The high hydraulic conductivity of three wooded tropical peat swamps in northeast Peru: measurements and implications for hydrological function.

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Abstract

The form and functioning of peatlands depend strongly on their hydrological status, but there are few data available on the hydraulic properties of tropical peatlands. In particular, the saturated hydraulic conductivity (K) has not previously been measured in Neotropical peatlands. Piezometer slug tests were used to measure K at two depths (50 and 90 cm) in three contrasting forested peatlands in the Peruvian Amazon; Quistococha, San Jorge, and Buena Vista. Measured K at 50 cm depth varies between 0.00032 and 0.11 cm s^{-1}, and at 90 cm it varies between 0.00027 and 0.057 cm s^{-1}. Measurements of K taken from different areas of Quistococha showed that spatial heterogeneity accounts for c. 20 % of the within-site variance, and that depth is a good predictor of K. However, K did not vary significantly with depth at Buena Vista and San Jorge. Statistical analysis showed that c. 18 % of the variance in the K-data can be explained by between-site differences. Simulations using a simple hydrological model suggest the relatively high K values could lead to lowering of the water table by > 10 cm within c. 48 m of the peatland edge for domed peatlands, if subjected to a drought lasting 30 days. However, under current climatic conditions, even with high K, peatlands would be unable to shed the large amount of water entering the system via rainfall through subsurface flow alone. We conclude that most of the water leaves these peatlands via overland flow and/or evapotranspiration.

1. Introduction

The hydraulic conductivity (*K*) of peat depends strongly on the type and degree of decomposition of plant material forming the peat (Boelter, 1969; Päivänen, 1973). Because it (in part) controls the rate at which water flows through a peatland, *K* affects the position and dynamics of the water table. The water-table behaviour in turn affects vegetation type and the rate of peat decomposition, so *K* is part of an ecohydrological feedback loop which is fundamental to the functioning of any peatland (Morris *et al.*, 2011). As such, an understanding of *K* is essential for understanding peat accumulation and soil carbon dynamics (Morris *et al.*, 2011; Baird *et al.*, 2012).

Most of the work on tropical peatlands has been undertaken in Southeast Asia (e.g. Anderson and Muller, 1975; Page *et al.*, 2004; Hooijer *et al.*, 2010). Whilst it has been known for some time that there are substantial peatland areas in Amazonia (Andriesse, 1988; Schulman *et al.*, 1999), field data on their properties have only recently begun to be collected (Lähteenoja *et al.*, 2009a,b, 2012; Lähteenoja and Page, 2011; Householder *et al.*, 2012). Amazonian peatlands, which are thought to cover c. 150,000 km^2 (Schulman *et al.*, 1999), are likely a globally-significant part of the carbon cycle (Lähteenoja *et al.*, 2009a, 2012; Lähteenoja and Page, 2011), storing around 9.7 Pg of carbon, out of a total of 88.6 Pg for all tropical peatlands (Page *et al.*, 2011).

Despite its importance as a factor in the ecohydrological functioning and development of peatlands, there are few published data on the *K* of tropical peats (e.g. Takahashi and Yonetani, 1997; Nugroho, 1997; Sayok *et al.*, 2007). Indeed, to our knowledge, there are no *K* data for Amazonian peatlands. Therefore, the aims of this study were to determine *K* in three typical Amazonian peatlands; to compare these values with measurements from peatlands in other parts of the world; and to explore the implications in terms of the likely functioning of Amazonian peatlands, including their likely response to climate change.

This study also sought to test three hypotheses relating to within-site and between-site variation. We selected three sites with different vegetation compositions and nutrient inputs, which broadly represent the range of sites that have been described from western Amazonia (Lähteenoja *et al.*, 2009a,b, 2011), but the full variability of Amazonian peatland form and function remain to be explored.

Hypothesis 1: K *varies within the uppermost c. 1m of the peat profile.*
In many peatlands *K* decreases with depth (*cf.* Armstrong, 1995), although this is not always the case (e.g. Chason and Siegel, 1986) and *K* can both increase and decrease abruptly between different peat layers (e.g. Baird *et al.*, 2008). For tropical peatlands there is no published information on variation in *K* near the peat surface where it is likely that *K* is highest and there is a substantial flow of groundwater (*cf.* Takahashi and Yonetani, 1997).

Hypothesis 2: K *varies spatially between different parts of the peatland.*

Models of groundwater flow in temperate peatlands have shown that it is important to consider spatial heterogeneity in physical properties such as *K* (*cf.* Beckwith *et al.*, 2003; Belyea and Baird, 2006). Lapen *et al.* (2005) suggested that water tables towards the centre of a peatland may be maintained, in part, by peripheral areas that have low *K*, these areas acting as a type of dam. Baird *et al.* (2008) showed that a lower-*K* margin may exist in some temperate raised bogs, and Lewis *et al.* (2012) found a comparable pattern in an Irish blanket peatland. As such, we sought to examine the heterogeneity of *K* in a tropical peat swamp by testing whether there was a significant difference in *K* values from three contrasting locations on the peatland (Figure 1).

Hypothesis 3: K *varies between different wooded tropical peatlands.*

In tropical peatlands, the depth of the active zone may be much greater than in most northern peatlands (Page *et al.*, 2006), and the distribution of major elements in tropical peat profiles has shown that the zone of elemental recycling by vegetation could extend from 50 to 200 cm (Weiss *et al.*, 2002). If vegetation has a significant effect on *K* through controls on the litter input (*cf.* Boelter, 1969; Päivänen, 1973), then this raises the possibility that there is a link between the recent vegetation which has grown over the last c. 200 years (*cf.* Weiss *et al.*, 2002; Lähteenoja *et al.*, 2009a), and the hydraulic properties (including *K*) in the top metre of the peat. We selected three forested peatlands spanning a broad nutrient gradient extending from highly minerotrophic (Buena Vista), through intermediate (Quistococha) to ombrotrophic conditions (San Jorge) (Lähteenoja *et al.*, 2009b). We hypothesised that the physical properties of the litter would be different, as all of these sites are occupied by different vegetation assemblages (Table 1). As such, the initial hypothesis was that there would be a significant variation in *K* between the sites.

We explored the implications of our findings through simulation modelling. Model runs were undertaken to estimate the effect of different *K* values on sub-surface flow, and by a process of elimination, the degree to which water loss from Amazonian peatlands occurs via overland flow and evapotranspiration. The models were run with the intention of examining how the length of a 'drought' period (or extended dry season) might affect the draw-down zone at the edge of the modelled peatland.

2. Materials and Methods

2.1 Site descriptions

K was measured at three different forested peatlands in the Peruvian Amazon using the piezometer method (*Section 2.7*). The first of these sites was examined in detail in order to test Hypotheses 1 and 2. The site is called Quistococha (3°50' S, 73°19'W), after the lake at its centre; the centre of the site lies 10 km west of the main channel of the Amazon River (Figure 1A). The site was chosen for detailed study both for its ease of access and because, on floristic grounds (Table 1), it may represent one of the most common types of peatland ecosystem in western Amazonia (Lähteenoja *et al.*, 2009a). The site consists of an approximately circular lake with a surface area of 1 km^2 (Räsänen *et al.*, 1991), around which are substantial (> 4 m depth) peat accumulations (Lähteenoja *et al.*, 2009a). The peatland abuts the edge of the lake, and field evidence suggests that this margin may be eroding. The peat lies on an impermeable substrate of riverine or lacustrine clay. Lähteenoja *et al.* (2009a) gave a radiocarbon date for the basal age of the peat in a core (390–400 cm depth) of 2335 ± 15 cal. yrs BP. Lähteenoja *et al.* (2009b) showed that the elemental composition of the peat at Quistococha is consistent with a dominantly ombrotrophic system, although the moderately high Ca/Mg ratio suggests that there is at least some groundwater input. The water table at Quistococha was monitored from the end of July 2011 to July 2012 using a pair of 'Micro-Diver' and 'Baro-Diver' self-logging pressure transducers (see *Section 2.7*). During the dry season, water levels varied from a minimum of 27 cm below the peat surface to 9 cm above the surface. During the wet season in 2012, the site was affected by a flood which reached a height of c. 1 m above the peat surface. However, this is untypical for the site (the site does not flood in most years; V. Reategui, pers. comm.).Wet season variation in the peat water table was from 5 cm below the surface to 18 cm above the surface, if the flood is excluded (T.J. Kelly *et al*., unpublished data).

Two other sites were also investigated during 2012 in order to test Hypothesis 3; San Jorge (4°03' S, 73°11' W) and Buena Vista (4°14' S, 73°12' W). The Buena Vista peatland lies 55 km south of Iquitos, adjacent to the Tahuayo River, which is a tributary of the Amazon (Figure 1A). The site was investigated by Lähteenoja *et al.* (2009a) who found peat accumulations of up to 290 cm. A radiocarbon date from the base of the peat produced an age of 1217.5 ± 42.5 cal. yrs BP. Unlike Quistococha, Buena Vista is flooded on an annual basis; this additional source of nutrients is reflected in a much higher peat Ca/Mg ratio, and markedly different vegetation presumably reflecting a greater supply of nutrients (Table 1).

