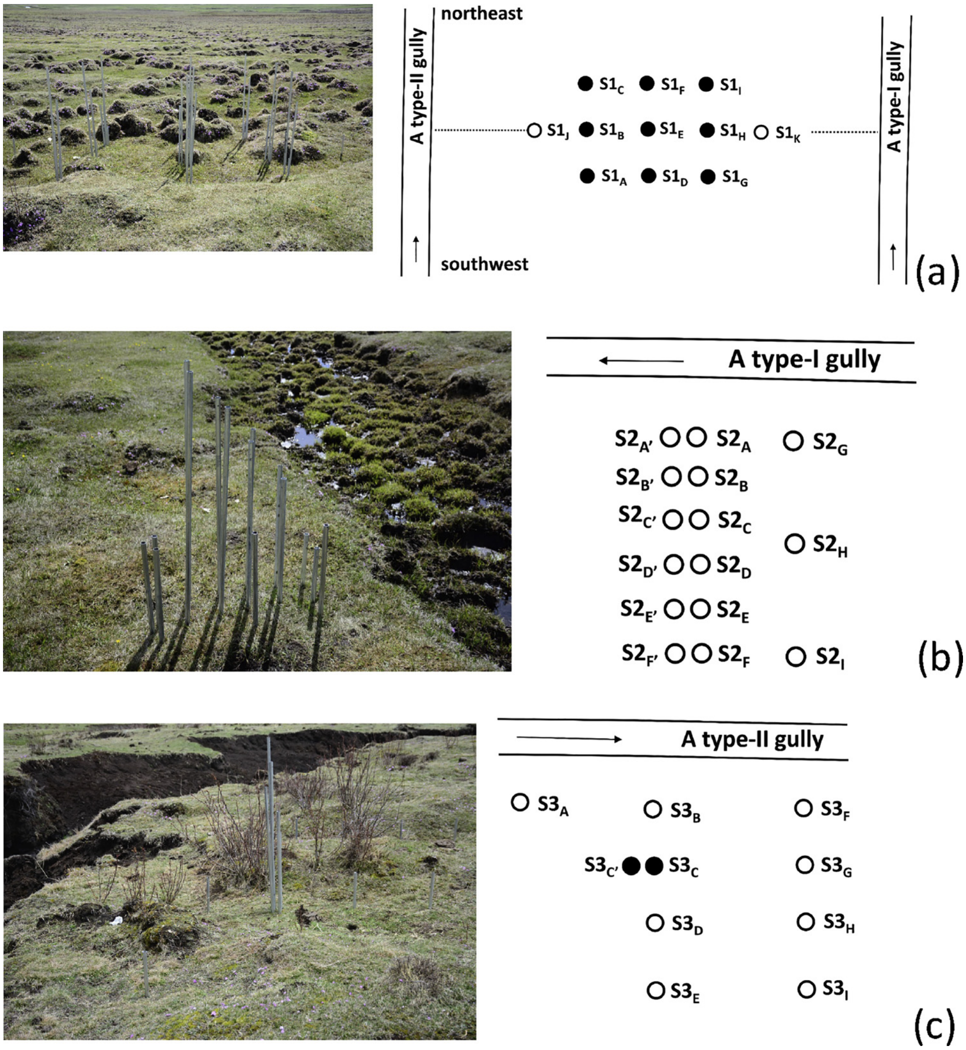

Fig. 2. Physical settings of the three sampling sites (the pictures on the left) and their detailed arrangements of piezometers. Each solid circle represents a nest of multiple piezometers at multiple depths, whereas each open one reflects a piezometer at a certain representative depth. Positions of the piezometers are not to scale. (a) Site 1; (b) Site 2; (c) Site 3; The arrow showed flow direction.

2.3. Sampling design

Both saturated hydraulic conductivity (*K*, cm/s) and hydraulic head (*H*, cm) were measured at variable depths of the peat at the three sites using self-designed piezometers similar to those described in Chason and Siegel (1986). It was made up of a 150-cm iron pipe with outer and inner calibers of 2 and 1.8 cm, respectively. Four rows of perforation holes (four in each row) were evenly distributed with equal intervals in the 10-cm section above the bottom of the pipe, which is open. No filter was installed at the bottom of the piezometer as it was only used within the peat layer. Following Chason and Siegel (1968)' s procedure of installation, an iron rod tightly fitting the piezometer with a tip low end was inserted into the piezometer at the beginning of the installation. It extended about 1 cm beyond the piezometer. Then, both of them were pushed or hammed into the desired peat depth and the rod was pull out.

At site 1, a nest of six piezometers were installed 35, 50, 65, 80, 95, and 125 cm deep at location $\mathbf{S1_E}$ for measuring *K* and *H* values (Fig. 2a). At five different locations ($\mathbf{S1_A}$, $\mathbf{S1_B}$, $\mathbf{S1_C}$, $\mathbf{S1_D}$, $\mathbf{S1_F}$, $\mathbf{S1_G}$, $\mathbf{S1_H}$, $\mathbf{S1_I}$ in Fig. 2a), similar nests of piezometers were placed for measuring *H* values only. The additional two ($\mathbf{S1_J}$ and $\mathbf{S1_K}$ in Fig. 2a) were placed only at the depth of 125 cm for examining the potential spatial variation of the *K* values. This design not only captured the potential spatial variations of *K* and *H* at this site, but also allowed for comparing these *K* values with those at sites 2 and 3.

At site 2, a nest of six piezometers ($\mathbf{S2_A}$, $\mathbf{S2_B}$, $\mathbf{S2_C}$, $\mathbf{S2_D}$, $\mathbf{S2_E}$, $\mathbf{S2_F}$) was placed 35, 50, 65, 80, 95, 125 cm deep for obtaining *K* and *H* values, accompanied by a similar set ($\mathbf{S2_{A'}}$, $\mathbf{S2_{B'}}$, $\mathbf{S2_{C'}}$, $\mathbf{S2_{D'}}$, $\mathbf{S2_{E'}}$, $\mathbf{S2_{F'}}$) for *H* values only (Fig. 2b). Three additional piezometers that were about 50 cm apart from each other with the first one 50 cm away from the gully edge ($\mathbf{S2_G}$, $\mathbf{S2_H}$, $\mathbf{S2_I}$), were placed 35 cm deep along a transect paralleling to the six piezometers for both *K* and *H* measurement (Fig. 2b). Because the 35-cm peat depth is where the type-I gully bed was located, the three piezometers will be used to examine the potential impact of the type-I gully on *K* and *H*. After the measurement, these three (**S2$_G$**, **S2$_H$**, **S2$_I$**) were pushed to the 95-cm depth for understanding the spatial variation of *K* and *H*.

