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Hydrological behaviour of a drained agricultural peat catchment in the tropics. 1: Rainfall, runoff and water table relationships

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Abstract Hydrological data of a drained tropical peat catchment have been analysed through conventional quantitative hydrological approaches to characterize its hydrological behaviours and changes due to continuous drainage for a long period. The results show that the hydrology of the catchment is extremely dynamic and the catchment is flashy in nature. A decreasing trend in peak flow amount and an increasing trend in baseflow amount was observed in the catchment, indicating that continuous drainage has reduced the risk of both flooding and water scarcity in the catchment. Correlation analysis among rainfall, runoff and groundwater table reveals that saturation excess-near surface flow is the dominant mechanism responsible for rapid runoff generation in the catchment. Therefore, any physical alterations or disturbances to the upper part of the peat profile would definitely affect the overall hydrological behaviour of the peat catchment.

Key words drained peat catchment; rainfall; water table; runoff ratio; tropics

Comportement hydrologique d'un bassin versant agricole drainé en zone de tourbière tropicale. 1: Relations entre la pluie, le ruissellement et la nappe

Résumé Les données hydrologiques d'un bassin versant tropical drainé en zone de tourbière ont été analysées par des approches hydrologiques quantitatives conventionnelles afin de caractériser son comportement hydrologique et son évolution en réponse au drainage continu pendant une longue période. Les résultats montrent que l'hydrologie la dynamique du bassin versant est très rapide, présentant des crues éclair. Une tendance à la diminution des débits de pointe et à l'augmentation des débits de base a été observée dans le bassin versant, ce qui indique que le drainage continu a permis de réduire à la fois le risque d'inondation et celui de pénurie d'eau. La corrélation entre les précipitations, les eaux de ruissellement et le niveau de la nappe phréatique révèle que l'écoulement de surface par excès de saturation est le mécanisme dominant responsable de la production de ruissellement rapide dans le bassin versant. Par conséquent, toutes les modifications physiques ou perturbations de la partie supérieure du profil de tourbe auraient certainement une incidence sur le comportement hydrologique global de ce bassin versant en zone de tourbière.

Mots clefs bassin versant drainé en zone de tourbière; précipitations; nappe phréatique; coefficient de ruissellement; zone tropicale

INTRODUCTION

Peats comprise partially decomposed organic matter accumulated over a period of time under saturated condition (Andriesse 1988, Allaby 2008). Formation of peat therefore occurs in regions with high precipitation excess, such as upland areas of temperate and tropical regions (Holden *et al.* 2004). Tropical peatlands occur almost everywhere in the tropical countries. Of more than 400 million hectares (or 11% of the world land area) of peatlands in the world, about 72 million ha are in the tropics (FAO 2004, Wetlands International 2004). Of this, about 23 million ha are in the South East Asian region, with about

2.4 million ha (7% of the total land area) located in Malaysia (Hooijer *et al.* 2010, Page *et al.* 2011) and 20 million ha in Indonesia (Dwiyono and Rachman 1996, Hooijer *et al.* 2010). Although historically considered to be regions of low value, the importance of peatlands in terms of ecological value and water supply is now increasingly recognized (Bonn *et al.* 2009).

Increasing demand for agricultural and forest products for both domestic consumption and foreign export has forced farmers and government agencies in Malaysia to reclaim or develop peatlands for plantation in recent years (Hooijer *et al.* 2006, Stone 2007). Increasing demand for real estate properties has also attracted developers to reclaim wet peatlands for developing new townships (Mutalib *et al.* 1992). Therefore, reclamation of peat swamps for agriculture and other purposes has received increased attention by researchers and relevant agencies in recent years (Melling 2005, Jaenicke *et al.* 2011).

The most common practice followed for peatland development is the lowering of the peat water table through drainage (Mulqueen 1986). The relative position of the water table within the peat controls the balance between accumulation and decomposition, and its stability (Holden *et al.* 2004). Peat is therefore very sensitive to changes in hydrology that may be brought about by drainage (Guertin *et al.* 1987). Changes in hydrological properties, oxidation and subsidence, peat water acidity, peat fire, flooding and losses of freshwater supply are some of the potentially most negative environmental impacts commonly experienced in tropical peatlands due to drainage (Holden *et al.* 2004, 2006, Worrall *et al.* 2007, Langner and Siegert 2009). Chason and Siegel (1986) and Holden *et al.* (2006) reported that reclamation, irrigation and drainage, road construction and other civil engineering activities disrupt the normal hydrology of peatlands. Watanabe *et al.* (2009) and Sillins and Rothwell (1998) found that draining of a naturally shallow water table expedites the oxidation process of the peat materials and thus inevitably results in land subsidence. Wilcox *et al.* (1986) and Worrall *et al.* (2007) reported that draining of naturally acidic peat water increases the acidity level of the peat water due to the increase of humification. This causes severe damage to the habitats of flora and fauna and the mangrove system. Page and Rieley (1998) and Langner and Siegert (2009) observed that lowering of the naturally shallow water table in peat swamp forest makes the highly-porous peat material catch fire easily when it has withstood the low water table conditions for a long time. Winston (1994) reported that drainage of a peat catchment, particularly at the dome part, increases the occurrence of flooding to neighbouring areas. It also causes peat shrinkage and decrease of storage capacity. It is anticipated that climate change may intensify some of such impacts in the future (Takahashi and Yonetani 1995, Hooijer *et al.* 2010).