San Jorge is a domed peatland (*cf.* Lähteenoja *et al.,* 2009b), which is not subjected to annual flooding at the point where the measurements were taken for this study. San Jorge lies 35 km south of Iquitos, adjacent to the Amazon River (Figure 1B). The low Ca/Mg ratio of the peat suggests that this is a strictly ombrotrophic system (Lähteenoja *et al.,* 2009b). Lähteenoja *et al.* (2009a) obtained a basal date of 2945 ± 65 cal. yrs BP from a depth of 560-570 cm, making this site the oldest of the three peatlands in this study.

2.2 Regional climate

The region in the vicinity of Iquitos is one of the wettest parts of Amazonia, with rainfall > 3000 mm yr^{-1} (Marengo, 1998). Whilst there is a dry season which peaks during June, July and August, rainfall does not drop much below c. 100 mm month^{-1} (Espinoza Villar *et al.*, 2009a). The wet season runs from November to May, and is accompanied by large scale flooding. At Tamshiyaku gauging station (near San Jorge; Figure 1), the 1974–2004 averages indicate that the peak river discharge occurs in April-May and that the lowest river discharges are in August, September, and October (Epinoza Villar *et al.*, 2009b). Mean annual temperature is c. 25 ˚C, with high relative humidity of 80–90 % throughout the year (Marengo, 1998).

2.3 Peat description

Descriptions of the peat were based on material observed during the process of augering the holes into which the piezometer tubes (see below) were placed, and on cores taken separately in each area using a 50 cm long, 5 cm diameter Russian corer manufactured by Eijkelkamp. Humification was estimated following the von Post (1924) scale (after Hobbs, 1986). Cores were tightly sealed in cling film to help prevent decay in the field, and were placed in cold storage (4 ˚C) on return to the UK. Further examination of the core material was undertaken in the laboratory using low-powered microscopy in order to confirm field observations. No evidence of significant decay in the peat samples was observed between field sampling and laboratory study.

2.4 Vegetation

Forest inventory plots (50 x 100 m) were established at all three of the sites during 2010, and a set of *K* measurements was performed within the plot at each of the three sites. In the case of Quistococha, this corresponds to Area B (Figure 1B). Individual plants with stem diameters ≥ 10 cm were measured and identified using the RAINFOR protocol (Phillips *et al.*, 2009). The Importance Value Index (IVI) was calculated as the sum of the relative values of abundance of individuals, basal area and frequency per species (*cf.* Curtis and McIntosh, 1951).

2.5 *K* sampling design: within-site variation in *K*

At Quistococha, piezometers were installed in three different areas at varying distances from the lake (Figure 1B), in order to test Hypothesis 2. Although the direction of groundwater flow is not known, it seems likely that any substantial flow would be to the south away from the lake. This was assumed because water flow to the east is restricted by the presence of a low clay levée, and to the west by the high terrace (Figure 1B).

All piezometers at area A were installed within 20 m of the lake edge. Area B was 250 m south of the lake edge, in the forest inventory plot, and area C was 900 m south of the lake edge. Piezometers were installed in batches of eight, each batch comprising four pairs. In order to test Hypothesis 1, the two tubes in each pair were installed 1 m apart at depths of 50 cm and 90 cm. The depth was measured to the midpoint of the piezometer (see below) intake.

All piezometers were installed in flat areas of accumulating leaf litter without any large pools of standing water. Piezometers were not placed along trails or where the peatland had obviously been disturbed by footfall. Micro-topography is likely to influence *K*, because it has a small but important effect on the position of the water table, and hence on vegetation and litter/peat decay. In addition to the litter flat areas, two other types of microhabitat were observed: *Mauritia flexuosa* L. palm leaf mounds, up to 50 cm in height and consisting of decaying leaves at the base of a living tree; and pools of standing water, which often contained pneumatophores (breather roots) of *Mauritia* and *Mauritiella*. As this study did not attempt to address the impact of micro-topography / microhabitat on *K*, sampling was restricted to litter flat areas at all sites.

2.6 *K* sampling design: between site variation in *K*

Sampling at Buena Vista and San Jorge was undertaken in areas which contained 0.5 ha forest inventory plots. Paired *K*-tests were undertaken at several different points throughout these areas. At both sites, several instances were observed where a mesh of coarse roots supporting a thin layer of leaf-litter and other material overlaid a large cavity or a pocket of very loosely consolidated peat. These areas were avoided during sampling. However, these cavities, if connected, may prove on further investigation to be important to the overall hydrology of the peatland (*cf.* Holden and Burt, 2002).

2.7 *K* measurement.

In the field, *K* is generally estimated using piezometer slug tests, although the specific design of the piezometer intake, the method used to install the piezometer tubes, and the means of measuring the head response may vary (e.g. Hvorslev 1951; Price, 1992; Baird *et al.*, 2008). Whilst *K* can be measured in the laboratory (e.g. the modified cube method: Beckwith *et al.* 2003), the transport of large numbers of samples from the field to the laboratory was impractical in this case.

For this study, piezometers were made of polyvinyl chloride (PVC) piping with an outer diameter of 34 mm and an internal diameter of 30 mm (*cf.* Surridge *et al.* 2005). The intake at the base of the pipe was 9 cm in length, and the pipe was sealed at the base. The intake was not screened with mesh, and was constructed such that 65% of it was open to water flow, following Baird *et al.* (2004).

K was estimated using slug withdrawal tests (Baird *et al.*, 2004) and by applying the equation of Hvorslev (1951):

$$K = -\frac{A}{Ft} ln\left(\frac{h}{h_0}\right) \tag{1},$$

where A is the inside cross-sectional area of the piezometer (units cm^2; in this case 7.07 cm^2), t is the time measured in seconds at which the head difference (h, measured in cm) between the water level in the piezometer during the test and that prior to the test, was recorded, h_0 is the initial head difference (at $t = 0$), and F is the shape factor of the piezometer intake (in this case a value of 36.2 cm was used). F was calculated using the formula of Hvorslev (1951) as modified by Brand and Premchitt (1980). For all of the piezometer tests t_{95}, the time taken for the head to recover by 95%, was used in the calculation of *K*.

K was standardised to a temperature of 20°C using the equation of Klute (1965):

$$K_{ST} = K_T \left(\frac{N_T}{N_{ST}} \right) \quad (2),$$

where K_{ST} is the hydraulic conductivity at the standard temperature (ST) (cm s^{-1}), K_T is the hydraulic conductivity at the temperature of measurement (T) (cm s^{-1}), and N is the viscosity (g s^{-1} cm^{-1}). Actual temperatures recorded in the piezometer tubes ranged from 24–26 °C when the middle of the intake was at 50 cm depth, and from 24.5–27 °C when it was at 90 cm depth.

The piezometers were inserted into holes made using a gouge auger with a slightly smaller diameter than the piezometers. A 'blocker' (Baird *et al.*, 2004) was used during installation to prevent material becoming entrained in the intake holes or entering the piezometer tube. Following installation, the piezometers were 'developed' (Surridge *et al.*, 2005). Development involves the removal of water from the piezometer tube to create large (>> 1) hydraulic gradients towards the piezometer, thus encouraging water to flow into the tube and unblock any pores which may have become obscured during installation. In particular, smearing around the intake can lower the recovery rate, and so cause erroneously-low values of K (Surridge *et al.*, 2005). Development is not always straightforward; it is possible to over-develop a piezometer, thereby eroding a cavity around the intake that can also lead to erroneous K calculations (Hvorslev, 1951; Surridge *et al.*, 2005). The peats at Quistococha were very fibrous, and so smearing around the intake is unlikely to have been a significant source of error. Therefore, the extensive development used by some previous studies (e.g. Baird *et al.*, 2004, 2008; Surridge *et al.*, 2005) was deemed unnecessary. Around 100 cm^3 of water was removed from the tube in order to ensure that no large peat fragments had become entrained in the piezometer intake during installation. At San Jorge and Buena Vista, a larger volume of water was removed during development, as suspended material could still be seen after having removed 100 cm^3 of water. At San Jorge 200 cm^3 of water was removed, while at Buena Vista the figure was between 200 and 400 cm^3.