At site 3, two nests of piezometers were installed in two locations at the same six different depths (i.e., 35, 50, 65, 80, 95, 125 cm), one for measuring *K* values (**S3$_C$** in Fig. 2c) and another for *H* values (**S3$_{C'}$** in Fig. 2c). Additional eight piezometers were installed at the depth of 125 cm for understanding spatial variations of *K* and *H* at the bottom of the peat. Three of them (**S3$_A$**, **S3$_B$**, **S3$_F$**) made a transect roughly parallel to the gully with the interval of about 100 cm among each other. They were about 50, 60, and 60 cm away from the gully, respectively (Fig. 2c). Seven of them (except **S3$_A$**) together with **S3$_C$** at the same depth also constituted two perpendicular transects. Piezometers along each transect have approximately the same spacing of 50 cm.

The symmetric design of piezometers was used at site 1 because we believed that at this ecohydrologically intact site, there is no preferential direction of groundwater. The design of piezometers in sites 2 and 3 intended to capture the lateral patterns of groundwater changes. More piezometers were used at site 2 than site 3 because we expected a less degree of groundwater variation at site 2 than site 3. Although it would be better to measure *K* values at all locations, the harsh weather on the Qinghai-Tibet Plateau and limited man power forced us to select only one nest at each site for measuring *K* values.

Besides *K* and *H* values, spatial and temporal variations of water table were also examined at sites 2 and 3. Along two transects perpendicular to each of the two selected gullies, four to five boreholes having the diameter of 10 cm were cored for measuring water table levels.

2.4. Sampling methods

At each peat depth, the *K* value was measured using the classic piezometer slug test method (Hvorslev, 1951), which may be expressed as follow:

$$H_r = \frac{H - h}{H - H_0} = e^{-\frac{FK}{\pi r^2}t} \tag{1}$$

where *H* is the equalization hydraulic head, H_0 is the initial hydraulic head, *h* is the hydraulic head in a piezometer at time *t* after the equalization process begins, *r* is the inner radius of the piezometer caliber, and *F* is the shape factor. After a piezometer was installed at a given depth, 14–18 h were waited before measurement for avoiding the potential impact of installation on measurements. The amount of water whose depth within a piezometer was typically between 10–20 cm was pumped out and H_0 and *H* were recorded. Two to three measurements of *h* and *t* were made depending on how fast the hydraulic head raised. The value of *h* with the highest equalization time (typically between 90% and 98%) was used for calculating the *K* value. The shape factor *F* was calculated using the equation developed by *Brand and Preemechitt* (1982).

At each location and depth, the hydraulic head (*H*) was measured as the length from the water level inside a piezometer to its top. This value was subsequently converted to the one based on (i) an arbitrary datum and (ii) the mean water table level at the same location (described later), respectively. The *H* values measured from multiple locations at the same depth were corrected by considering the differences of their surface elevations. Water table levels along each transect created at sites 2 and 3 were measured from the water surface within the borehole to the peat surface. These values were then adjusted in terms of the differences of their surface elevations. All measurements were performed from May 11 to 23, 2017 with most of them repeated for 3 to 7 times with the average temporal interval of 1 day.

Table 1
Values of hydraulic conductivity ($10^{-5}k$, cm/s) measured in the field.

Peat depth (cm)	Average	St. Dev	CV
Site 1			
−35	1.135	0.562	0.495
−50	2.002	2.086	1.042
−65	2.055	1.602	0.780
−80	1.442	0.865	0.600
−95	2.109	1.258	0.597
−125	2.520	0.552	0.219
Site 2			
−35	0.641	0.122	0.190
−50	0.992	0.447	0.451
−65	2.088	0.849	0.406
−80	1.921	0.856	0.446
−95	1.513	0.781	0.516
Site 3			
−95	1.892		
−125	1.3	0.773	0.595

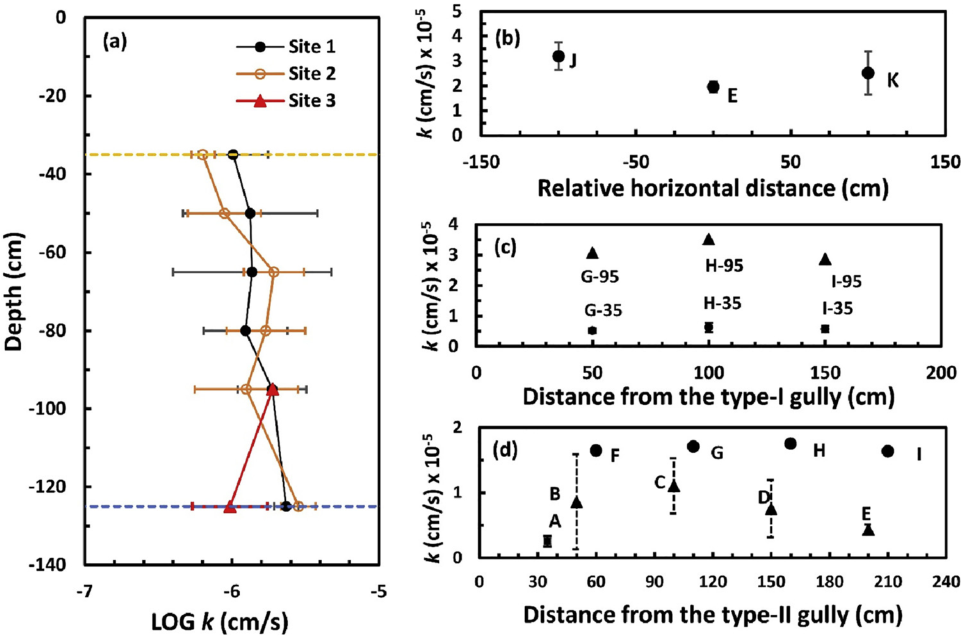

Fig. 3. Spatial variations of saturated hydraulic conductivity measured at the three sampling sites (points with no error bars represented single measurements). (a) Vertical variations of the *K* values at the three sites. The yellow line marked the depth of the type-I gully bed near site 2, while the blue line denoted the depth of the peat bottom; (b) The *K* values measured at the 125-cm depth at site 1; (c) The *K* values measured along the same transect (GHI), but at two different (35- and 95-cm) depths of site 2; (d) The *K* values measured along three different transects at the 125-cm depth of site 3.

