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HYDROLOGIC CHARACTERISTICS OF A DRAINED TROPICAL PEAT CATCHMENT: RUNOFF COEFFICIENTS, WATER TABLE AND FLOW DURATION CURVES

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Abstract. Reclamation and drainage of peat basin is an important land development in Malaysia. A clear understanding on the hydrologic behavior of a drained peat basin is the essential factor towards an optimal management of the resource. Hydrological data from Madirono peat catchment located in Johor State, Malaysia was collected and used to characterise its hydrologic characteristics. The characterizations were made using the ordinary quantitative hydrologic approach. The magnitude of changes in the major hydrologic component of the study catchment was quantified. The study catchment experienced a large variation in runoff coefficient, indicating that a drained peat basin is a highly dynamic hydrologic system. A decaying trend in the annual runoff coefficient was observed. The annual runoff coefficients were large, ranging from 0.32 to 0.92. This indicates that the hydrology of the study catchment was extremely dynamics, highly permeable and very flashy. The low flow condition of the basin was extremely small but improving over time indicating that the basin could not sustain river flow during dry spell. The mean annual water table decreased over time by 2.7 cm per year.

Keywords: Hydrology, tropical peat, flow duration curve, water table duration curve

Abstrak. Penebusgunaan serta penyaliran lembangan bertanah gambut merupakan suatu kerja pembangunan tanah yang penting di Malaysia. Kefahaman yang jelas terhadap sifat-sifat hidrologi lembangan tanah gambut bersaliran adalah faktor perlu ke arah pengurusan optimum sumber tersebut. Data-data hidrologi daripada lembangan bertanah gambut di Parit Madirono, Johor, Malaysia, telah di kutip dan digunakan untuk mencirikan hidrologi lembangan tersebut. Pencirian hidrologi telah dibuat menggunakan pendekatan hidrologi kuantitatif biasa. Perubahan dalam magnitud komponen-komponen hidrologi kawasan kajian telah ditentukan. Kawasan kajian mengalami variasi pekali air larian yang besar, menunujukan bahawa lembangan tanah gambut bersaliran merupakan satu sistem hidrologi yang amat dinamik. Penurunan nilai pekali air larian tahunan yang amat ketara telah didapati. Nilai pekali air larian tahunan juga besar, pada julat 0.32 ke 0.92. Ini menunjukkan bahawa hidrologi kawasan kajian amat dinamik, amat telap air dan sangat 'flashy'. Keadaan aliran rendah juga sangat kecil tetapi meningkat mengikut masa, menunjukkan bahawa kawasan tadahan tidak mampu menampung aliran semasa cuaca kemarau. Nilai paras air tanah purata tahunan didapati mengurang pada kadar 2.7 cm setahun.

Kata kunci: Hidrologi, tanah gambut tropika, lengkung aliran, lengkung paras air tanah

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1.0 INTRODUCTION

Peat lands are found in many parts of the world both in the temperate and tropical region. Tropical peat lands occur almost everywhere in the tropical countries. Out of more 400 million hectares (Hugo, 1960) (or 11 percent of the world area) peat lands resources in the world; about 72 million hectares are in the tropics. Out of this 20 to 22 million hectares are in South East Asian region with about 2.7 million hectare (7% of the total land area) is located in Malaysia (Mutalib et al., 1992) and 20 million hectares occur in Indonesia (Dwiyono and Rachman, 1992). At the national level, out of more than 2.7 million hectares of peatland resources, about 1 million ha occurs in Peninsular Malaysia, 1.6 million in Sarawak and about 0.8 million is Sabah. It is estimated that more than 0.3 to 0.5 million ha of the peat lands resources in this country has been developed mainly for agriculture cum settlement areas (Mutalib et al., 1991).

In recent years, the conversion of peat swamps into other purposes, such as for physical and agricultural development has received increased attention by researchers and relevant agencies. The increasing demand in agricultural and forest goods for both domestic consumption and export has forced producers and related government agencies to reclaim or develop these marginal lands for plantation. In some part of the country the increasing demand in housing and industrial needs had also forced developers to reclaim peatlands for housing area and new township. These activities resulted in the decreasing area of peatlands due to increased in logging operation of peatland forest (Kyuma et al., 1991; Chai, 1999), transformation of peatlands into the agriculture (Mutalib et al., 1991) and housing (Ahmad Sanusi, 1999). In general, reclamation and development of peat swamp causes adverse environmental and hydrological impacts if precaution measures are not undertaken (Mamit, 1999; Guertin et al., 1987).