Following installation, piezometers were allowed to settle for 20 minutes before the pressure transducer and slug were inserted. The piezometer was then left to allow the water level to equilibrate with pore water pressures in the peat before the slug withdrawal test was undertaken. The slug itself was made from acrylic rod, and when withdrawn caused a drop in head of c. 4 cm. The water level during head recovery was measured using Schlumberger 'Mini-Diver' and 'Micro-Diver' self-logging pressure transducers, set to take measurements at 0.5 Hz. The two types of pressure transducer have nominal full-range (10 m) accuracies of 0.5 and 1.0 cm respectively, and a resolution of 0.2 cm. However, laboratory tests showed that the accuracy was similar to the resolution. The pressure transducers record total pressure (atmospheric plus water), and need to be corrected for changes in atmospheric pressure where this changes during a slug test. Accordingly, the background atmospheric pressure was recorded every hour over the course of the study using a Schlumberger 'Baro-Diver'.

2.8 Statistical models

In order to test the initial Hypotheses (see *Section 1*), a total of seven statistical models were used (Table 4). Linear mixed effect models were constructed (*cf.* Bolker *et al.*, 2009), incorporating different combinations of random (site, area, batch) and fixed (depth) effects, and then compared using ANOVA to establish which models provide the best fit for the data. All analyses were conducted using *R 2.15.0* (www.R-project.org).

2.9 Hydrological simulation modelling

Simulations were run using the hydrological part of the DigiBog model (Baird *et al.*, 2012; Morris *et al.*, 2012). The median K values obtained as part of this study (see *Section 3.4*) were used to parameterise the models in order to examine whether the differences in K observed at the three sites might have a discernible effect on hydrological behaviour. Two further models were also constructed in order to:

> i) Assess the sensitivity of the models to differences in drainable porosity. Because no data are available for the drainable porosity of Amazonian peats, a value of 0.42 was used in several cases, as given by Boelter (1969) for fibric (≥ 66 wt. % fibre) peats in North America. However, this is at the upper end of values quoted for peats. The true drainable porosity of the peat at the sites studied may well be lower, which would lead to a more extensive drawdown zone. As such, two models were run with a lower (0.3) drainable porosity.
>
> ii) Assess the potential impact of a 10 cm thick zone of high K in the upper part of the peat profile on water table draw down ($K = 0.11$ cm s^{-1}).

The model scenarios comprised simple, two-dimensional representations of a virtual peatland 500 m long positioned between two water bodies, with a maximum peat thickness of 1 m. The base of the peatland was represented as a flat impermeable bed, and the water table at the start of the model run was positioned at the peat surface.

No net precipitation input was used in any of the model runs, but a water level was set for the two constraining water bodies. In each of the model runs, the water levels in both water bodies were the same (both either 0 or 75 cm above the base of the peat). In effect, therefore, the models simulated the loss of water from the peatland purely by flow through the peat itself. From the initial condition of a surface water table, the model runs considered drainage over 30 days or 90 days. At the end of each model run, the total amount of water lost from the peatland via groundwater flow was calculated as a percentage of the water present at the beginning of the simulation.

3. Results

3.1 Peat composition and structure

At Quistococha, the top 90–100 cm of peat consisted of fibrous peat with variable mixtures of fine roots (diameter ≤ 3 mm) and larger, often hollow, root fragments (diameter ≤ 8 mm) typical of *Mauritia flexuosa*. Visual inspections in the field did not reveal any identifiable leaf fragments except at the peatland surface. The peat also contained occasional large fragments of woody material, some of which were identified as *M. flexuosa* leaf stems. Living roots of *M. flexuosa* were observed down to depths of c. 1.5 m. Below 1 m, the peat became less fibrous in all the cores. Humification varied from H4 to H7 on the von Post (1924) scale (after Hobbs, 1986); peat in the top 50 cm was generally less humified with more intact root remains.

At San Jorge, the top 90–100 cm of peat was similar in composition to that at Quistococha, consisting of abundant root remains within a relatively well humified matrix. Close examination revealed the presence of some small *M. flexuosa* flower remains at 90 cm. The level of humification (H7 to H8) was fairly uniform, and higher than in the upper 50 cm at Quistococha.

No large roots were observed in the top 100 cm of peat at Buena Vista, which instead consisted of a well humified matrix with some fine roots and occasional small wood fragments. Humification (H6-H7) was fairly uniform from 0–100 cm and similar to that at San Jorge.

3.2 Peatland vegetation

The tree flora in the forest inventory plot at Quistococha appeared to be representative of the vegetation across the studied part of the peatland. Three species, *Mauritia flexuosa, Mauritiella armata* (Mart.) Burret (both Arecaceae) and *Tabebuia insignis* Sandwith (Bignoniaceae), together represented 82% of the individuals (Table 1). Species richness was much lower than would be expected for *terra firme* rain forest (*cf.* De Oliveira and Mori, 1999).

The diversity of the peatland forest at San Jorge was very low, with only 10 species identified in the inventory plot (Table 1). As at Quistococha, the assemblage was dominated by individuals from just three (different) species, which make up 83% of the individuals; *Pachira* aff. *brevipes* (A. Robyns) W.S Alverson (Malvaceae), *Remijia* aff. *ulei* K. Krause (Rubiaceae)*,* and *Calophyllum brasiliense* Cambess (Clusiaceae). Palms were much less abundant at this site, and most species (including *M. flexuosa*) showed the slender growth form typical of 'dwarf' or 'pole' forest.

The forest at Buena Vista was more diverse, with 42 species. Whereas at Quistococha and San Jorge the three most abundant species accounted for >80% of the individuals, at Buena Vista the ten most abundant species made up < 70% of the individuals (Table 1). Buena Vista was also the only site where the palms *M. flexuosa* and *M. armata* were absent; the only palm species observed was *Astrocaryum jauari* Mart., represented by one individual. The growth habit of the trees at Buena Vista was also different; many more species had the stilt roots typical of black-water seasonally-flooded forests (tahuampa).

3.3 Normal and non-normal slug-test recoveries

A total of 108, 28 and 30 piezometer measurements were undertaken at Quistococha, San Jorge and Buena Vista, respectively. Of these, 91, 27 and 23 respectively were used to calculate *K*. A ‘normal’ recovery was defined as one where the head returned to h_0 by the end of the test (Normal recovery type A: Figure 2). Non-normal recoveries fell into four categories (Figure 2). In the case of non-normal recovery type A, it was possible to re-define h_0 as the stable head level observed at the end of the *K*-test. In several cases recovery was less than half that of the initial head difference (non-normal recovery B). One possibility is that, as the slug was removed at the start of the test, the pressure drop caused any gas bubbles around the piezometer intake to increase in size thereby blocking pores (*cf.* Beckwith and Baird, 2001). Non-normal recoveries of type B were thus excluded from the final analysis.

Non-normal recoveries C and D (Figure 2) were most likely caused by atmospheric pressure change over the course of the test which makes it more difficult to identify t_{95}. Between 10:00 and 15:00 on most days there was a considerable drop in air pressure of 5–6 cm water equivalent (Figure 3). In such cases, the head recoveries can be corrected by subtracting the atmospheric pressure from the pressure recorded by the transducer in the piezometer. The corrected data can then be used to calculate *K* in the same way as for the other recovery types. An alternative approach is to use the inflection point to re-define h_0. In this study recoveries were corrected using the atmospheric pressure data.

3.4 Hydraulic conductivity (*K*) estimates

The *K* estimates for Quistococha, San Jorge and Buena Vista are presented in Table 2, Table 3, Figure 4, and Figure 5; Figure 4 also shows some comparable data from other published sites. Figures 6 and 7 show some illustrative head recoveries.

3.5 Testing Hypotheses 1 and 2 (K *varies within the uppermost 90 cm of the peat profile* and K *varies spatially between different parts of the peatland*)

At the three study areas at Quistococha, there is a significant difference in *K* at 50 and 90 cm depth (Figures 5–7). In each area, the median value for *K* was higher at 50 cm than at 90 cm and when the data for all areas are combined there is an order of magnitude difference in median *K* for the two depths (Table 2). *K* also appears to vary with area (Table 2; Figure 5). In the area of the swamp nearest to the lake (area A), the median *K* is 0.0037 cm s^{-1} at 50 cm, and 0.0018 cm s^{-1} at 90 cm. These values are substantially lower than those obtained for area B, where the median *K* is 0.016 cm s^{-1} at 50 cm and 0.0063 cm s^{-1} at 90 cm. *K* values for area C are most similar to those for area A (Table 1). Indeed, area B differs most from the other two areas, and the *K* values at 50 cm for area B have a smaller variance than areas A and C (Figure 5).

The model incorporating area, batch, and depth (Model A: Table 4) was not significantly different ($p > 0.05$) from a simpler model incorporating only depth and area (Model B; Table 4), suggesting that small-scale spatial variation (within individual areas) did not contribute systematically to the variation. The Akaike Information Criterion (AIC) and the Bayesian Information Criterion (BIC) were almost identical between models, which confirmed that there was little difference between the two models. However, a model incorporating only area (Model C: Table 4) was significantly different ($p < 0.001$) from the model incorporating both depth and area (Model B: Table 4). This demonstrates that depth makes a significant difference to the variation in *K* at Quistococha. In Model B, area was found to explain 20.4% of the variance. Therefore, the preferred linear model supports both Hypothesis 1 and 2 (see *Section 1*).