3. Results and analysis

3.1. Hydraulic conductivity

In general, *K* values in all sites varied within one order of magnitude (Table 1). The values of their coefficient variance (CV) indicated that *K* values at site 1 had the highest degree of variation. At site 1, vertical distribution of *K* values showed a general increasing trend from the 35-cm depth (1.135×10^{-7} m/s) to the 125-cm depth (2.444×10^{-7} m/s), though around the 80-cm depth, the *K* value became smaller again (1.442×10^{-7} m/s) (Fig. 3a). Even taking account the relatively high variations of the *K* values at most depths (i.e., the error bars in Fig. 3a), this trend apparently persisted. At the 125-cm depth, which was close to the bottom of the peat at this site, *K* values along the JEK transect with the interval of 100 cm (Fig. 2a) did not display any spatial pattern (Fig. 3b). Indeed, *K* values at both J and K locations, which were 3.194 and 2.518×10^{-7} m/s, were about three and two times higher than that at location E, making the mean of *K* values at the 1.25-m depth higher. This further confirmed the increasing trend of *K* values with peat depths at site 1. Given that the peat in site 1 was not disturbed by gullies, the *K* values at all depths and the associated vertical trend at site 1 represent 'standard' characteristics of saturated hydraulic conductivity compared with those in the other two sites.

At site 2, *K* values also displayed an increasing trend with the depth, but had greater variations among the depths (Fig. 3a). In particular, this trend was highlighted by a higher *K* value at the 1.25-m depth (2.335×10^{-7} m/s) and a lower one at the 35-cm depth (0.641×10^{-7} m/s) than those at site 1. Along the GHI transect perpendicular to the type-I gully at the 95-cm depth (Fig. 2b), *K* values were 3.079, 3.520, and 2.872×10^{-7} m/s (Fig. 3c), showing spatial and temporal variations of the *K* values. Their mean, 3.157×10^{-7} m/s, was greater than those at both the 95- and 125-cm depths of site 1 (2.109 and 2.444×10^{-7} m/s), but still comparable. Thus, the differences more likely reflected the spatial variation of the *K* values, rather than the impact of the type-I gully on hydraulic conductivity at these depths. At the 35-cm depth, *K* values along a similar transect to that at the 95-cm depth increased from 0.515 to 0.625 and then decreased to 0.572×10^{-7} m/s (Fig. 3c). These values did not show any specific trend along the transect, but their mean, which was 0.571×10^{-7} m/s, was slightly less than that at the top of the vertical profile depth (0.641×10^{-7} m/s). Compared with that at the same depth of site 1, the *K* value was reduced by 44% to 50% at this site, representing a significant reduction from the 'standard' value. This reduction reflected the clear impact of type-I gully on hydraulic conductivity as this is the depth of the gully bed.

At site 3, hydraulic conductivity was mainly measured at the 125-cm depth (i.e., the bottom of the peat layer) with merely one *K* value available at the 95-cm depth of location C (Fig. 2c). This was because water table at this site varied greatly and may drop to around the 90-cm depth during the sampling period (based on our field observation). Along the FGHI transect, *K* values slightly increased from 1.651 to 1.757×10^{-7} m/s and decreased to 1.640×10^{-7} m/s at the location I, the farthest away from the gully

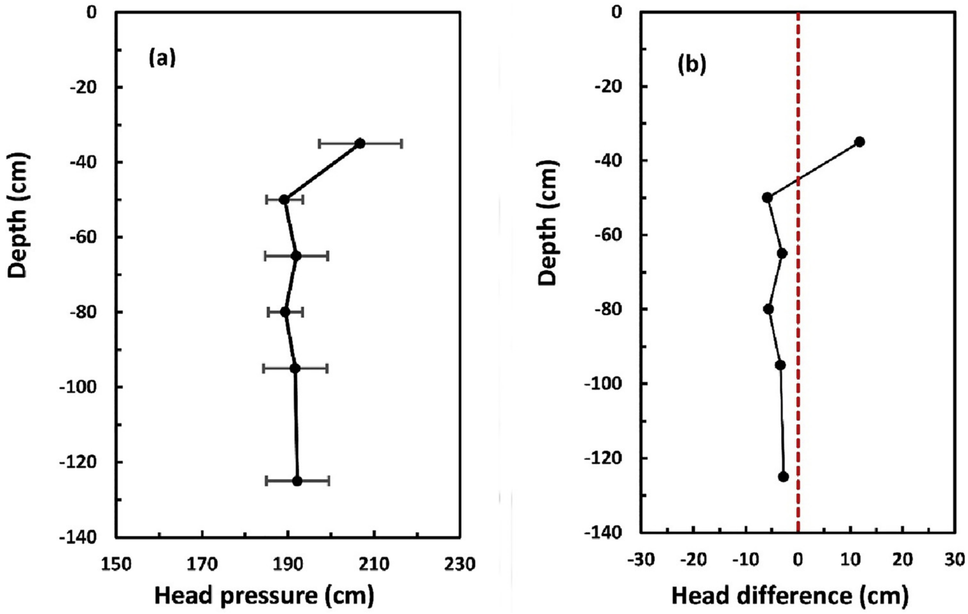

Fig. 4. Hydraulic heads along a vertical profile at site 1. (a) Head pressure denoted the value of hydraulic head above an arbitrary datum; (b) Head difference reflected the difference between the mean hydraulic head and the mean water table at each depth. The red line represented the mean water table level.

edge (Fig. 3d). A similar trend with generally lower magnitudes may be observed along the BCDE transect. The *K* value increased from 0.860 to 1.104 × 10^{-7} m/s and then continuously decreased till 0.434 × 10^{-7} m/s at location E (Fig. 3d). These trends indicated that hydraulic conductivity was highly variable at the bottom of the peat layer nearby the type-II gully. Along the ABF transect (Fig. 2c), *K* values increased significantly from location A (0.254 × 10^{-7} m/s) to F (1.165 × 10^{-7} m/s). Yet, the three distances to the gully edge increased from 35 cm at A to 60 cm at F (Fig. 3d). These two different trends suggested that the type-II gully could cause a significant reduction of hydraulic conductivity at the bottom of the peat close to it and this influence gradually declined with the increase of the distance from it. Comparing that at site 1, the mean *K* value at the 125-cm depth was decreased by 54% (Fig. 3a), further confirmed the strong impact of the type-II gully on hydraulic conductivity. At the 95-cm depth, the *K* value at site 3 was 1.892 × 10^{-7} m/s, which was 10% less than that at site 1, suggesting the weakened effect of the type-II gully on hydraulic conductivity as the peat depth decreases.