The reclamation of peat lands however, often leads to unforeseen problems, due to the lack of understanding of their underlying hydrological causes. The formation of drainage schemes and the provision of drainage canals and water control structures of the reclaimed peat lands areas has somewhat minimized some of the problems with environmental impacts. The effect of climate change to their hydrological behavior is expected to be significant (Takahashi and Yonetani, 1997). However, there is relatively little research findings in hydrology of both reclaimed and undeveloped tropical peat swamp particularly in Malaysia. Basic knowledge in the hydrological component of the watershed would be required to further explain the hydrological processes of the reclaimed areas. This would include the rainfall-streamflow-groundwater table relationship in relation to the changes in physical behavior of the peat basin. Having known all these relationships, decision on the number of hydraulic structure required, how much water can be conserved and the range and extent of water level control in the drains and adjacent land can be made.

A detail research project focusing on hydrologic dynamics of the stream flows and groundwater table responses of an artificially drained peat catchment under the

Malaysian environment was conducted (Ayob and Khairi, 1999). Various study scope was established which cover the field investigation and quantitative hydrologic method and time modelling approaches. The ultimate goal of this study was to provide substantial evidence and establish scientific background for evaluation of hydrologic effects of common management practices on peat land systems. It is therefore to provide basic information and guidelines for the management of peat land ecosystem in this country.

This paper highlights only part of the research finding from the above-mentioned research project. Specifically, the objectives of this paper are; to investigate the runoff ratio variation over time during drainage; to establish flow and water table duration curves of the study sites. The research output presented in this paper provides useful contribution to hydrologic impact assessment method of drained peat catchment.

2.0 MATERIALS AND METHOD

2.1 The Study Site

A study site was selected as the basis for data collection. The study site is located at Parit Madirono in the district of Benut, Johor, South-West of Peninsular Malaysia, (103°16'15"E, 01°42'35"N), about 80 km from Universiti Teknologi Malaysia main campus in Skudai (Figure 1). It is located inside one of the major peatland reclamation scheme found in this country and managed by the Western Johore Reclamation Project (WJRP) Phase One. The size of the catchment is 1.84 km2 or 184 Hectares. The area has been drained since 1975 to convert the peat swamp forest into rural settlement and crop cultivation area. According to the local drainage design criteria, catchment of this size is equivalent to one typical drainage block served by a single collector drain (Lim, 1992). This type of land is classified as a communal land where rural population are living and practicing mixed agriculture. The study site was planned as one of the Malaysian Representative Experimental Catchment established by the Department of Irrigation and Drainage (D.I.D.), Malaysia. The hydrological monitoring program was started in 1981 hydrological year and terminated in 1996. Though the data collection has been carried out for more than ten years, they remained untouched and unpublished.

The peat depth was in the range of 10 cm at point close to the river to 3.5 m at point in the middle far end of the area. According the Von Post Scale of peat humification (Melling, 2000) generally, the degree of peat decomposition found in the study site varied with the soil depths and according to the following order. Nearly complete decomposed (H7-H9) at the top 15 cm followed by moderate to strong decomposed (H5-H6) at the deeper level. As according to USDA scale (Soil Survey Staff, 1975) the peat materials of the study site can generally be classified as 'moderately to strongly decomposed' peat.

The area was covered by different vegetation type during different time period. No proper land use record was available. However, according to the West Johore Phase 1