Examination of the data from San Jorge and Buena Vista showed that depth did not exert a significant influence on *K* at these sites. A model incorporating only site (Model G: Table 4) was not significantly different from a model incorporating both site and depth (Model E: Table 4). Hypothesis 1 was therefore not supported by the data from these two sites.

3.6 Testing Hypothesis 3 (K *varies between different wooded tropical peatlands*)

Figure 4 suggests that there are substantial differences between the *K* values obtained from the different sites. As discussed in Section 3.5, the variation in *K* with depth at San Jorge is not significant, whereas *K* does vary significantly with depth at Quistococha; this in itself constitutes a difference between the sites. Model C (Table 4) also showed that site explained 18.7 % of the variance in the data. This result supports Hypothesis 3, and shows that there are variations in *K* between different wooded tropical peatlands.

3.7 Simulations

The results of the simulations are shown in Figure 8, with some details of the outputs summarised in Table 5. The extent of the draw down zone, as defined by a lowering of the water table by > 10 cm, varied slightly between the different model runs. The draw down zone was most extensive for models Quistococha type 2 & 3, and least extensive for the San Jorge type model. The most extensive draw down zone extended 72.5 m into the peatland, the least extensive 25 m. Similarly, the greatest proportion of water was lost from the Quistococha type 3 model, and the lowest proportion from the San Jorge type model. In all model runs, the water table at the centre of the peatland was not greatly lowered (< 0.5 cm).

4. Discussion

4.1 Simulated groundwater flow

This study has found evidence that *K* can vary both within and between sites, and that *K* measurements from different areas and sites contribute 20 % and 18 % of the variance in the data respectively. However, the majority of the K values obtained fall between 0.001 and 0.02 cm s^{-1}, and models show that this variation may only have a minor impact on hydrological function. The difference in K observed between the different peatlands does not seem to have a substantial effect on the amount of water lost or the extent of the draw down zone (Table 5), although the models here do not take into account peatland geometry. Nevertheless, further models show that as yet unexplored hydrological properties could have a significant effect on hydrological behaviour in tropical peatlands. In particular, lower drainable porosity values can create more extensive draw down zones. A higher K surface layer does not always result in a more extensive draw down zone (Table 5), in part because it allows water to travel from more central parts of the peatland to raise water levels at the margins.

The main purpose of the model runs (Figure 8) was to examine subsurface flow and whether this might create differences in the hydrological behaviour of these peatlands; this was most simply achieved by running the models without a precipitation input. However, the DigiBog simulations also provide insights into how the high K of forested tropical peatland systems might affect peatland water balance during a drought. Although there is some debate, climate models show substantial reductions in rainfall (1 mm day $^{-}$1) in north western Amazonia by 2080 (e.g. Betts *et al*., 2004), and others have suggested the possibility of reduced dry season rainfall in particular (Malhi *et al.* 2009).

The model setup more closely reflects the behaviour of a domed peatland such as San Jorge than that of a peatland like Quistococha, which is bounded on two sides by an impermeable clay ridge and terrace. The simulations show that flow out of the modelled peatland causes water-table lowering for 30–50 metres into the peatland within 30 days (Figure 8). Where there is a prolonged dry season, this could result in substantial lowering of the water-table if there is no water entering the system from other sources, such as groundwater springs (e.g. Householder *et al.*, 2012).

However, prolonged droughts are unlikely to occur under current climatic conditions. The simulations also suggest that, with K set to the values obtained from the three sites in this study, groundwater flow alone would be unable to shed the large quantity of water currently entering Amazonian peatlands from rainfall (> 3000 mm yr^{-1}; Marengo, 1998). Even without rainfall, over a 90-day period the modelled water table in the centre of the peatland remains at the surface. Therefore a large proportion of the water entering Amazonian peatlands must exit the system via overland flow or evapotranspiration. Hoekman (2007) came to a similar conclusion in Indonesia using a combination of remote sensing and terrain relief modelling. Although connected drainage channels were not apparent at the sites visited, water has been observed flowing out from the margins of other peatland sites in Amazonia (e.g. Aucayacu peatland; G. Swindles, pers. comm.; see Lähteenoja *et al.* 2012 for site details). Rapid drops in water level have also been observed in long term data from Quistococha when water levels have risen above the peat surface (T.J. Kelly *et al.*, unpublished data), and this may be due to surface flow. Pool features can also become connected during heavy rainfall events.

During large rainfall events the water table rises to the peat surface and a substantial proportion of the water exits the peatland (or is re-distributed to lower areas) via overland flow. Following a large rainfall event, the water-table will continue to fall as a result of groundwater flow and evaporation. Evaporation rates are also likely to be high, and in peatlands bounded by impermeable barriers (e.g. Quistococha) the majority of water may leave the system via this pathway. Published estimates for evaporation rates are in the region of 1500 mm yr^{-1} for lowland tropical forests with > 3000 mm yr^{-1} of rainfall (*cf.* Bruijnzeel, 1990). This suggests that regular rainfall may be more important for maintaining tropical peatland wetness than individual large rainfall events.

4.2 Tropical peatland *K* values

Relative to other peatlands, the *K* values reported here are typically an order of magnitude higher than those estimated for northern hemisphere ombrotrophic bogs (see Lewis *et al.*, 2012 for a review), although recent work at an ombrotrophic peatland in Wales has shown that high *K* values can be obtained in fibrous *Sphagnum* peat at depths of 40–60 cm (Baird *et al.*, unpublished data). The tropical *K* values reported closely resemble those estimated for the root mat at the temperate Sutton Fen site (Norfolk, UK) reported by Baird *et al.* (2004), who used a similar *K*-measurement method to that used here. The root mat at Sutton Fen was composed predominantly of roots and rhizomes of the sedge *Cladium mariscus* (L.) Pohl and the grass *Phragmites australis* Cav. (Streud), along with some well-decomposed plant matter. The median value for *K* at 50 cm for Quistococha is slightly higher than at 45 cm for Sutton Fen, but the median values from Buena Vista and San Jorge are very similar (Figure 4). Despite the obvious floristic dissimilarities, the peat at the three Peruvian sites and in the Sutton Fen root mat is structurally similar, being composed of poorly-decomposed roots, wood and other coarsely fibrous material, which accounts for their hydraulic similarities.

Measurements of *K* have also been made at a number of tropical peatlands in Southeast Asia. Some caution is needed in comparing our data with these results, primarily because many of the published studies do not provide a detailed description of the measurement method. This is potentially problematic because small differences in method, such as using an open sided auger hole instead of a piezometer tube, can be significant when measuring *K* (Surridge *et al.*, 2005).

Takahashi and Yonetani (1997) measured *K* from 1.0–1.7 m depth in a wooded peat swamp in Kalimantan (Indonesia) using piezometers, but published only a rounded value ($K \geq 0.01$ cm s^{-1}) for depths < 1 m. Hoekman (2007), studying a peatland in Kalimantan, found a much higher value of *K* of 0.23 cm s^{-1}, but gave no details of how this estimate was obtained. For a peatland in Sumatra, Nugroho *et al.* (1997) provided a more extensive data set, and gave a list of *K* estimates which range from 0.0035 to 0.19 cm s^{-1} (n = 28). However, they did not indicate how their *K* estimates were derived, and provide no depths to accompany their data. Sayok *et al.* (2007) presented *K* values for peatlands in Sarawak (Malaysia) derived from 59 auger hole slug tests (*cf.* Bouwer, 1989) with a mean value of 0.039 cm s^{-1} for swamp forest peatland (n = *15*). In all four cases, these estimates are larger than the values obtained at Quistococha, San Jorge, and Buena Vista, but it is unclear whether this represents a real difference or simply an artefact of differing measurement methods.

5. Conclusions.

The results of this study have shown that there is within-site variation in *K,* and that *K* also varies between sites with different vegetation assemblages, although whether there are systematic spatial patterns (e.g. lower *K* at the peatland margin; similar *K* values across similar vegetation types) must be the subject of future work. *K* can also vary with depth in the top metre of the peat profile, but evidence of this was found at only one of the three sites studied. However, hydrological models demonstrate that the level of variation in *K* encountered at the different sites may not necessarily result in large differences in hydrological behaviour. The models also show that there is a need for further research into peat properties, such as specific yield.

The *K* values obtained from the three peatlands studied are at least an order of magnitude higher than *K* values reported for many northern peatlands (*cf.* Lewis *et al*., 2012), and are similar to the *K* of a temperate sedge fen (*cf.* Baird *et al*., 2004). They are an order of magnitude lower than the few existing *K* estimates for Indonesian peatlands, but it is difficult to tell whether this represents a real or a methodological difference. Although the *K* values appear high relative to those obtained at some other sites, hydrological models show that under current climatic conditions, the *K* values obtained are insufficient to shed the water entering the system via rainfall. This suggests that most of the water in these tropical peatlands is lost through overland flow and evapotranspiration. As such, sustained rainfall may be more important for maintaining tropical peatland wetness than individual large rainfall events.