3.2. Hydraulic heads

Values of hydraulic heads for site 1 were summarized using the data measured from locations of A, B, C, D, E, F, G, H, and I at different peat depths (Fig. 2a). The vertical profile of hydraulic heads did not show a clear gradient below the 50-cm peat depth (Fig. 4a), while the hydraulic head increased from the 50-cm to the 35-cm depth. This spatial pattern implied relatively less vertical movement of groundwater in the lower zone from the 50-cm depth to the bottom of the intact peat, though hydraulic conductivity increased with the depth. Comparison of the mean hydraulic heads at multiple peat depths with the mean water table indicated (Fig. 4b) that the lower zone in the intact peat belonged to a recharge zone, suggesting that groundwater may be supplied from the upper peat (above the 50 cm) to this zone. Although the hydraulic heads in the 35-40-cm depth, which were higher than water table (Fig. 4b), may cause possible groundwater upwelling (Siegel and Glaser, 1987), this upward discharge may not be stable because of variable water table, which will be described later. Nonetheless, Figs. 4a and b described the ‘standard’ patterns of the hydraulic head along a vertical profile of the intact peat in the study area.

Values of hydraulic heads measured by two nests of piezometers at six different depths of site 2 (Fig. 2b) were averaged at each depth for the entire sampling duration. These data displayed (Fig. 5a) that though hydraulic heads were generally lower than those at site 1 (Fig. 4a), they developed a gentle gradient from the 35- to 80-cm peat depth and then remained similar from the 80-cm to the 125-cm depth. Comparing with the vertical pattern at site 1, the gradient at site 2 was apparently caused by the less reduced hydraulic heads from the 80-cm to the 35-cm depth. Furthermore, these less reduced hydraulic heads were higher than the mean water table (Fig. 5b), generating a similar vertical pattern to that at site 1. On the one hand, higher hydraulic heads around the 35–60 cm depth turned the deep peat between 80 and 125 cm into a recharge zone. On the other hand, the higher hydraulic heads at these depths created a possibility of groundwater upwelling. Horizontally, the mean hydraulic heads along a transect perpendicular to the type-I gully at the 35-cm peat depth not only showed no significant gradient, but also changed in magnitudes only by less than 3% among each other (Fig. 5c), indicating no clear lateral hydraulic gradient toward the type-I gully in its neighboring peat.

Hydraulic heads at site 3 were only measured from the 60- to 125-cm depths due to significantly lowered water table. These

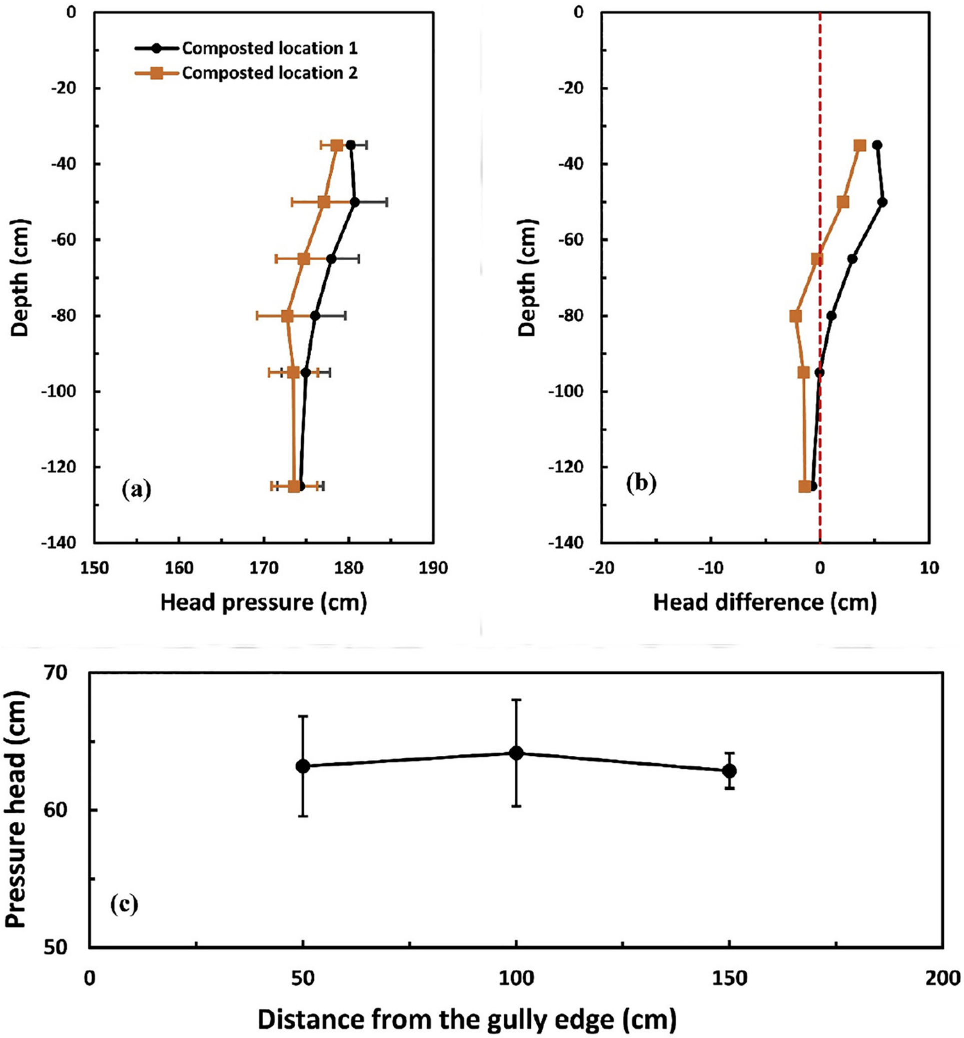

Fig. 5. Spatial distributions of hydraulic heads at site 2. (a) The *H* values along two vertical profiles. Composited location 1 reflected the depths at A, B, C, D, E, and F in Fig. 2b, while Composited location 2 reflected the depths at A', B', C', D', E', and F' in Fig. 2b; (b) The differences of *H* values and the mean water table at all depths; (c) The *H* values along a horizontal transect at the 35-cm depth.

values were also less than those at similar depths of site 1 and the degree of reduction was greater than those at site 2 (Figs. 4a, 5a, and 6a). Vertically, they created a steeper gradient within the 60–95 cm depth compared with that at site 2 (Fig. 5a and 6a). From the 95-cm depth to the bottom of the peat, the hydraulic head continued to decrease, but with a less gradient. These changes led to a discernable low hydraulic head at the bottom of the peat layer. This low value clearly indicated the strong impact of the type-II gully on the hydraulic head at the bottom of the peat layer. Levels of the hydraulic heads at all depths were much lower than that of water table (Fig. 6b), again indicating groundwater in the peat depths close to the bottom was recharged from that in the upper part. Associated with this spatial pattern were the relatively higher variations of the hydraulic heads at each peat depth compared with those at sites 1 and 2 (Figs. 4a, 5a, and 6a), which further embodied the impact of the type-II gully on the hydraulic heads of the nearby peat. Horizontally at the 125-cm depth, averaged values of hydraulic heads along two transects perpendicular to the type-II gully demonstrated evident gradients toward the gully edge (Fig. 6c). The gradient along the BCDE transect (Fig. 2c) was greater than that along the FGHI transect, which is associated with the fact that the former was closer to the gully edge than the latter. These gradients suggested the existence of groundwater flow to the gully bank at the depth equivalent to the bottom of the peat layer.