Although several problems are associated with peatland drainage activities, the reclamation of peatlands for agriculture, forestation and other development purposes is difficult to avoid. Consequently, conflict between land developers and conservationists often arises. To address such concerns, as well as to preserve and manage the tropical peatland, it is essential to have a good understanding of the hydrological behaviours of peatland. According to the basic laws of the soil–water relationship, such interactions depend on both the storage and the transmission capacities of the watershed system (Bradford and Watt 2000). Being wetland systems in nature, peat swamps are very sensitive to the groundwater regime (Mitsch 1988). Understanding hydrological behaviour through groundwater dynamics in relation to rainfall and streamflow is therefore of fundamental importance in addressing the environmental issues associated with peatland development and management. Unfortunately, except for some economic aspects of peatland reclamation, hydrological impacts have not been given due emphasis so far in the tropics. Knowledge about hydrological changes due to continuous drainage is still insufficient, and we are still far from having proper technical guidelines for peatland management.

The objective of the present research is to study the hydrological behaviour of a tropical peat catchment and the changes in its hydrological characteristics due to drainage. This paper is the first of two papers describing the hydrological behaviour of a drained agricultural peat catchment in the tropics (Johor, Malaysia). This first part focuses on water table responses to the hydrodynamics of shallow streamflows in a tropical peatland to enable us to understand the interactions between rainfall, streamflow and groundwater table. In Part 2 (Katimon *et al.* 2013), transfer function models of the rainfall–runoff relationship of various complexities are developed to investigate the changes in hydrological behaviour of a drained tropical peat catchment. It is expected that the research will help to understand the hydrological behaviour of a peat catchment with a view to formulating management guidelines of peatland systems.

In the next section, a brief description of the study area is given. This is followed by a description of data used, and the methods used herein are discussed next. Then the results and discussion section discusses the hydrological behaviours of the study peat catchment and their changes with time.

STUDY AREA

To address the aim of the research, a peat catchment located at Parit Madirono (latitude: 01°42′35″ N; longitude: 103°16′15″ E) in the southwest of Peninsular Malaysia was selected for the study. The size of the catchment is 1.84 km^2 (184 ha) and its location in the map of Malaysia is shown in Fig. 1. The study catchment was under one of the major peatland reclamation schemes of Malaysia, known as the Western Johor Reclamation Project (WJRP), Phase-I, and has undergone a continuous drainage process since 1975 to reclaim the peat swamp forest for rural settlement and cropland. A catchment of this size is equivalent to one typical drainage block served by a single collector drain (Lim 1992). Land in the catchment can be classified as communal land where a rural population is living and practicing mixed agriculture. The hydrological monitoring programme in the catchment was started in 1981 and terminated in 1996; thus, long-term reliable hydrological records to facilitate comparative analysis of hydrological parameters at different time periods are available for the catchment.

The peat depth in the catchment ranges from 10 cm near the river to 3.5 m at the middle of the far end of the catchment. According to the Von Post scale of peat humification (SCS 1975), the degree of peat decomposition in the study area is found to vary from nearly complete decomposed peat (H7–H9) at the top (down to 15 cm below the surface) to moderate to strong decomposed peat (H5–H6) at deeper levels. According to the US Department of Agriculture scale (SCS 1975), the peat materials of the study catchment can be classified as "moderately to strongly decomposed" peat.

In Malaysia, the peat bodies generally have a dome-shaped surface. The peats are generally classified as ombrogenous peat. Due to the coastal and

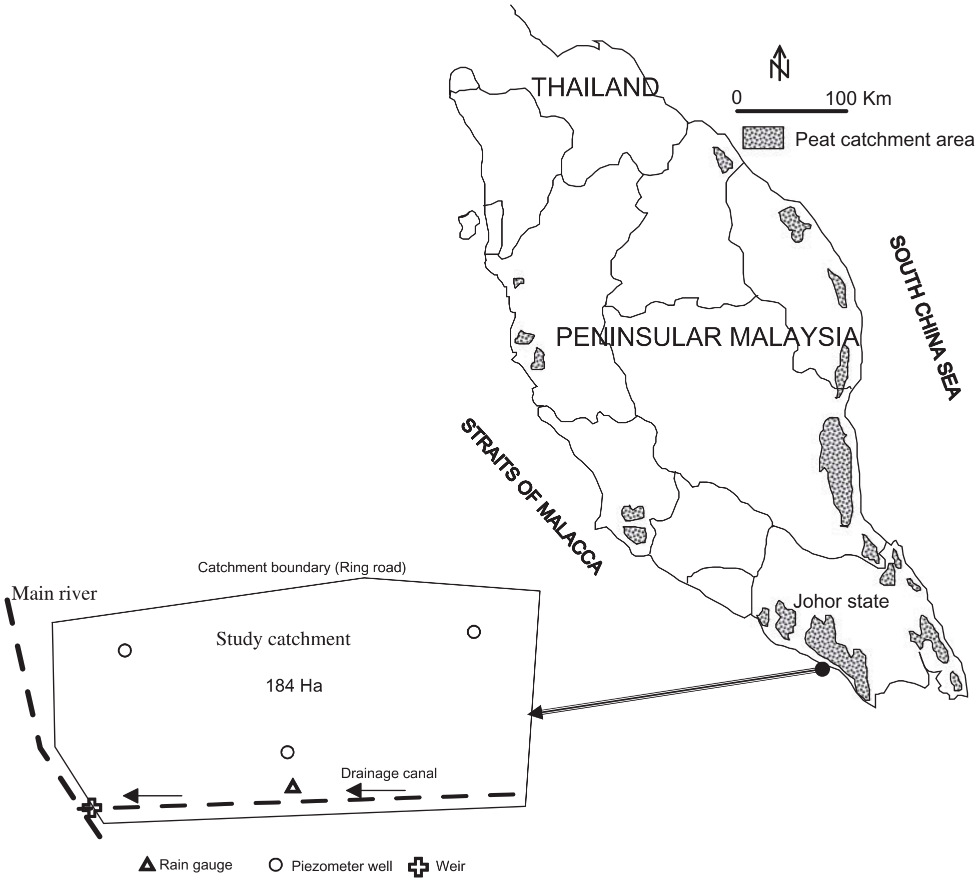

Fig. 1 Location of the study catchment in Malaysia.

alluvial geomorphology, they are often elongated and irregular, rather than the typical round bog shape. The elevation of the study peat basin varies from about 7 m in the southwest to about 16 m in the east. Relatively steep gradients are found at the periphery, while the central peat plain is almost flat. Surface slopes vary up to 2 m/km at the sides of the dome near the adjacent channel, but in the central part of the peat dome the slope is less than 0.5 m/km.