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Table 1. List of the ten most important species ranked by the Importance Value Index (IVI) which were found in the 0.5-ha plots at Quistococha (Area B in Figure 1B), San Jorge, and Buena Vista. IVI was calculated as the sum of the relative (Rel.) values of abundance of individuals (Ab.), basal area (BA) and frequency (Fr., 50 subplots). Only individuals with ≥ 10 cm diameter are included.

Quistococha

Species	Family	Ab.	BA	Fr.	(%) Rel. Ab	(%) Rel. Do	(%) Rel. Fr	(%) IVI
Mauritia flexuosa	Arecaceae	92	6.29	41	22.38	53.86	23.16	99.41
Tabebuia insignis	Bignoniaceae	131	2.77	46	31.87	23.69	25.99	81.56
Mauritiella armata	Arecaceae	113	1.17	26	27.49	10.02	14.69	52.20
Symphonia globulifera	Clusiaceae	31	0.76	23	7.54	6.51	12.99	27.05
Hevea guianensis	Euphorbiaceae	11	0.19	10	2.68	1.62	5.65	9.95
Amanoa aff. *guianensis*	Phyllanthaceae	11	0.16	10	2.68	1.37	5.65	9.70
Virola surinamensis	Myristicaceae	4	0.06	4	0.97	0.49	2.26	3.72
Brosimum utile	Moraceae	4	0.04	4	0.97	0.35	2.26	3.58
Alchornea schomburgkii	Euphorbiaceae	3	0.06	3	0.73	0.51	1.69	2.94
Alchorneopsis floribunda	Euphorbiaceae	3	0.04	2	0.73	0.35	1.13	2.21
Other 6 species		8	0.14	8	1.95	1.22	4.52	1.95
Overall total	16 species	411	11.7	177	100	100	100	300

San Jorge

Species	Family	Ab.	BA	Fr.	(%) Rel. Ab	(%) Rel. Do	(%) Rel. Fr	(%) IVI
Pachira aff. *brevipes*	Malvaceae	225	3.35	45	38.79	25.24	21.74	85.78
Remijia aff. *ulei*	Rubiaceae	143	4.68	46	24.66	35.30	22.22	82.18
Calophyllum brasiliense	Clusiaceae	116	1.92	47	20.00	14.45	22.71	57.16
Mauritia flexuosa	Arecaceae	51	2.69	31	8.79	20.30	14.98	44.07
Dendropanax aff. *resinosus*	Araliaceae	28	0.37	23	4.83	2.79	11.11	18.73
Mauritiella armata	Arecaceae	6	0.08	5	1.03	0.63	2.42	4.08
Oxandra riedeliana	Annonaceae	6	0.08	5	1.03	0.58	2.42	4.03
Ormosia coccinea	Fabaceae	2	0.05	2	0.34	0.40	0.97	1.71
Hevea guianensis	Euphorbiaceae	2	0.03	2	0.34	0.25	0.97	1.56
Tabebuia insignis	Bignoniaceae	1	0.01	1	0.17	0.06	0.48	0.71
Overall total	10 species	580	13.3	207	100	100	100	300

Buena Vista

Species	Family	Ab.	BA	Fr.	(%) Rel. Ab	(%) Rel. Do	(%) Rel. Fr	(%) IVI
Inga aff. *stenoptera*	Fabaceae	89	1.22	31	20.32	11.07	10.84	42.22
Matayba sp.	Sapindaceae	38	1.85	25	8.68	16.86	8.74	34.28
Diospyros poeppigiana	Ebenaceae	54	1.40	26	12.33	12.73	9.09	34.15
Triplaris weigeltiana	Polygonaceae	26	0.49	17	5.94	4.50	5.94	16.38
Elaeoluma glabrescens	Sapotaceae	23	0.48	19	5.25	4.34	6.64	16.23
Hydrochorea corymbosa	Fabaceae	17	0.50	12	3.88	4.53	4.20	12.61
Amanoa aff. *sinuosa*	Phyllanthaceae	17	0.42	13	3.88	3.82	4.55	12.24
Terminalia aff. *oblonga*	Combretaceae	9	0.66	9	2.05	6.01	3.15	11.22
Myrtaceae sp2.	Myrtaceae	16	0.32	11	3.65	2.94	3.85	10.44
Eschweilera aff. *ovalifolia*	Lecythidaceae	11	0.50	9	2.51	4.51	3.15	10.17
Other 32 species		138	3.15	114	31.51	28.68	39.86	100.05
Overall total	42 species	438	11	286	100	100	100	300.00

Table 2: Summary statistics for the hydraulic conductivity (*K*) estimates for areas A-C at Quistococha as determined using equation (1) and standardised to 20 °C using equation (2). The summary statistics for *K* data from all areas have also been included. *K* values are given in cm s^{-1}.

Quistococha	Area A		Area B		Area C	
Depth (cm)	50	90	50	90	50	90
Median	0.00369	0.00167	0.01606	0.00627	0.00387	0.00164
Lower Quartile	0.00099	0.00099	0.00948	0.00241	0.00255	0.00063
Upper Quartile	0.01036	0.00434	0.02252	0.01072	0.01865	0.00400
Max	0.02761	0.00982	0.05695	0.03735	0.05586	0.00751
Min	0.00038	0.00035	0.00236	0.00043	0.00081	0.00027
n	11	10	21	23	13	13

Table 3: Summary statistics for K estimates from the three sites studied; Quistococha, San Jorge, and Buena Vista. In the case of Quistococha, this summarises all K data from areas A-C. K values are given in cm s^{-1}.

	Quistococha		San Jorge		Buena Vista	
Depth (cm)	50	90	50	90	50	90
Median	0.01247	0.00278	0.00464	0.00414	0.00664	0.00624
Lower Quartile	0.00315	0.00106	0.00134	0.00119	0.00576	0.00450
Upper Quartile	0.01899	0.00737	0.00579	0.00748	0.01753	0.01569
Max	0.05695	0.03735	0.05657	0.01409	0.11248	0.05638
Min	0.00038	0.00027	0.00032	0.00039	0.00380	0.00125
n	45	46	14	13	10	13

Table 4: Summary of the linear mixed effects models used to test the initial hypotheses (*section 1*). AIC = Akaike Information Criterion, BIC = Bayesian Information Criterion. The models which best fit the data have been marked *.

Model	**Data used**	**Fixed effects**	**Random effects**	**Log Likelihood**	**AIC**	**BIC**
A	QT	Depth	Area (batch)	-143.7	297.3	309.9
B*	QT	Depth	Area	-145.1	298.1	308.2
C	QT		Area	-153.4	312.7	320.3
D*	QT, SJO, BVA	Depth	Site	-233.6	475.3	487.0
E	QT, SJO, BVA		Site	-238.5	482.9	491.8
F	SJO, BVA	Depth	Site	-79.75	167.5	175.1
G*	SJO, BVA		Site	-79.62	165.2	171.0

Table 5: Outline of the main parameters used in the five hydrological models. Summarised outputs of the models are given to supplement the diagrams in Figure 8. The percentage water loss is given, followed in parentheses by the extent of the draw down zone in metres (water table drop > 10 cm). *K* = hydraulic conductivity of the layers (*K* is given in cm s^{-1} with values listed from the base upwards), DP = Drainable porosity.

				Water loss, % (extent of drawdown zone in m)			
				30 days		**90 days**	
Model	**No. of layers**	***K* (base → top)**	**DP**	**0 cm**	**75 cm**	**0 cm**	**75 cm**
San Jorge type	2	0.0041, 0.0046	0.42	3.3 (35)	0.7 (25)	6.5 (55)	1.7 (35)
Buena Vista type	2	0.0062, 0.0066	0.42	5.1 (42.5)	1.1 (30)	8.9 (67.5)	2.6 (45)
Quistococha type 1	2	0.0027, 0.0125	0.42	4.7 (42.5)	1.2 (30)	7.7 (62.5)	2.8 (45)
Quistococha type 2	2	0.0027, 0.0125	0.3	5.5 (47.5)	1.6 (32.5)	9.0 (72.5)	3.4 (52.5)
Quistococha type 3	3	0.0027, 0.0125, 0.11	0.3	5.8 (45)	2.1 (35)	9.3 (70)	4.0 (52.5)