3.3. Water table levels

Much of the time during the field measurement, the peat surface at site 1 was saturated. Its temporal variation was limited with the mean value approximately around the 5-cm depth, which was the one used as a reference for calculating relative hydraulic heads at the same site (Fig. 4b). Along transect 1 at site 2, the mean water table level was lower at the location 100 cm away from the gully edge (Fig. 7a) and linearly increased to that 200 cm away from the gully edge. It then stayed about the same level in the next 100 cm.

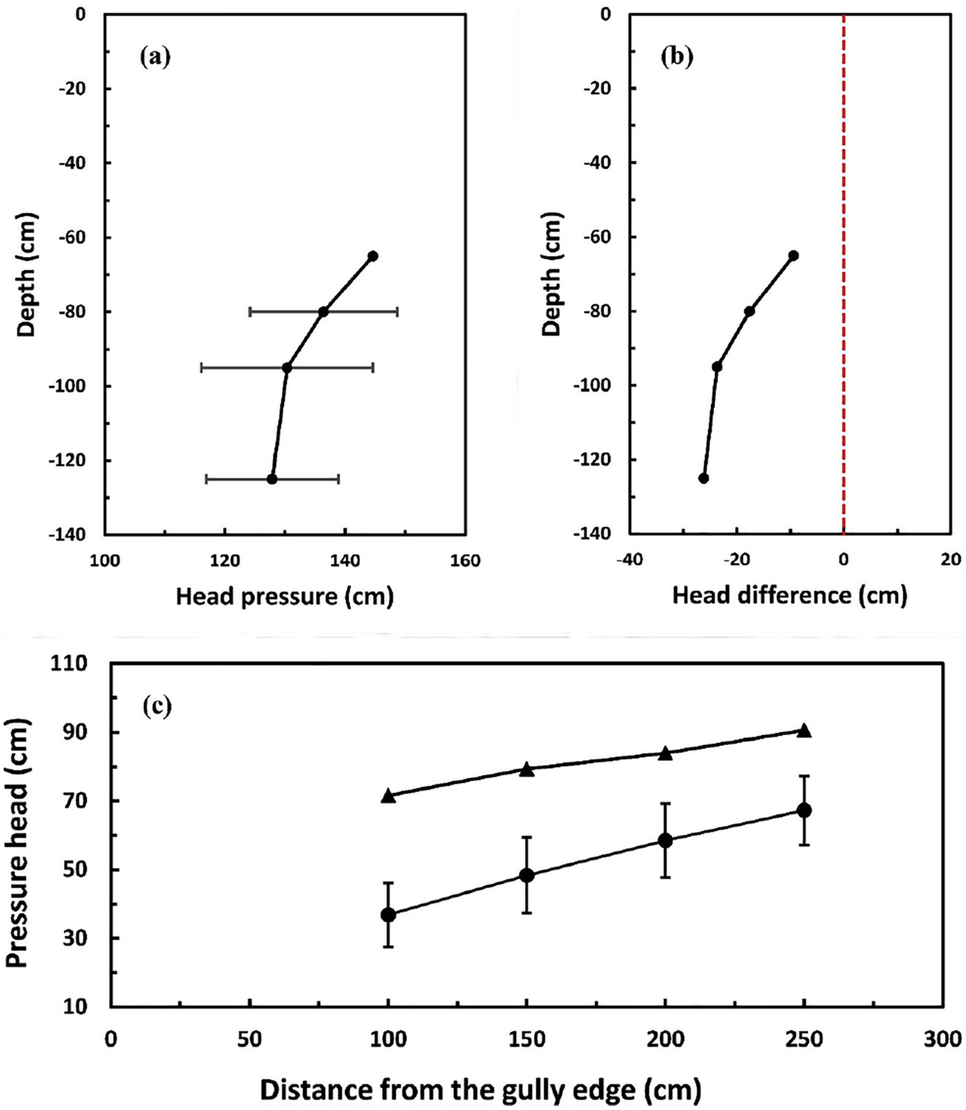

Fig. 6. Spatial distributions of the mean hydraulic heads at site 3. (a) Mean *H* values along a vertical profile at site 2; (b) The same mean *H* values based on the mean water table; (c) Mean *H* values along two horizontal transects at the 125-cm depth.

This spatial pattern was apparently similar to the drawdown effect of water table. Yet, water table along transect 2 displayed a different trend. While it raised from the distance of 100 to 150 cm away from the edge, water table dropped in the following 150-cm distance to lower levels (Fig. 7a). On average, the two transects at site 2 were apart from each other for only about 160 cm. Thus, the different trends of water table levels along them suggested that reduction of water table as the distance away from the gully edge increases was not consistent in the peat next to the type-I gully. The relatively high error bars in all locations at site 2 (Fig. 7a) suggested that temporal variation of water table at site 2 was relatively high.

Our field observation at site 3 indicated that water table changed obviously and consistently along the distance away from the gully edge. This was corroborated by the measured changes of water table along two transects perpendicular to the type-II gully (Fig. 7b). At the location around 100 cm away from the gully edge, water table level was on average 61.6 cm and 51.8 cm below the peat surface, respectively, regarding to each transect. In the following 400-cm distance, it raised to 39.5 and 35.1 cm along the two transects, respectively. The significant and consistent changes of water table along these two transects suggested that the type-II gully clearly caused the drawdown effect of water table in the peat close to it. Water table levels were generally lower with higher degrees of variation in transect 1 than in transect 2. This might reflect the nature of its high spatial variation.