The area was covered by different types of vegetation during different time periods. No proper land-use records are available for the area. However, according to the WJRP implementation schedule, the land-use pattern of the catchment has changed significantly over time, as follows. The reclamation works (e.g. peat swamp clearing, de-stumping and first drainage) were started in 1974. In the early 1980s, a mixed plantation of rubber trees and short-term vegetables was grown by the local settlers. In the early 1990s the old rubber trees were replaced by palm oil trees. Classified as a communal land, the catchment is now provided with basic infrastructure and public utilities. The number of households has increased from none in 1974 to about 20 at present.

DATA AND SOURCES

The Water Resources Division of the Department of Irrigation and Drainage, Malaysia, installed four rainfall stations in the study area in 1978. However, only one station was well maintained and produced quality long-term data. There are many breaks in the data series of other stations due to either instrument malfunction or improper maintenance. Therefore, rainfall records from only one station that has quality rainfall time series data are used in the present study. Rainfall at the station was measured using a daily autographic recorder. Hourly rainfalls were obtained by digitizing the recorder chart.

Streamflow in the catchment was measured by using a 120° V-notch weir equipped with a water-level and chart recorder. Stage–flow curves for different years were established for the gauging station to estimate the flow of the catchment. The daily flow records from 1981 to 1995 are available from this weir. In 2000, the gauging station was re-activated with a new water-level recorder. The purpose of this new equipment was to obtain event-based storm runoff data of the catchment. Streamflow measured by this new recorder is also used in this study for detailed analysis of the rainfall–runoff relationship.

Three piezometric wells equipped with water-level recorders were installed at three different locations inside the study area to record groundwater fluctuations. Although the complete piezometric design and recording charts are supposed to be available, they are reported to have been misplaced and remain undiscovered. Nevertheless, the manually written records of mean daily water table depth are available. As the details (such as exact location and elevation) of the piezometric wells are not available, to avoid confusion, the record from one well is used in this study, although its exact location is unknown (the person responsible for equipment maintenance identified its location most close to the gauging station); its elevation is known. The daily water table record for 1982–1994 is available for this station and was used in the present study. In 2000, a new piezometric well equipped with a water-level logger was installed in the middle of the catchment to obtain a water table fluctuation record at smaller time resolution. High-resolution data recorded by this new logger are also used to study water table response to rainfall events. The annual rainfall, annual runoff, average groundwater level and daily average pan evaporation of the catchment for the period 1982–1994 are given in Table 1.

METHODOLOGY

Selection of storm hydrographs

To characterize the hydrological behaviour of the catchment and decipher the changes in hydrological properties of the catchment over time, storm hydrographs are selected from streamflow time

Table 1 Summary of annual hydrology of the study area (1982–1994)

Year	Rainfall (mm)	Runoff (mm)	Mean water table (cm)	Daily pan evaporation (mm)
1982	2837	2207	23.2	4.1
1983	1824	1121	37.7	4.1
1984	3069	1829	26.6	3.9
1985	2884	1500	26.6	4.1
1986	2561	2049	55.1	4.2
1987	2783	1239	55.5	4.2
1988	2895	1819	59.7	4.0
1989	2026	1023	58.2	4.1
1990	2544	1074	68.6	4.1
1991	2051	1881	71.7	4.0
1992	2880	2018	71.8	4.2
1993	2531	798	71.5	–
1994	2609	1890	69.6	–

series (1982–1996). Robinson (1986) proposed a subjective approach for selecting independent storm hydrographs. He suggested that the minimum flow between two peaks must be less than 66% of the first peak, and the successive peaks must be at least four days apart. In practice, it is difficult to meet these criteria. In the present study, single peak hydrographs are selected considering that an independent rainfall event produces only a single peak in the hydrograph. In total, 75 individual storm hydrographs produced by rainfall events with similar volumetric rainfall, antecedent conditions and temporal distributions over the study period were selected in the present study. To understand the mechanisms responsible for runoff generation in the catchment, the rainfall and antecedent water table depth data for the respective storm hydrograph are analysed.

Baseflow separation and storm hydrograph analysis

To quantify the amount of direct or surface runoff produced by individual rainfall events, the streamflow hydrographs must be separated from their baseflows. Baseflow is an important genetic component of a streamflow hydrograph that comes from groundwater and/or shallow subsurface storage (Romanowicz 2010). Two techniques are used in the present study for baseflow separation in order to examine the changes in the low-flow characteristic of the catchment: (a) the graphical approach proposed by Dickinson *et al.* (1967), and (b) the recursive digital filter approach proposed by Nathan and McMahon (1990). According to the graphical approach, separation of baseflow from a stream hydrograph is done by identifying the points at which the direct runoff starts and ends (Kawi and Greer 1997). The start point is identified as the time when the flow starts to increase, while the end point is taken at the time where the graph of log discharge against time becomes a straight line (Chapman 1999). The main disadvantage of this technique is that the result depends on individual judgement in locating the inflection point of the hydrograph. In contrast, the second technique is based on a continuous flow time series analysis using a recursive digital filter approach (Nathan and McMahon 1990), which considers that the daily streamflow time series is a mixture of quick flow (high-frequency signal) and baseflow (low-frequency signal). The method calculates the baseflow response of a catchment by:

$$Q_{e(k)} = \alpha Q_{e(k-1)} + \frac{(1+\alpha)}{2}\left(Q_{t(k)} - Q_{t(k-1)}\right) \quad (1)$$

where $Q_{e(k)}$ is the filtered quick flow at time k; $Q_{t(k)}$ is the original flow at time k; and α is the filter parameter.