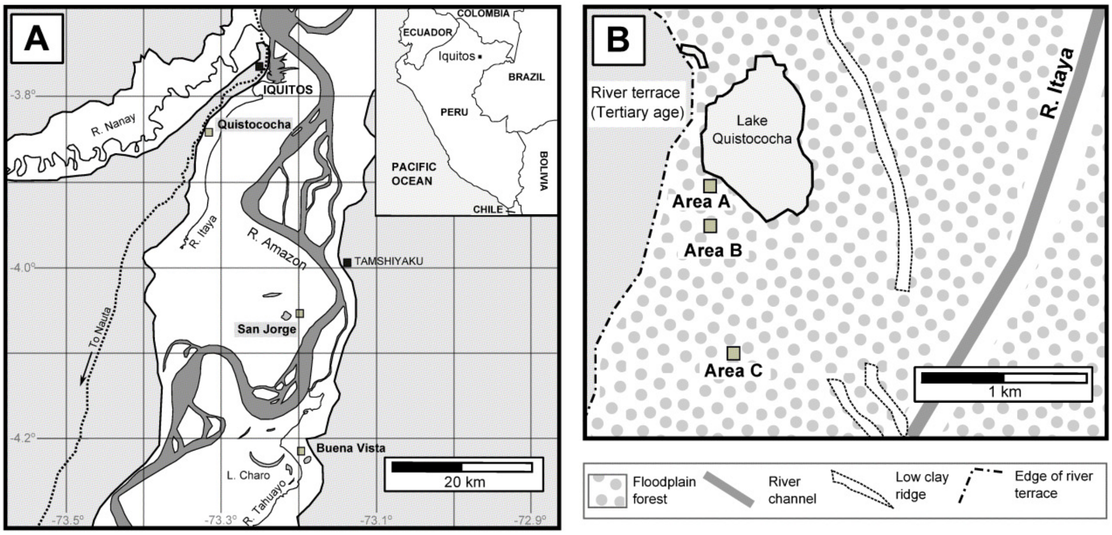

Figure 1: A: Map showing the position of the three sites within the region of Loreto (near the city of Iquitos), and within Peru (inset). Dark shading = rivers; light shading = terra firme areas; no shading = floodplain areas; dotted line = main highway. B: Map of Quistococha showing the areas where piezometers were installed. The 0.5 ha forest plot is located in Area B. The peatland covers the area to the north and south of the lake and to the east of the lake up to the clay ridge. The height of the Tertiary river terrace is c. 15 m above the surface of the lake.

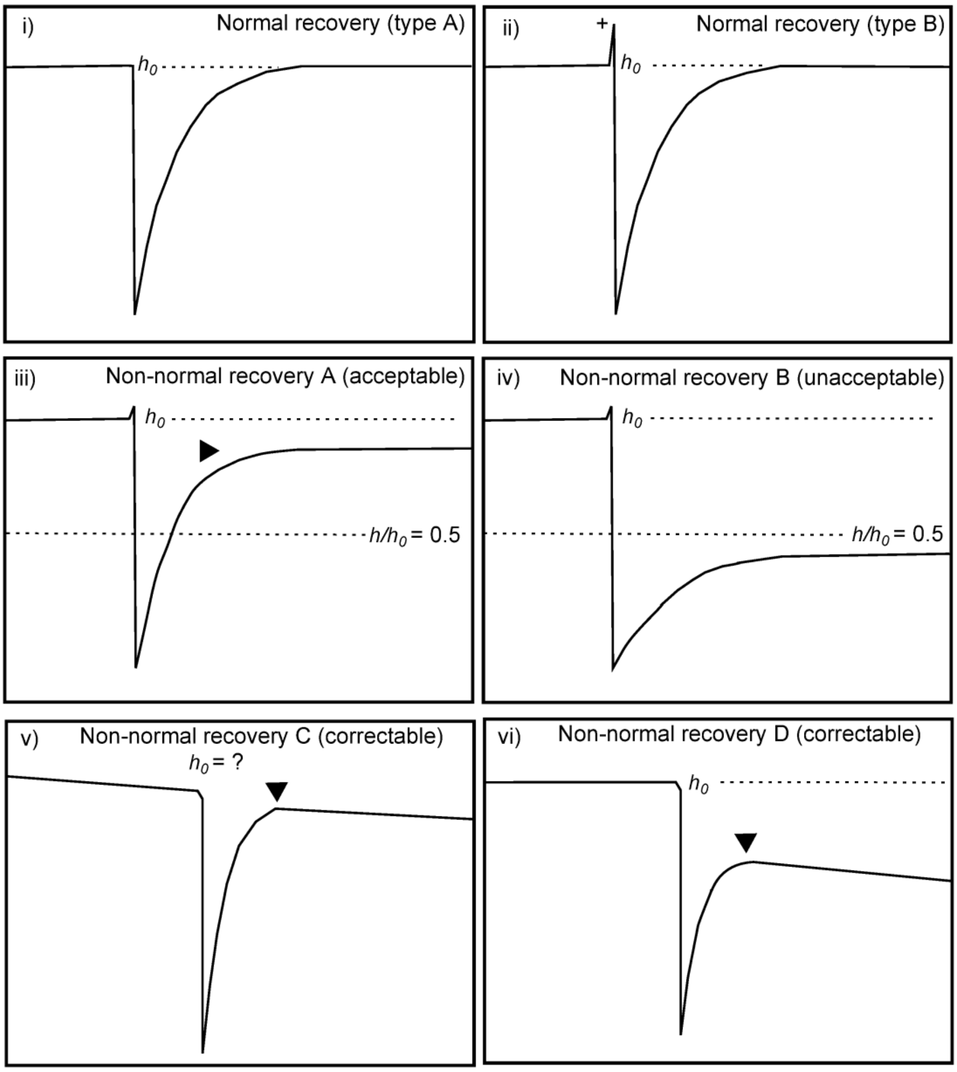

Figure 2: Figure showing the six main recovery types, as discussed in the text. i) Normal recovery. The head fully recovers to its original position before slug removal (h0). ii) Normal recovery. The head fully recovers to its original position before slug removal, but there is a slight increase in head at the point where the slug is removed (marked +). iii) Non-normal recovery A (acceptable). In this case, the head does not fully recover to h0. However, it does reach a stable level which can be used to redefine h0 (marked ▶) and so produce an estimate of t95. iv) Non-normal recovery B (unacceptable). In this case, the head does not fully recover to h0. Whilst it does reach a stable level, this level is below h/h0 = 0.5. v) Non-normal recovery C (correctable). The level of the water is apparently unstable either before or after slug removal;h0 can be redefined using the inflection point (marked ▼) or the recovery can be corrected using atmospheric data. vi) Non-normal recovery D (correctable). Although the head is stable prior to slug removal, allowing h0 to be defined, the head does not fully recover during the K-test; h0 can be redefined using the inflection point (marked ▼) or the recovery can be corrected using atmospheric data.

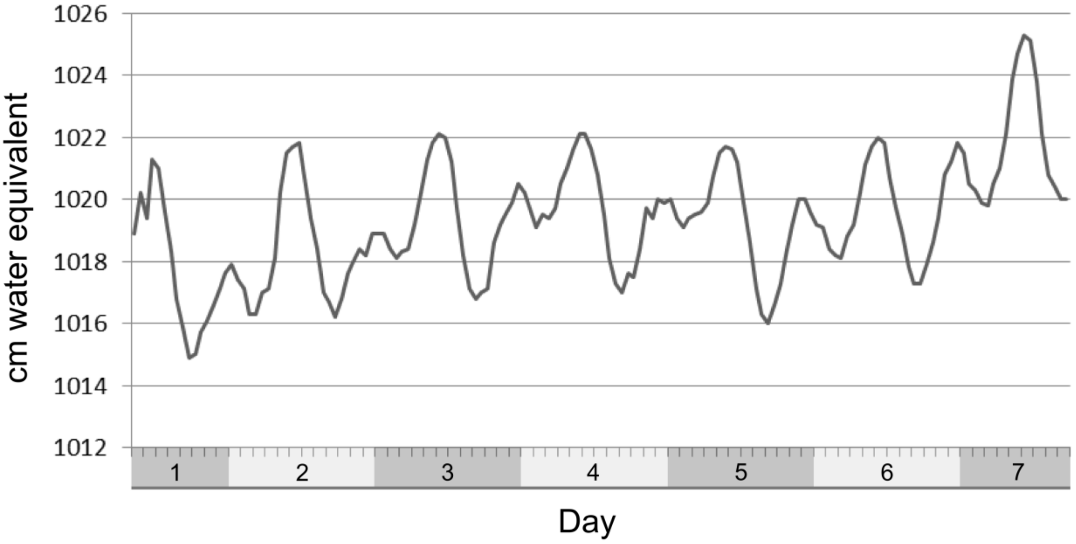

Figure 3: Atmospheric pressure over the course of seven days in the vicinity of Quistococha, beginning at 08:00 on 29th July 2011 and ending at 17:00 on 4th August 2011 (tick marks every two hours). On all days, there was a substantial drop in pressure between around 10:00 and 15:00. Measurements were taken once every hour.