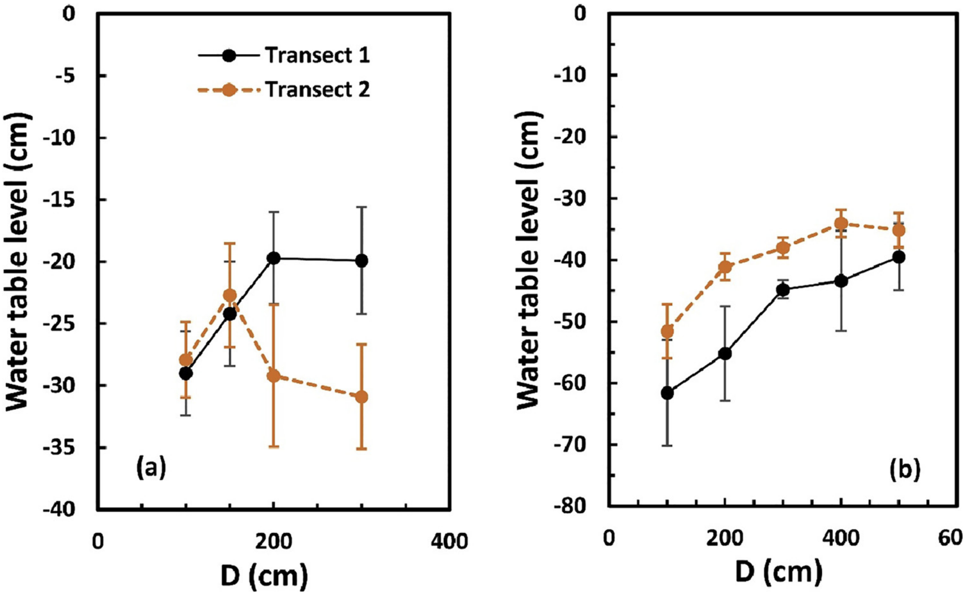

Fig. 7. Water table levels along transects perpendicular to the gullies. The horizontal axis represents the distance away from the gully edge. (a) Site 2; (b) Site 3.

4. Discussions

4.1. Uncertainties in measuring hydraulic conductivity and its variability

Field methods of determining hydraulic conductivity are essentially derived from the rigid soil theory assuming that Darcy's law holds and soil is incompressible. Eq. (1) holds when (i) soil is incompressible and (ii) water table is not affected by flow required for equalization (Hvorslev, 1951). Unfortunately, the compressible nature of the peat and possible smearing of the peat around the piezometer intake could affect the equalization process (Baird et al., 2004; Hogan et al., 2006; Holden and Burt, 2003b), leading to errors in calculating K values. Although this method has been widely used (Fraser et al., 2001; McCarter and Price, 2013; Robbins et al., 2009; Rossi et al., 2012; Whittington and Price, 2006), few have addressed potential errors explicitly. Holden and Burt (2003a)'s investigation showed that K_{90} was generally six times higher than K_{50}, where K_{90} and K_{50} are values of hydraulic conductivity calculated using the 90% and 50% equalization time in Eq. (1), respectively. They also reported that K values calculated using the monograph method (Brand and Preemechitt, 1982) was not only significantly smaller than those based on Eq. (1), but also more sensitive to spatial locations. Baird et al. (2004) found that the equalization process is consistent with that based on Eq. (1) for root mat. Surridge et al. (2005) scrutinized Eq. (1) by performing carefully designed slug tests and concluded that though the recovery processes were generally not log-linear, the estimated K values using Eq. (1) were acceptable. Thus, we think that Eq. (1) is the appropriate one for determining K values and used it in this study.

In reality, however, peat matrix is highly deformable (Price and Schlotzhauer, 1999) and the resultant peat expansion and compaction inevitably affect the K values computed using Eq. (1). During our field measurement, we examined the stability of the equalization hydraulic head (i.e., H, cm) by recording water levels within piezometers adjacent to the test piezometer at the beginning and end of each slug test and comparing these levels between the two. We found that in many tests, these water levels changed with different magnitudes at different peat depths (Fig. 8a). The greater error bar of the top point indicated a higher temporal variation of the hydraulic head changes at the 35-cm depth. These changes suggested that the inflow rate was not stable during the slug test. Thus, the assumption that the original inflow rate remained unchanged as required by Eq. (1) (Freeze and Cherry, 1979) was invalid. This variation directly affected calculation of the head ratio (i.e., H_r) and subsequently the K values. Our examination showed that K values estimated by considering the variable inflow rates were on average close to the non-adjusted ones except at the 50- and 80-cm peat depths where the former were about 35% higher than the latter (Fig. 8b). This relatively small difference, compared with the high variability of hydraulic conductivity (Holden and Burt, 2003b; Surridge et al., 2005), allowed us to treat the variable equalization hydraulic head as one of the errors in the calculation and adopt the non-adjusted K values in the analysis.

As site 1 was located in the ecohydrologically intact peat, the K values at this site represent the first measured set of primitive saturated hydraulic conductivity in the Zoige peatland, which varied from 1.135 to 2.520 × 10^{-5} cm/s (Table 1). The variation was within one order of magnitude and seemed less than that in many other peatlands (Hobbs, 1986; Surridge et al., 2005; Whittington and Price, 2006). Although these K values were within the same range as those in the north Pennines, UK (Holden and Burt, 2003a), they were at least one order of magnitude less than those in an undisturbed blanket peat in British Isles. The difference might be due to the fact that the latter were measured using a different method based on a mini-disc tension infiltrometer (Wallage and Holden,