The filtered baseflow, $Q_{b(k)}$ is calculated by:

$$Q_{b(k)} = Q_{t(k)} - Q_{e(k)} \quad (2)$$

Knowing the observed daily flow series $Q_{t(k)}$ and filter parameter α, equations (1) and (2) can be solved to obtain the baseflow. Once the baseflow volume is separated from total flow, the baseflow index (BFI) of the catchment can be calculated as the ratio of baseflow to total streamflow (Nathan and McMahon 1990).

RESULTS AND DISCUSSION

Hydrological behaviour of the peat catchment

The hydrographs are characterized according to their four components: lag time (T_L), peak flow (Q_p), effective flow or quick flow (Q_e) and baseflow (Q_b). The mean and standard deviation of the hydrograph variables are tabulated in Table 2, which shows that mean peak flow of the study catchment is small (<1.0 m^3 s^{-1}). Annual maximum peak flow and BFI are plotted against time (Fig. 2) to show the changes of these parameters during the period 1982–1994. It can be seen from the Fig. 2 that peak flow has reduced over time. The figure also shows that baseflow for similar rainfall events has increased significantly over the 1982–1994 period. Peak discharge depends on many factors, including rainfall volume, rainfall intensity, antecedent soil moisture condition and land cover. To understand the influences of rainfall amount and

Table 2 Summary of the statistics of the study catchment parameters

Hydrograph variable	Mean	SD
Rainfall depth, P_d (mm)	37.16	18.39
Rainfall duration, P_T (h)	2.96	1.58
Rainfall intensity, P_I (mm h^{-1})	15.08	9.43
Peak flow, Q_p (m^3 s^{-1})	0.9458	0.9776
Baseflow, Q_b (mm)	7.4062	5.3023
Effective flow, Q_e (mm)	12.9592	16.7809
Baseflow index, BFI	0.47	0.19
Lag time, T_L (h)	4.48	2.084
Separation line slope, S	0.00298	0.00927
Water table depth, WT (mm)	51.19	26.08
Runoff–rainfall ratio, q_c	0.6232	0.5724

Note: SD, standard deviation.

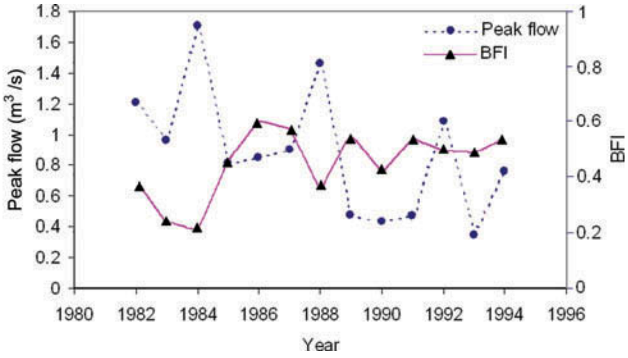

Fig. 2 Annual maximum peak flow and baseflow index (BFI) in the study catchment, 1982–1994.

intensity on peak flow, the ratio of peak flow to corresponding rainfall amount and rainfall intensity is plotted in Fig. 3, which also shows that peak flow has reduced over time. Higher amounts of rain and more intense rainfalls in the later years produced lower peaks in stream discharge compared to early years. To understand the change in peak flow over time more clearly, hydrographs produced by rainfall events with similar volumetric rainfall, antecedent conditions and temporal distributions in different years in the study catchment are shown in Fig. 4. Figure 4 also shows that peak flow has reduced over time.

It can be seen from Table 2 that the runoff ratio of the catchment is about 62%, which means that more than 60% of rainfall during storm events ends up as effective flow or quick flow. Therefore, it can be stated that the catchment is flashy in nature. When compared to peat catchments of temperate regions and non-peat catchments of Malaysia, the study peat catchment is found flashier. For example, the mean storm runoff ratio in a blanket peat catchment of the United Kingdom is about 40% (Evans *et al.* 1999).

Analysis of annual rainfall, runoff and mean groundwater level (Table 1) by using the Mann-Kendall trend test (Mann 1945, Kendall 1975) shows that there is no significant change in annual rainfall and runoff in the study area. However, the groundwater table has declined significantly (99.9% level of confidence).

To analyse the temporal changes in hydrograph characteristics, the annual runoff ratios obtained from 75 selected individual storm hydrographs were plotted against the time, as shown in Fig. 5. A nonlinear regression line is fitted to quantify the change in runoff ratio with time. The result shows that the runoff ratio decreases with time according to the following equation:

$$q_c = 1.22t^{-0.5471} \tag{3}$$

where t is the year after the first observation year and q_c is the runoff ratio. The regression coefficient (R^2) of the fitted model is 0.4, which is significant at the 99% level of confidence. This means that the fitted model explains 40% of the variability in runoff ratio. It can be clearly observed from Fig. 5 that the runoff ratio was large during the first few observation years before it attenuated to a constant rate in the later years. This strongly indicates the behaviour change of the peat catchment due to continuous drainage.