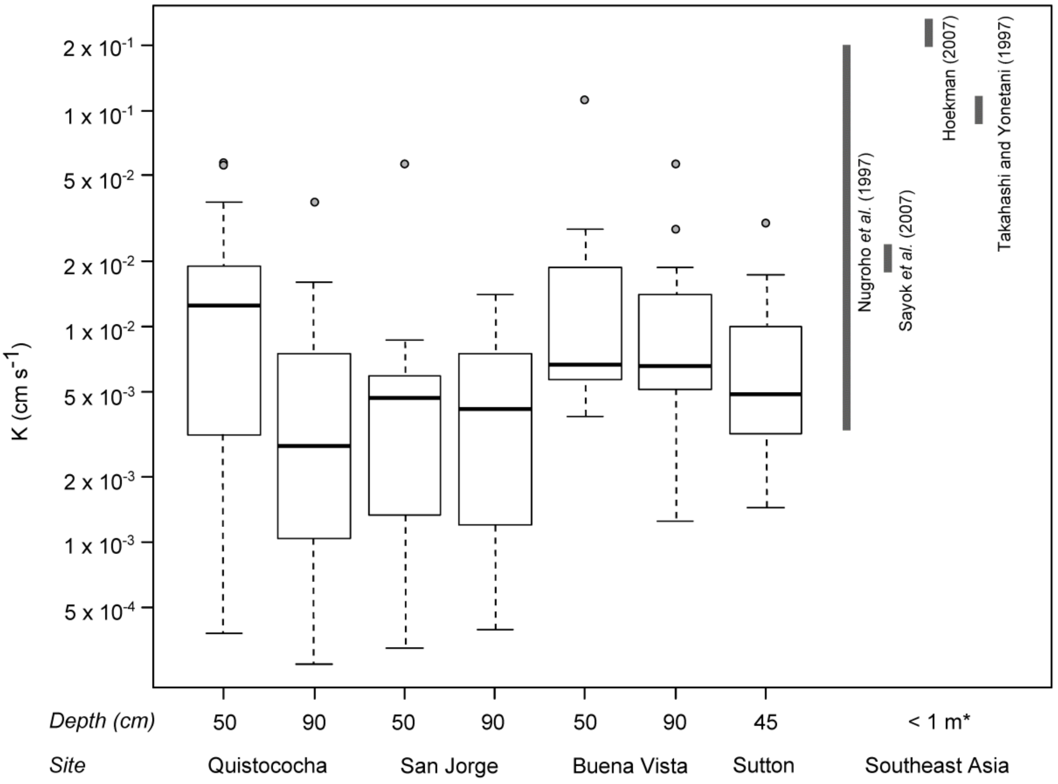

Figure 4: Summary of hydraulic conductivity (K) data for Quistococha (n = 91), San Jorge (n = 27), Buena Vista (n = 23), and for a fen root mat at Sutton Fen in Norfolk, UK (n= 14; Baird et al., 2004). The diagram shows the median (bold bar) and the interquartile range (white box). The full range of the data (minimum to maximum value) is shown by a dotted line, except where there are outliers which lie more than 1.5 times the interquartile range from the upper or lower quartile. In this case outliers are shown as grey circles, and the dotted lines indicate the range of the rest of the data. Note that K estimates have been standardised to 20°C to aid comparison. K values from four studies in Southeast Asian peatlands have been included for comparison, but these values were generated using different field methods. * Nugroho et al. (1997) do not specify the measurement depth.

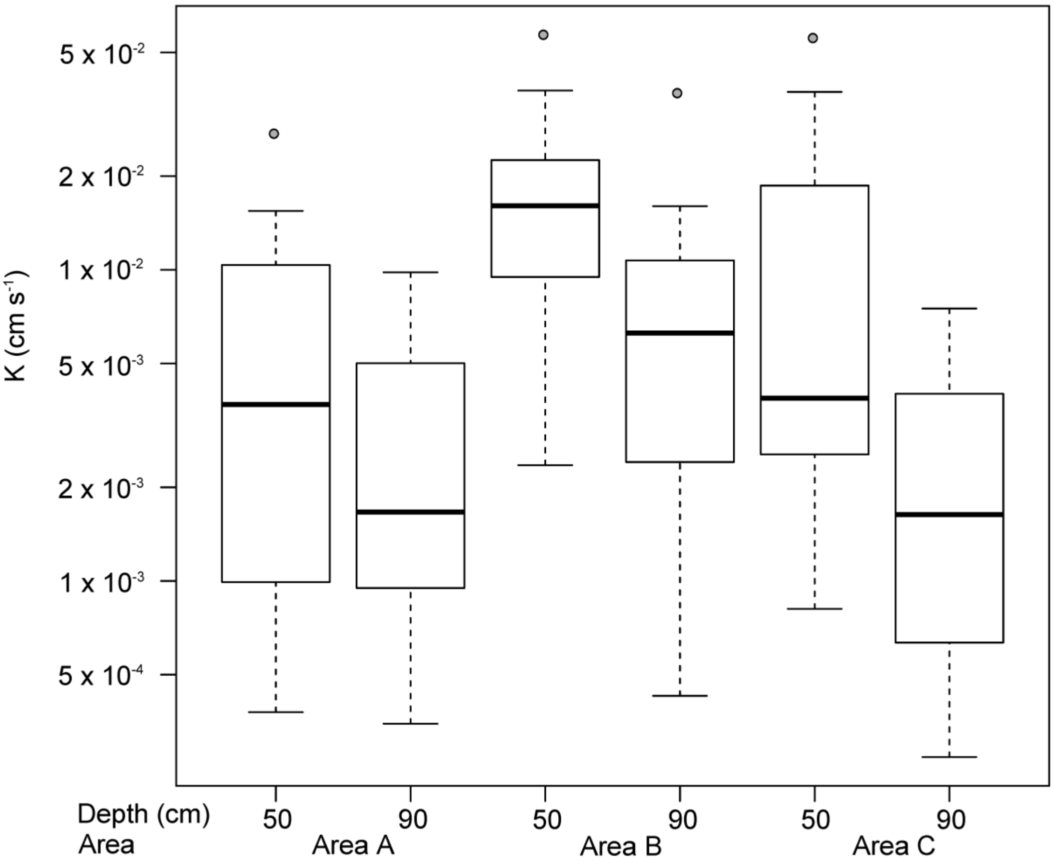

Figure 5: Box plots summarising K data for the three different areas of Quistococha situated at varying distances from the lake edge. Format follows that described in figure 4.

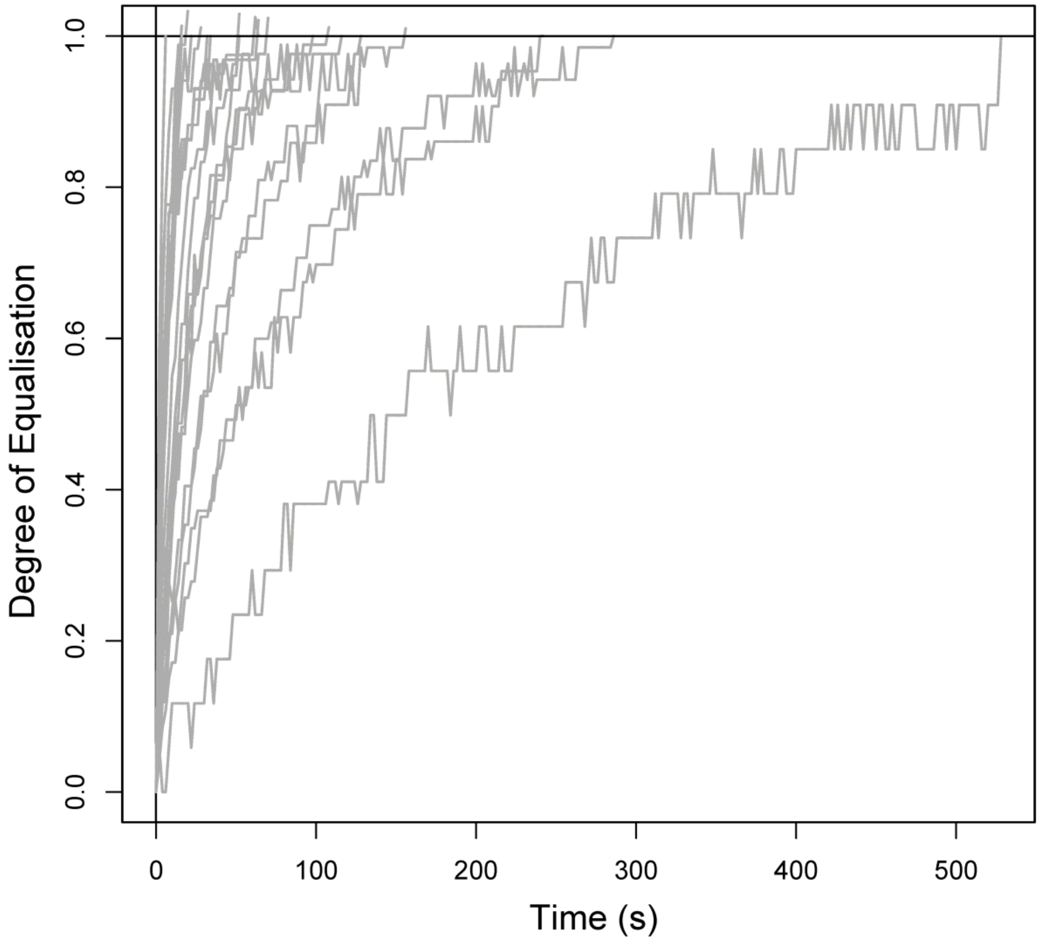

Figure 6: Normalised head recovery data for piezometers installed at 90 cm in Area B at Quistococha (n = 23). Note that in some cases, the degree of equalisation exceeds one due to the typical errors associated with the use of pressure transducers.