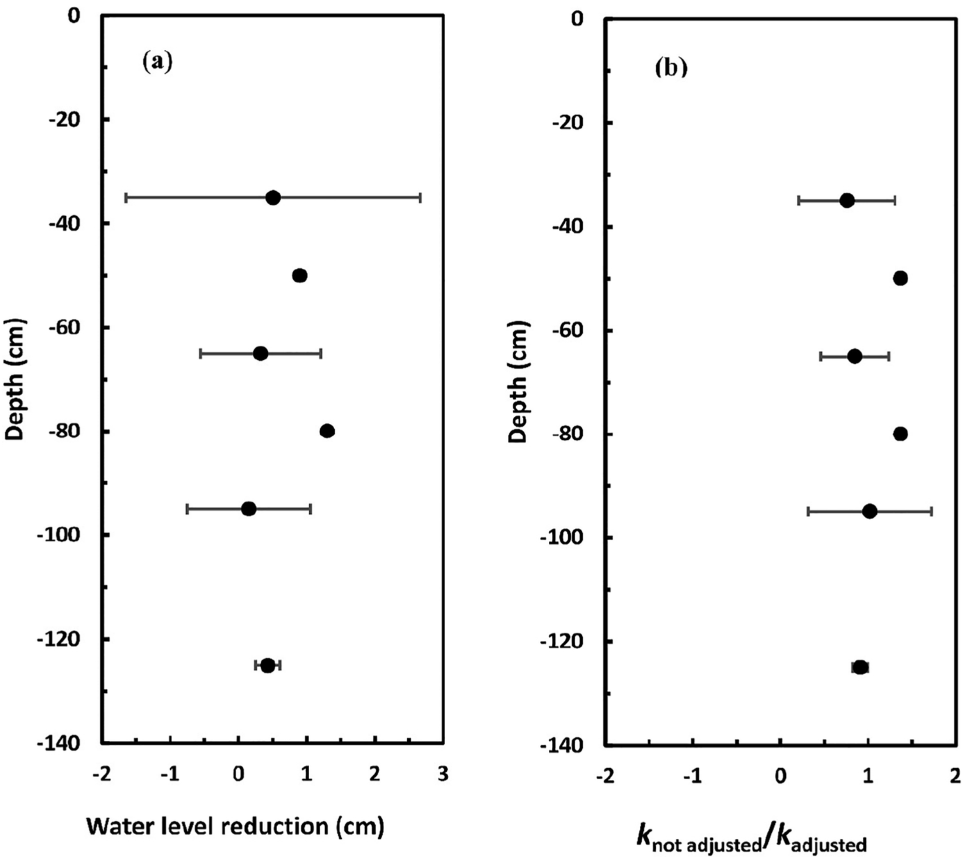

Fig. 8. Impact of variable inflow rates on calculation of the K values. (a) Variable equalization hydraulic heads at different peat depths. Water level reduction referred to the difference of equalization hydraulic heads between the test piezometer and its surrounding ones; (b) Ratio of the K value calculated using the equalization hydraulic head at the test piezometer ($K_{\text{not-adjusted}}$) to that based on the surrounding piezometers (K_{adjusted}).

2011). Since the study area is representative of the Zoige peatland that is mainly made of fabric peats with a low deteriorated root system (Chai and Jing, 1963; Sun, 1992), our measured K values may be compared with those obtained in Canada and indeed were within the range of those values (Letts et al., 2000). The increasing trend of the mean K values with the peat depth (Fig. 3a) is at odds with many previously reported results (Fraser et al., 2001; Glaser et al., 1981; Hoag and Price, 1995; Whittington and Price, 2006), while consistent with others in different peatlands (Baird et al., 2008; Clymo, 2004). Apparently, saturated hydraulic conductivity in the study area within the Zoige peatland seems not drastically different from that in blanket peatlands of other places, though more measurements in other summer months are needed to show its temporal variations.

4.2. Distinct impacts of two types of gullies on peat groundwater

According to Darcy's law, hydraulic properties of groundwater flow are primarily controlled by hydraulic conductivity (K) and hydraulic head (H). The different K and H values between site 1 and the other two sites presented a possibility that two types of gullies might have different impact on groundwater flow in the Zoige peatland. The type-I gully modestly reduced hydraulic conductivity at the 35-cm depth by about 30% as the gully bed only reached this depth (Fig. 3a). From this depth to the bottom of the peat, the differences of the K values between sites 1 and 2 were well within the typical range of spatially variable hydraulic conductivity in blanket peats (Surridge et al., 2005), suggesting that these values were not subject to the impact of the type-I gully at least during the study period. The relatively lower H values at all depths than those at site 1 and a gentle hydraulic gradient crated by the higher H values at the 35–65 cm depths than the mean water table level (Fig. 5a and b) signified a possibly greater influence of the type-I gully on the hydraulic head than the hydraulic conductivity. While these changes of H values may result in possible groundwater downwelling, the reduced hydraulic conductivity (Fig. 3a) within these depths may offset this possibility. Therefore, the type-I gully had limited influence on hydraulic properties of groundwater. This limited influence was supported by the insignificant changes of water table levels along the two horizontal transects perpendicular to the gully at the 35-cm depth. Comparing with the variation of water table at site 1, which was typically between 0 and 15-cm depths, the change at site 2 ranged from 20- to 31-cm depths. This difference is more likely related to the topographic difference of the two sites (elevations of site 1 were much lower than those of surrounding hummocks than those at site 2), as earlier studies have shown that topography is a dominant control on the change of water table levels of peats (Holden et al., 2006, 2011).

At site 3, the type-II gully had a significant impact on not only water table but also K and H values. The water table level at the location of 100 cm away from the gully edge dropped about 22 cm compared with that at the location 500 cm away from the gully edge (Fig. 7b), clearly showing the distance decay effect as observed in other peatlands (Allott et al., 2009; Boelter, 1972). Compared with that at site 1, the water table level decreased significantly, but the K value at the 95-cm depth was very close to that at the same depth of site 1 (Fig. 3a). Nonetheless, at the bottom of the peat, the mean K value was reduced by 50% compared with that at site 1. This reduction was more likely affected by the nearby type-II gully, which cut through the peat layer along the banks. In addition, this gully induced significantly decreased hydraulic heads at all depths, such that their levels were all lower than that of the water table (Fig. 6b). These decreased hydraulic heads also created a significant downward hydraulic gradient with the slope of 0.305 (Fig. 6b), which was much steeper than that in a blanket bog located in Newfoundland, Canada (Price, 1992). It followed that the peat body around the bottom became a strong recharge zone. The discovery of this recharge zone explained the significant drop of water table at this site and suggested that groundwater steadily moved toward the bottom of the peat layer.

More importantly, at (or near) the bottom of the peat (i.e., 125 cm deep), the type-II gully created a clear and strong hydraulic gradient horizontally toward the gully edge with an average slope of 0.051 (Fig. 6c). Therefore, though the mean hydraulic conductivity decreased from 2.444 to 1.129×10^{-5} cm/s at this peat depth, the emerged horizontal gradient (i.e., 0.051) led to an approximate rate of groundwater flow (i.e., specific discharge) at 0.0576 mm/day draining out of the gully banks, Given that this calculation ignored anisotropy of hydraulic conductivity, it may not be truly accurate (Beckwith et al., 2003; Fraser et al., 2001). However, this flow rate provided the first estimation of groundwater flow through the broken bottom of the peat at the banks of the type-II gully in the Zoige peatland. *Holden et al.* (2006) believed that enhanced flow in deeper peat that is affected by artificial ditches is possibly attributed to the increased hydraulic conductivity. However, our data showed that the K value at the bottom of the peat (the 125-cm depth) next to the type-II gully was indeed decreased compared with that of the intact peat (i.e., site 1). Thus, the increased lateral discharge at site 3 was groundwater flow mainly due to the development of both vertical (downward) and horizontal (toward the gully edge) hydraulic gradients. Because our findings were only based on measurements in 13 days of May 2017, whether these interpretations remain true in other summer months is still unknown and requires further data collection to confirm. Nonetheless, these findings provided the first field-based evidence on how the type-II gully may change the groundwater of the Zoige peatland. It should be noted that though hydraulic conductivity at the bottom of the peat was reduced, it is still two orders of magnitude higher than that in deeper peats in north Pennine, UK (Holden and Burt, 2002). Whether it is due to the limitation of the current data or the fact that the Pennine peat depth, which is about 250 cm, is higher than that (i.e., 125 cm) in our study area awaits for more in situ studies.