Conflicting results have been reported by various authors working on hydrological responses to artificial drainage in peatlands. Many have reported that drainage increases flood peaks (Robinson 1980, 1986). However, a decrease in flood peaks has also been reported by some authors (Baden and Egglesmann 1970, Newson and Robinson 1983). The gradual decline of peak flow in the study area could have multiple reasons.

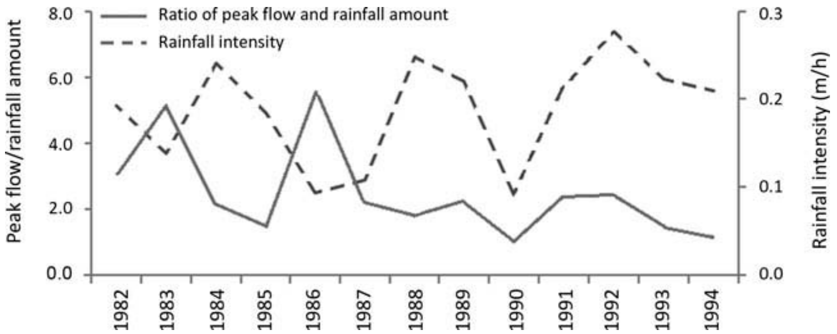

Fig. 3 Ratio of annual maximum peak flow and rainfall amount, and rainfall intensity responsible for peak flow, 1982–1994.

One of the important causes of gradual reduction in peak flow may be the progressive changes of peat compressibility in the area after drainage. Usually, tropical peat swamps of Malaysia compress and subside after drainage and reclamation (Ritzema *et al.* 1998). Wosten *et al.* (1997) reported that the

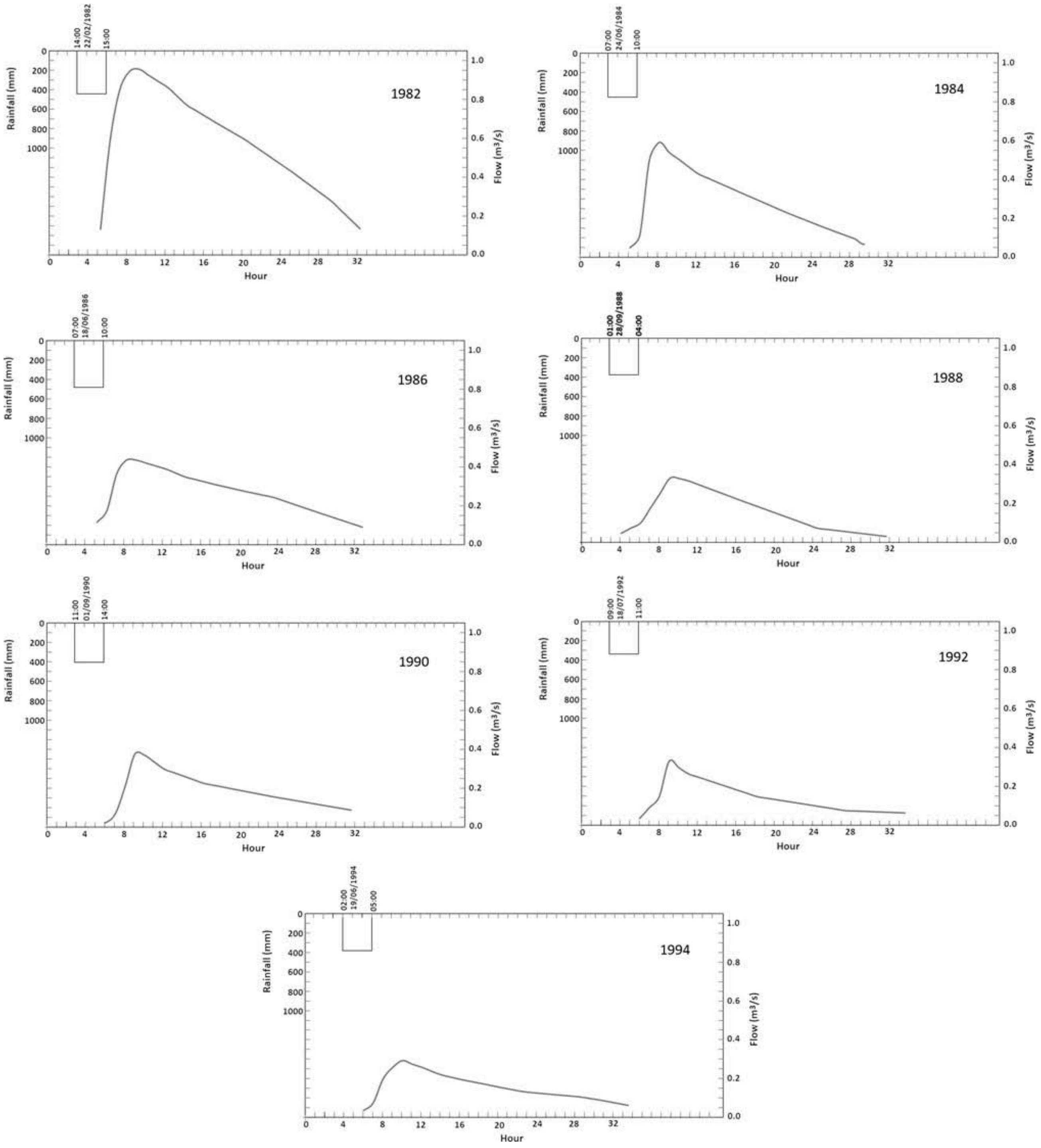

Fig. 4 Hydrographs produced by similar rainfall events in different years in the study catchment.