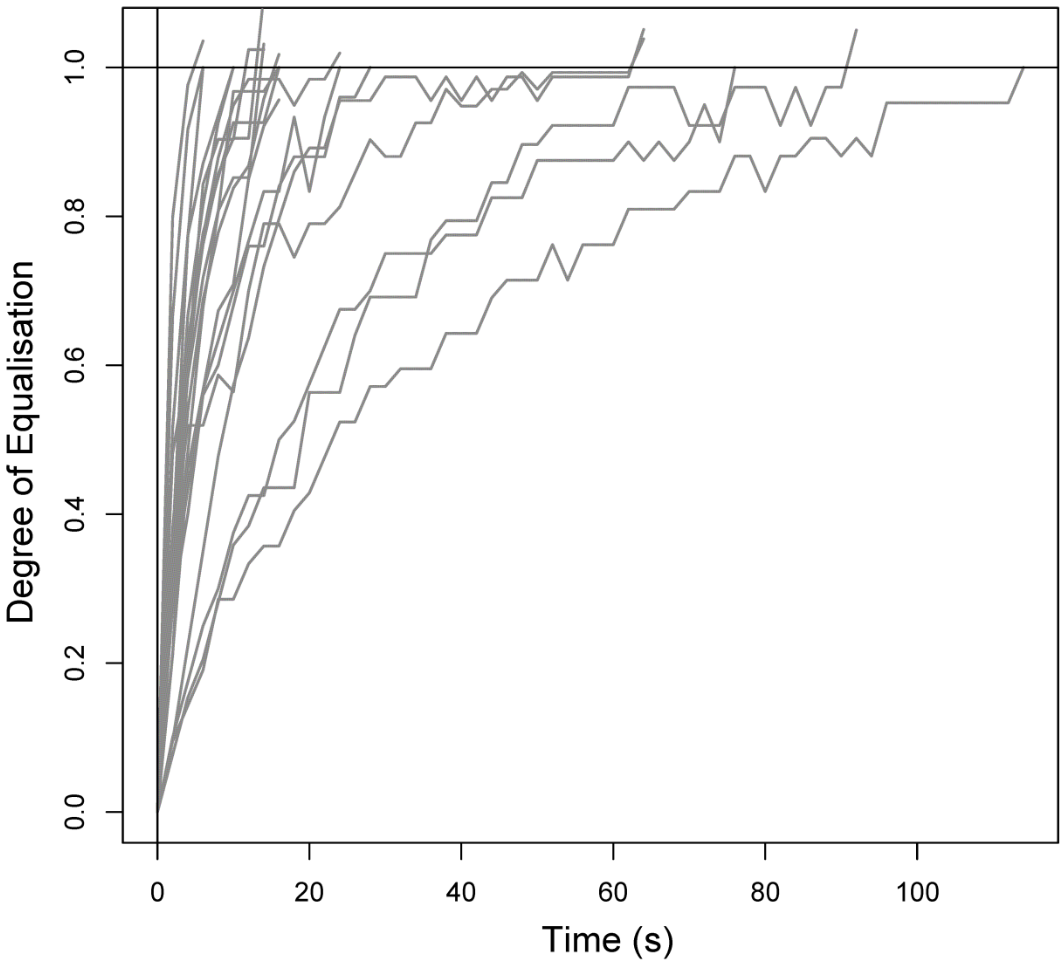

Figure 7: Normalised head recovery data for piezometers installed at 50 cm in Area B at Quistococha (n = 21). Note that x axis scale is different from that in Figure 6.

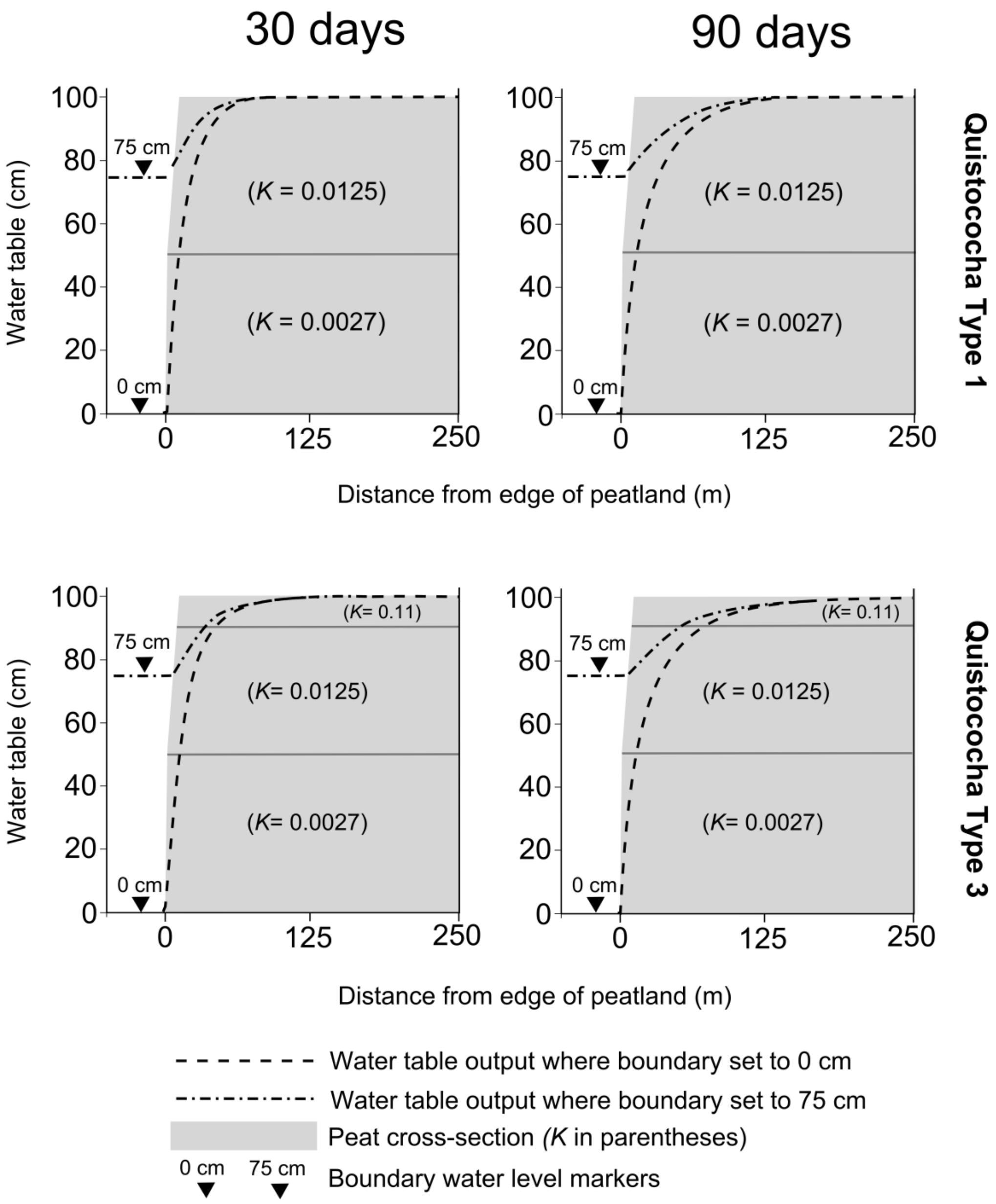

Figure 8: Two-dimensional representation of hydrological simulations. The diagrams represent a vertical plane running from the modelled peatland edge to the centre. Two different models are shown: Quistococha Type 1 and Quistococha Type 3 (for details see Table 5). The models were run for 30 days (left) and 90 days (right) without rainfall or evapotranspiration in order to examine water losses due to subsurface flow alone. For each model setup and run time, the water table was simulated assuming two different boundary water table positions (0 cm and 75 cm), and these outputs are shown using dashed lines. The peat is denoted by the shaded area, which also represents the initial water table position. K for the different layers has also been indicated. The other models produced outputs which were not significantly different from that of Quistococha Type 1, and have not been shown.