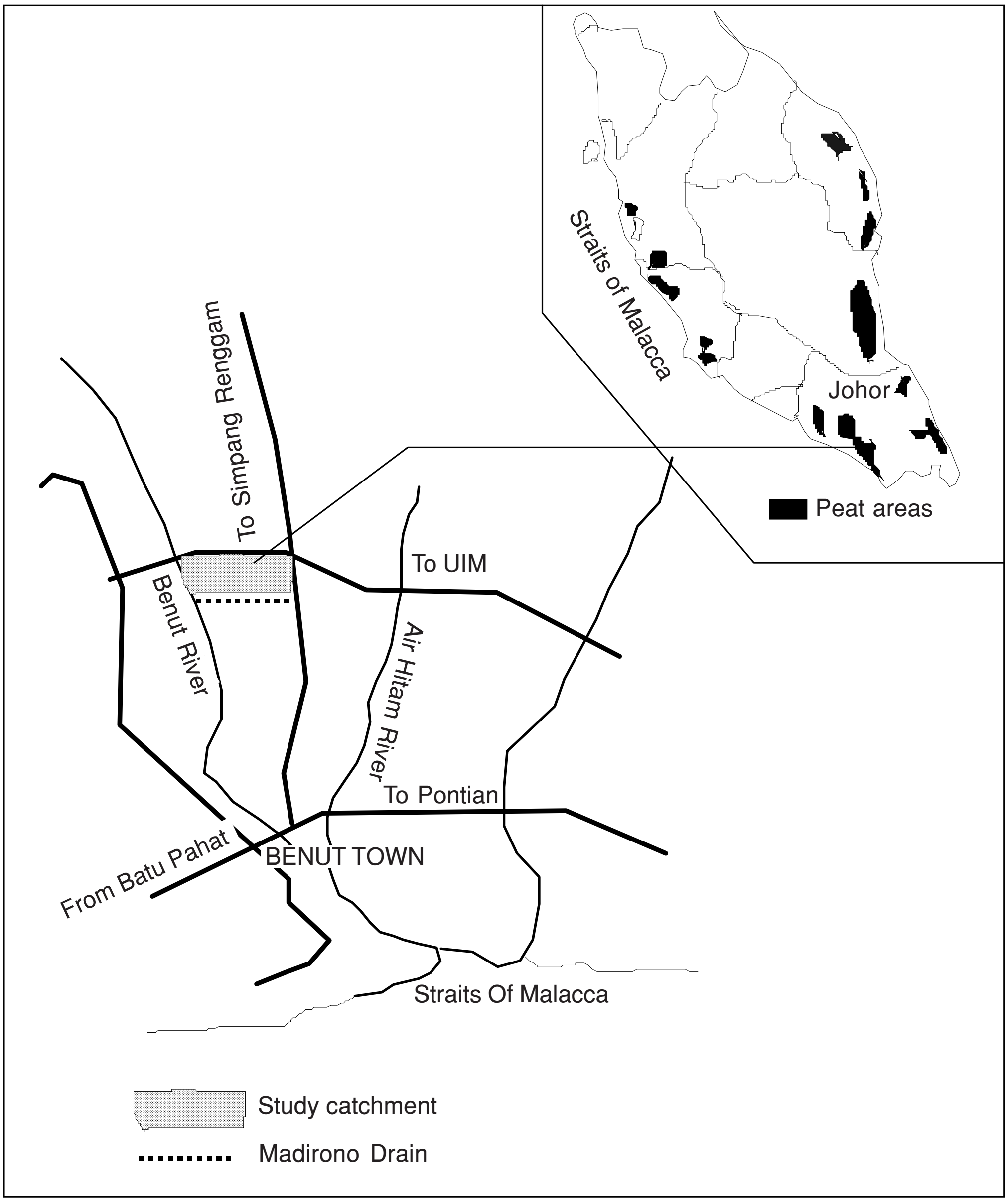

Figure 1 The study location

project implementation schedule (Lim, 1992), the land use pattern has changed significantly and can be estimated as follow. The reclamation works (eg. Peat swamp clearing, de-stumping, first drainage) was started in 1974. In early 1980's, a mixed rubber trees and short terms vegetables were grown by the local settlers. In early 1990's the old rubber trees were felled and replaced by palm oil trees. Classified as a communal land provided with basic infrastructures and public utilities, the number of household was increased from none in 1974 to about 20 households at present.

2.2 Hydrologic Data

Rainfall record from the Irrigation and Drainage Department (D.I.D.) station 1732004 was used extensively in this study. Rainfall at station 1732004 was measured using autographic recorder with a daily chart. Hourly rainfalls were obtained by digitizing the recorder chart. Stream flows were measured using V notch weir equi pped with a water level and chart recorder. Details of the weir and copy of the recording chart were obtained from the D.I.D Branch, Hydrological Section. The gauging station is referred to Station number 1732401. A stage-flow curve was established for this gauging station and was used to estimate the catchment's flow record. Three piezometric wells equipped with water level recorder to measure ground water table were installed in three different locations inside the study area. For this particular study only piezometric record from Station 1732702 was used. The daily rainfall, flow and water table records are available from 1981 to 1995 with substantial missing data.