subsidence rate is higher (about 4.6 cm/year) in the first few years after drainage, due to the removal of surface and subsurface woody materials during the first stage of reclamation works. Further draining of the peat can cause the area to steadily subside at about 2 cm/year due to soil decomposition processes (Wosten *et al.* 1997). Initially, this involves the loss of buoyancy and compaction of the organic column under its own weight. The compaction changes the hydro-pedological parameters, such as hydraulic conductivity, bulk density, pore volume and moisture content. The subsequent dominant processes, which may last for decades, are oxidation and shrinkage. Long-term subsidence monitoring in the study

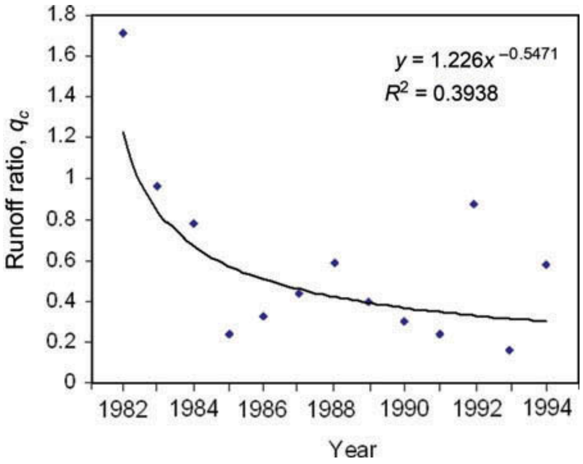

Fig. 5 Variations in runoff ratio with time in the study catchment.

peat catchment shows that the subsidence rate was 20–50 cm/year at the very beginning of the drainage processes, and this reduced to 4.6 cm/year during the next 10 years. Therefore, rapid decline of peak flow during the first few years of drainage may be due to the higher compression of the peat.

Decline of the water table may be another important factor for the gradual reduction of peak flow. Due to the removal of soil water to the drain, the groundwater table falls to greater depth in the drained area. Changes in mean, minimum and maximum depths of groundwater table in the study area are shown in Fig. 6, which shows that the groundwater table has fallen with drainage in the study area. The deeper the water table, the higher the storage capacity in the soil layer (Schlotzhauer and Price 1999). Thus, more rainwater temporarily stores in the unsaturated soil layer which, in turn, reduces the runoff.

Even though no proper record of land-use changes is available, from the rough estimate of the land-use changes given in the description of the study area, it can be remarked that gradual reduction of peak flow with time may also happen with the progression in rubber tree growth in the 1980s. Clearing of land for cultivation of palm oil trees in the early 1990s caused an increase in peak flow for that year.

Therefore, from the above discussion, it can be stated that the reduction in peak flow after drainage in the study area may be due to a combination of: progressive changes in peat compressibility, the increase in storage capacity of the soil layer due to the decline of the groundwater table, and the changes in land cover. A similar conclusion is reached by Holden *et al.* (2004) about the decrease of peak flow with drainage. They conducted a review on peat hydrological changes due to artificial drainage and reported that "*decreases in flood and annual runoff may come about following drainage because of a reduction in hydraulic conductivity, loss of surface runoff by storage in the upper peat layers, flow loss by storage on soil and depressions caused by subsidence, and increased evaporation related to changes in vegetation.*"

Baseflow index

As the baseflow index (BFI) is the ratio of baseflow to total streamflow, it can be regarded as an index

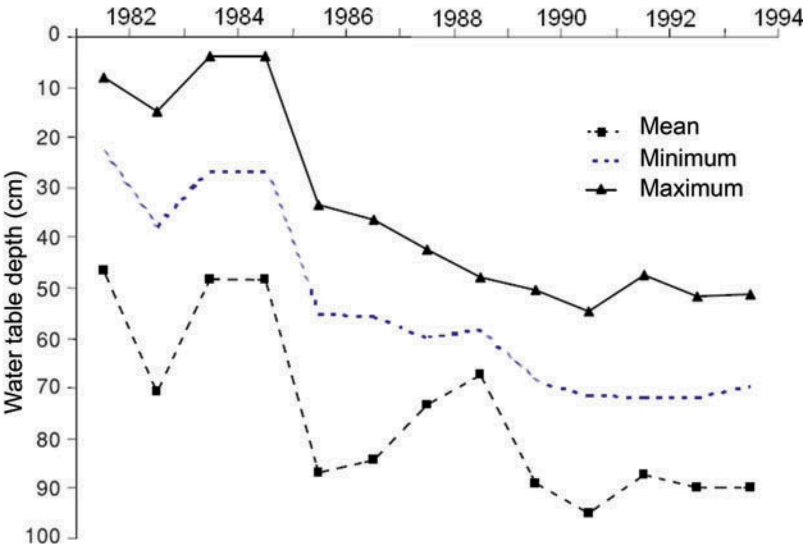

Fig. 6 Changes in mean, minimum and maximum depths of water table in the study catchment over the period 1982–1994.

to show the contribution of shallow groundwater discharge to the streamflow. The study shows that the mean BFI of the catchment is 0.47 with a standard deviation of 0.19 (Table 2). This means that subsurface flow is a major contributor to streamflow in the catchment.

Rainfall–runoff relationships

Correlation analysis between hydrograph parameters and rainfall parameters was carried out to give a general overview of the hydrological processes, as well as to identify the mechanisms responsible for runoff generation in the catchment. The detailed results of correlation analysis are presented in Table 3.

The correlation analysis reveals a strong correlation between streamflow and rainfall. Rainfall characteristics such as total precipitation (P_t), precipitation average intensity (P_i) and precipitation duration (P_d) are found to correlate strongly with hydrograph components such as peak flow (Q_p), effective flow (Q_e), baseflow (Q_b), runoff ratio (q_c), lag time (T_L), separation line slope (S) and groundwater table (WT). In many cases, correlations are significant at the 99% level of confidence. Strong correlation among these parameters supports the hypothesis of rapid and efficient transfer of rainwater from the land to the drainage canal.