Our data signified the possibility that the altered groundwater hydrology of peatland by a neighboring type-II gully may occur at or near the bottom of peat. Since the type-II gully has already cut through the peat layer, exactly how deep the gully bed goes further down seems to have no impact on the altered groundwater hydrology of peat. On the contrary, the change of hydraulic properties of groundwater in the peat next to a type-I gully appears to be related to the depth of the gully bed, though in our case at site 2, the change was not significant. So, it is not clear whether a type-I gully with a deeper bed would cause an alteration of groundwater at the similar depth in the nearby peat. Putting these together, gully depth in general may not be a sensitive parameter that can test the impact of gullies on water table. This might be a factor causing the poor relationship between the two in an earlier study (Allott et al., 2009). Nonetheless, the high degree of water table drop near the type-II gully did support the term ‘erosional acrotelm’ coined to describe the enlarged acrotelm due to the nearby gully (Daniels et al., 2008).

4.3. Possible implication of gully impact on peat

Our field observation indicated that groundwater seepage from the bottom of the peat layer may be easily identified along banks of the type-II gully. Different from that caused by perched water table, which may be substantial and initiate soil erosion (Fox et al., 2007), this groundwater seepage was not large enough to even contribute to the baseflow of the gully channel. Yet, it had persisted over the entire sampling period, keeping the underlying mineral bank wet all the time (Fig. 9). We noticed that the wet mineral banks did not necessarily exist everywhere along the longitudinal direction of the gully. Some sections of gully banks were covered by collapsed bank materials and hence groundwater seepage was not observable. Wherever the mineral bank and its immediate top peat were dry, the peat layer that constitutes a series of roughly paralleled stratification or stratigraphy (Hughes et al., 2000) showed

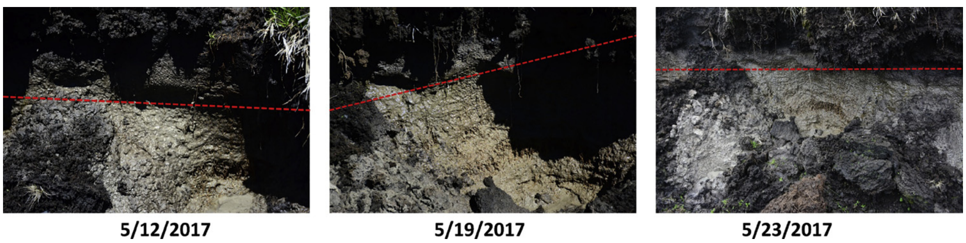

Fig. 9. Evidence of wetted mineral soils immediately below the broken peat layer. The red line indicated the bottom of the peat layer. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

Fig. 10. Evidence of cracks and small holes near or at the bottom of the peat layer. (a) Cracks around the peat bottom; (b) Small holes at the peat bottom.

horizontal cracks near or at the bottom of the peat or a few small holes (Fig. 10). These cracks and/or small holes that have been also reported in other peatlands (Grab and Deschamps, 2004; Holden and Burt, 2002) suggested that the preferential flow (or pipe flow), which moves much faster than groundwater flow (Holden and Burt, 2002; Holden et al., 2001; Wallage and Holden, 2011), facilitated water to drain quickly and resulted in the dried minerals at these locations. Our data and field observation suggested that enhanced groundwater flow through type-II gullies created by intense erosion processes could be a significant cause for it, though data collected over longer time periods (e.g., two to three years) are required to further confirm our findings.

5. Conclusions

Impact of gullies on hydrological properties of groundwater in the Zoige peatland, China was investigated using field-measured data for saturated hydraulic conductivity (K), hydraulic head (H), and water table levels at three representative sites, one (site 1) on the intact peat that has not been disturbed by gullies and the other two (sites 2 and 3) next to the type-I and type-II gullies, respectively. In comparison with those at site 1, spatial patterns of these data at sites 2 and 3 revealed the distinct effects of the two types of gullies on groundwater hydrology. The type-I gully with a shallow bed located at the 35-cm peat depth only caused the reduction of the K value at this depth by 30%, which was most likely related to the lowered water table level that may be at the 25-cm peat depth, and may had less effect on the distribution of hydraulic conductivity in the direction perpendicular to the gully. It also led to generally decreased hydraulic heads along a vertical profile of the peat. These H values created a downward hydraulic gradient with the upper peat at the 35–50 cm depth having hydraulic heads higher than the mean water table level. This change may cause possibly weak upwelling and downwelling of groundwater from this depth because of the gentle hydraulic gradient. Thus, the impact of the type-I gully on groundwater seems to be fairly limited. Given that artificial ditches created in the Zoige peatland during 1950–1980 s generally have beds within the peat layer, these ditches share similar hydrological functions with type-I gullies and might have limited impact on groundwater hydrology as well.

Groundwater in the peat near the type-II gully could be strongly affected by the broken bottom of the peat. Water table level decreased significantly and demonstrated a strong distance decay effect. Associated with it was the decrease of hydraulic conductivity by 50% around the bottom of the peat. In addition, hydraulic heads along a vertical profile were all lower than the mean water table level with a steep downward hydraulic gradient. This change made the deep peat a recharge zone and had maintained groundwater moving downward. Horizontally at the bottom of the peat, reduced hydraulic heads formed a clear hydraulic gradient toward the gully edge, which resulted in a 'leaking effect' (i.e., groundwater seepage) at the bottom of the peat along the gully banks.

Because our data were only obtained in May 2017, whether this leaking effect persists through the summer and winter is uncertain. If it exists over the whole year, then enhanced groundwater flow from the type-II gullies may be a significant cause for Zoige peatland shrinkage. Since gully erosion in the Zoige peatland is geomorphologically controlled by the geologically lowered base level of the Upper Yellow River downstream of the Zoige basin, development of the type-II gullies will continue even if climate change remains the minimum. Therefore, more studies are necessary for confirming this potentially important cause.

Acknowledgements

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