2.3 Method of Analysis

For this particular paper, the hydrological characterization of the study site was made according to three major hydrologic behaviors. They are runoff coefficient, flow duration curves and low flow condition and storm hydrograph characteristics. Long-term rainfall, stream flow and water table record of the study site was quantitatively analyzed according to conventional quantitative method. The runoff coefficient is simply defined as the ratio of total runoff to total rainfall at a specific time period. Quantitatively,

$$Q_c = \frac{Q_t}{P_t} \tag{1}$$

$$Q_c = \frac{Q_t}{P_e} \tag{2}$$

and

$$P_e = P_t - L \tag{3}$$

where Q_c is the runoff ratio, Q_t is the total runoff, P_e is the total net rainfall, P_t is the total gross rainfall and L is losses. The hydrologic losses, L can be in the form of interceptions, evapotranspiration and groundwater deep percolation. Under the highly dynamic hydrologic system of the present study site, it is unlikely to obtain the observed data of the losses component. Thus, equation 1 was considered as fairly enough to estimate the catchment's runoff coefficient at yearly basis (Spieksma, 1999). Daily flow duration curves and daily water table duration curves were established according to procedures described in most of the hydrology textbook (eg. Shaw, 1994; Spieksma, 1999). The shape of the curve was examined to obtain the low flow condition of the catchment.

3.0 RESULTS AND DISCUSSIONS

3.1 Runoff Coefficient Variation, Q_c

The simplest way to visualize the behavioural change of a watershed system is by examining the variability of runoff coefficient. Thus, for certain time duration of interest, the runoff coefficient of a particular watershed is computed by dividing the total runoff to the total rainfall ratio for that particular time span (Bay, 1969; Spiekma, 1999). The summary of annual water balance of the study site during 1982-1994 is presented in Table 1. The runoff coefficient, Q_c (1982-1994) is shown in Figure 2. It is apparent that the variation in Q_c of the study catchment was large showing that the study catchment was highly dynamic during the study period. Its variation followed a decaying trend. The declining trend in Q_c is observed from 1982 to 1990. The Q_c started with high fraction at 0.80 in 1982, decreased to 0.42 in 1990 before increasing again to 0.92 in 1991 and again afterward. This de-trending and cyclic behavior of the Q_c is probably due to several factors. The first factor could be due to the significant change in land use pattern of the ground cover. Even though no proper record on land use change is available, a rough estimate of the cropping pattern for the area could be made to provide some indication of the ground cover. For simplification in the entire analysis,

Table 1 Summary of annual water balance of the study site

Year	Rainfall, P, (mm)	Runoff Q, (mm)	Estimate Evapotran -spiration, ET (mm)	Mean water table (cm)	Runoff ratio, Q_c	Mean daily E_{pan} (mm)
1982	2837.30	2207.24	630.06	23.15	0.78	4.13
1983	1823.90	1120.50	703.40	37.73	0.61	4.06
1984	3069.00	1829.29	1239.71	26.60	0.60	3.94
1985	2884.00	1500.34	1383.66	26.60	0.52	4.05
1986	2561.20	2048.96	512.24	55.09	0.80	4.15
1987	2783.00	1239.40	1543.60	55.54	0.45	4.16
1988	2895.00	1819.00	1076.00	59.68	0.63	3.96
1989	2026.10	1022.82	1003.28	58.15	0.50	4.05
1990	2544.30	1074.25	1470.05	68.60	0.42	4.14
1991	2050.90	1880.55	170.35	71.72	0.92	3.97
1992	2879.90	2017.93	861.97	71.80	0.70	4.22
1993	2530.80	798.32	1732.48	71.49	0.32	*
1994	2609.10	1889.80	719.30	69.55	0.72	*

* data not available

the whole data was divided into three drainage periods. They were 1982 to1985 (first period), 1986-1990 (second period) and 1991 to 1994 (third period). If continuous drainage had a significant effect on the stream flow regimes, it might be expected that this effect would easily detectable from a comparison of the frequency distribution of the flow duration curves. The hydrological change during the first period of drainage can be considered as predominantly a result the early stage of drainage processes and with premature rubber trees. The second period of drainage can be considered as predominantly a result of combined drainage process and progression in rubber threes growth. The third period of drainage (1991-1994) was considered as another drainage period with the ground covered by oil palm trees.