Usually, strong negative correlations between water table and hydrograph parameters Q_p, Q_b and Q_e are expected in peat basins, in accordance with the principle of the water table–aquifer flow system. In a peat basin, the volume of drained water is a direct function of the unsaturated depth above the water table. Therefore, a lower water table depth means smaller storativity of the aquifer and, consequently, a smaller amount of drained water (Fetter 1994). The study shows that the groundwater table depth of the study catchment is negatively correlated with storm hydrograph characteristics (at 99% level of confidence) (Table 3). Therefore, the obtained result is consistent with the general theory of peat catchment hydrology.

A strong correlation between runoff ratio (q_c) and peak flow (Q_p) suggests that runoff generation is not limited to overland flow alone. This is as expected, since the porosities of most tropical peat materials are very high (Andriesse 1988). Infiltration, storage and subsurface flow probably influence the runoff generation in the catchment to some extent. As the water table is negatively correlated with peak flow (Q_p), and there is a strong negative correlation between time lag (T_L) and runoff coefficient (q_c), it can be suggested that, at lower rainfall intensities, transmission of rainfall to the channel may be delayed. This is consistent with the physical concept of infiltration and subsurface storage in the peat (Bradley and Van den Berg 2005).

From the correlation matrix given in Table 3, it is also obvious that the most important contribution to the variance of the streamflow is made by rainfall depth (P_d). The stronger correlation of P_d, rather than P_i, with Q_p and Q_e suggests that overland flow could be generated from saturated areas and, thus, the role of infiltration excess flow may be limited. Weak correlations between rainfall intensity and hydrograph components indicate that the rapid flow mechanism within the study basin is generated by the non-infiltration excess principle. Therefore, it may be concluded that the saturation excess mechanism is the dominant mechanism for runoff generation in the basin.

Quick and rapid flow components of a storm hydrograph can be further sub-categorized into two different mechanisms according to the exact location of flow within the soil profile (Bruijnzeel 1982).

Table 3 Correlation of rainfall and hydrograph parameters

	P_d	P_t	P_i	Q_p	Q_b	Q_e	T_L	S	WT	q_c
P_d	1.000	0.431^{**}	0.366^{**}	0.636^{**}	0.287^{*}	0.607^{**}	-0.367^{**}	0.313^{**}	-0.235^{*}	0.266^{*}
P_t		1.000	-0.506^{**}	0.423^{**}	0.120	0.387^{**}	0.075	0.161	-0.249^{*}	0.171
P_i			1.000	0.080	0.039	0.120	−0.183	0.021	0.138	0.086
Q_p				1.000	0.592^{**}	0.934^{**}	−0.174	0.345^{**}	-0.499^{**}	0.803^{**}
Q_b					1.000	0.488^{**}	−0.091	0.464^{**}	-0.371^{**}	0.529^{**}
Q_e						1.000	−0.144	0.161	-0.509^{**}	0.856^{**}
T_L							1.000	0.035	0.226	−0.056
S								1.000	−0.165	0.067
WT									1.000	-0.558^{**}
q_c										1.000

Note: **Significant at 0.01 level of confidence; *Significant at 0.05 level.

These are quick-flow surface runoff and quick-flow subsurface runoff. Quick-flow surface runoff occurs due to saturated soil, even if the infiltration capacity is not exceeded. In contrast, quick-flow subsurface runoff occurs due to lateral flow in the soil under saturated conditions.

In peatlands with a high water table, streamflow is directly proportional to water table depth, in accordance with the principle of subsurface flow of the water table–aquifer system. Burt (1992) and Holden and Burt (2000) identified five potential mechanisms for the generation of runoff from a peat catchment. These are: (1) infiltration-excess overland flow (HOF); (2) saturation-excess overland flow (SOF); (3) rapid acrotelm flow, generated by percolation excess at the boundary between the acrotelm and a saturated catotelm; (4) rapid acrotelm flow, generated by percolation excess at the acrotelm/catotelm boundary where the upper layers of the catotelm are unsaturated; and (5) pipeflow.

According to Burt's definition (Burt 1992), the runoff mechanism of the present catchment is most likely of Type 3 or 4. The rapid acrotelm flow is generated by percolation excess at the boundary between the acrotelm and a saturated catotelm, or by percolation excess at the acrotelm–catotelm boundary where the upper layers of the catotelm are unsaturated. Evidence obtained through correlation analysis also indicates that the saturation-excess lateral subsurface flow is the main mechanism of rapid water transfer to the stream.

Water table depth–runoff relationships

There is a close association between water table depth and soil moisture in peat catchments (Schlotzhauer and Price 1999). This has a significant effect on storm hydrograph performance. The soils of the study catchment were found to be saturated for most of the year. The results of hydrograph analysis also show that the runoff process in the study area is mainly driven by the saturation-excess lateral subsurface flow mechanism. Although these two findings are consistent with each other, analysis of water table dynamics was carried out to establish the hypothesis of a saturation-excess lateral flow mechanism of runoff generation more candidly. According to the subsurface flow theory, lateral groundwater movement is essentially driven by water table gradient (Fetter 1994). The water table is the level at which the water pressure is equal to the atmospheric pressure and, hence, the level at which water will stand in a well that is hydraulically connected with the groundwater body (Gilman 1994).

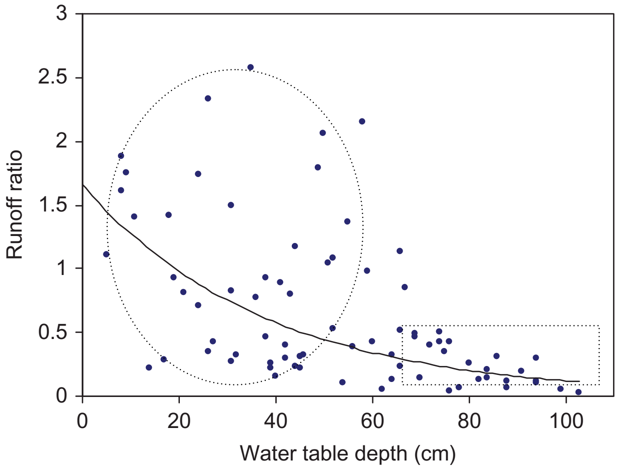

Fig. 7 Relationship between runoff ratio and antecedent water table depth.

The 75 individual storm hydrographs produced by rainfall events with similar volumetric rainfall, antecedent conditions and temporal distributions over the study period were used to obtain the relationship between runoff ratio and antecedent water table depth. Figure 7 shows the change in runoff ratio *vs* antecedent water table depth. It is clear from Fig. 7 that runoff volumes are smaller when the water table is deeper below the ground surface (indicated by the dotted rectangle). The highest variability of runoff occurs when the water table is less than 55 cm below the ground surface (dotted circle). This suggests that the shallow water table has less control on rapid flow generation in the study catchment.

Hourly data were used to decipher the relationship between runoff and groundwater level more

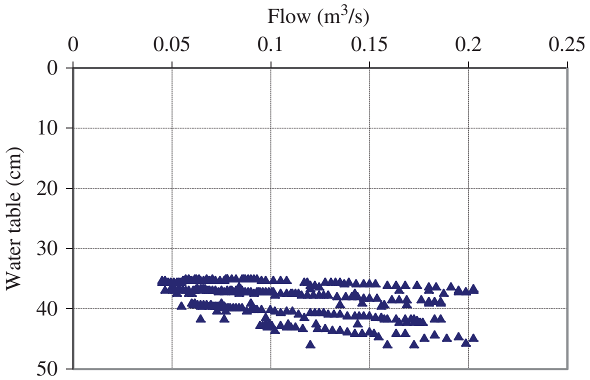

Fig. 8 Relationship of streamflow with water table depth (hourly data from 3–15 August 2000) illustrating the importance of subsurface water table in generating runoff.

clearly. Figure 8 shows the variation in groundwater levels with runoff for a period between 3 and 15 August 2000. It can be seen from Fig. 8 that significant storm discharge occurred when the water table was within 35–45 cm of the surface. This signifies the importance of peat saturation in the production of near-surface flow in the catchment.

The hydrological behaviour of a drained peat catchment helps us to understand peat hydrology at the regional scale. Many developed peat areas of Malaysia are composed of several small-scale drained peat catchments, like the catchment used in the present study. Usually, a regional drainage scheme is adopted to reclaim land over an area having many small peat catchments (Singh 1989, Lim 1992). Individual catchments are provided with collector drains at uniform intervals of about 800 m. However, the drainage systems are uncontrolled and the flows are naturally unregulated. It can be stated that the hydrological behaviour and changes in hydrological parameters of the study peat catchment represent the peat hydrology of the region.

CONCLUSIONS

Traditionally, paired-catchment experiments are used to evaluate changes in the hydrological behaviour of drained catchments, which is time-consuming and requires properly planned and instrumented catchments. Alternatively, comparison of hydrological records before and after a catchment has been altered may be done to assess the change, and this requires pre- and post-drainage hydrological data. Neither of the aforementioned approaches is applicable in the present study catchment, due to the absence of paired catchments and the unavailability of pre-drainage hydrological records. Therefore, an attempt was made at quantitative analysis of storm hydrographs and their relationships with rainfall and water table levels to understand the hydrological mechanisms responsible for stormflow generation in a drained tropical peat catchment, as well as changes in the hydrological behaviour of the catchment due to continuous drainage for a long period. It is not possible to come to a concrete decision about the impacts of drainage on peat hydrological behaviour from the data available in the study area and the analysis presented herein. However, the study indicates that continuous drainage may have reduced the peak flow and increased the baseflow over time. As the peak flow represents the severity of floods and low flow leads to water scarcity or hydrological droughts, decreasing peak flow and increasing baseflow indicate that continuous drainage in the peat catchment may have reduced flood risk due to heavy rainfall and, at the same time, augmented water availability during dry spells. However, it should be noted that this may not be true for all peat catchments; it may be different for peat catchments with different characteristics. One of the major outcomes of the present study is that it has successfully identified the saturation excess-near surface flow mechanism as the dominant mechanism responsible for runoff generation in a drained peat catchment. Most of the stormwater flows through the subsurface just above the water table. The greatest variability of runoff production occurs when the water table is less than 55 cm from the ground surface. Therefore, any physical disturbances to the upper part of the peat profile would definitely affect the overall hydrological performance of the peat catchment.

Peatlands are very sensitive to hydrological changes due climate or land-use change. Therefore, understanding the hydrological behaviour of peat catchments and their changes due to drainage is essential for peatland reclamation and management. In the second of these two papers describing the hydrological behaviour of a drained tropical peat catchment (Katimon *et al.* 2013), transfer function models of rainfall–runoff relationships are developed to investigate the changes in hydrological behaviour. It is expected that the study will be beneficial to a number of stakeholders, particularly land developers, but also the agricultural organizations, development/planning authorities, and environmental agencies, to improve their understanding of the hydrological behaviour of peatlands. It is hoped that the study in general will assist in guiding the operational responses of various authorities, especially in terms of those interventions aimed at peatland development in the tropical region.

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