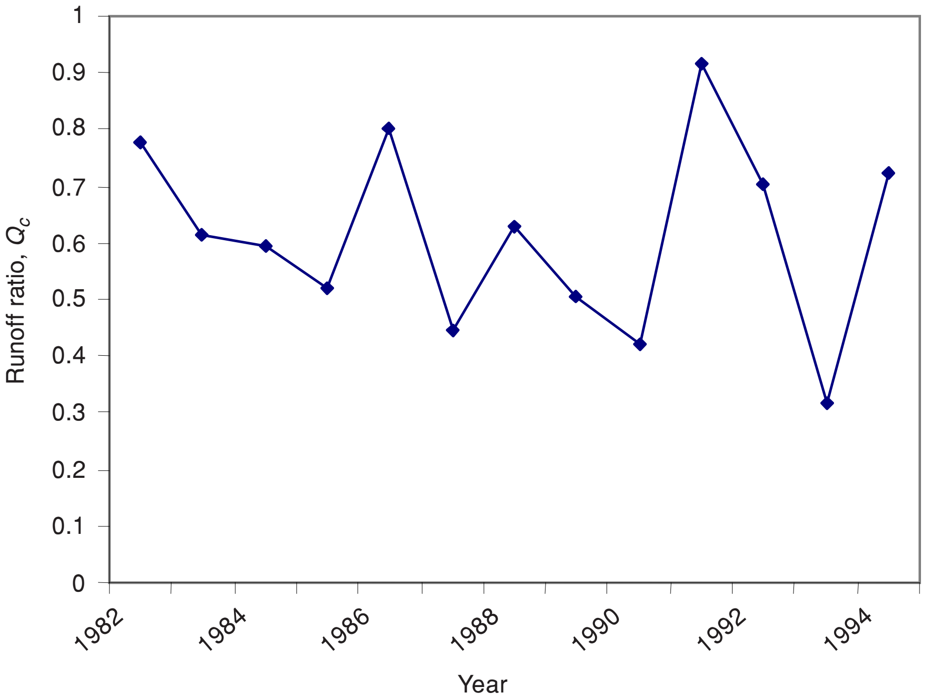

Figure 2 Variation in annual runoff coefficient of the study catchment

Another important factor contributing to the large variation in Q_c of the basin is the progressive change in peat compressibility of the area after drainage. Upon reclamation and drainage, tropical peat swamps of Malaysia would compress and subside. As experienced in the Western Johore Reclamation scheme, the subsidence rate was higher during the first few years after drainage at about 4.6 cm per year (Ritzema et al., 1998; Wosten et al., 1997). This is due to the removal of the surface and subsurface woody materials during the first stage of reclamation works. The further draining of the peat can cause the area steadily subsides at about 2 cm per year due to soil decomposition process (Wosten et al., 1997; Stephen and Speir, 1969). The rapid declined in runoff coefficient during the first period of drainage probably due to that fact.

The third important factor attributing to the large variation in Q_c could be the variation in water table depths of the drained area. In drained areas, the tendency of ground water table to get deeper is great, as the removal of soil water to the drain is more rapid. Figure 3 shows the annual mean water table over the study period, which shows a remarkable declining pattern. The deeper the water table, the higher is storage capacity in the soil layer (Schlotzhauer and Price 1999). Thus more rainwater can be temporarily stored in the unsaturated soil layer. Consequently, the runoff component of the basin hydrological cycle decreases, as does the runoff coefficient.

The rapid changes in crop's evapotranpiration rate, ET of the area due to the progress in land use change and water table lowering is likely to affect the runoff coefficient variation. An increase in total evapotranspiration as crops develop and a fall in the catchment's mean water table would collectively result in the reduction of the total streamflow runoff. Being an ombrothrophic peat catchment, the study area can be considered as a closed systems, receiving no surface water or ground water inflow so

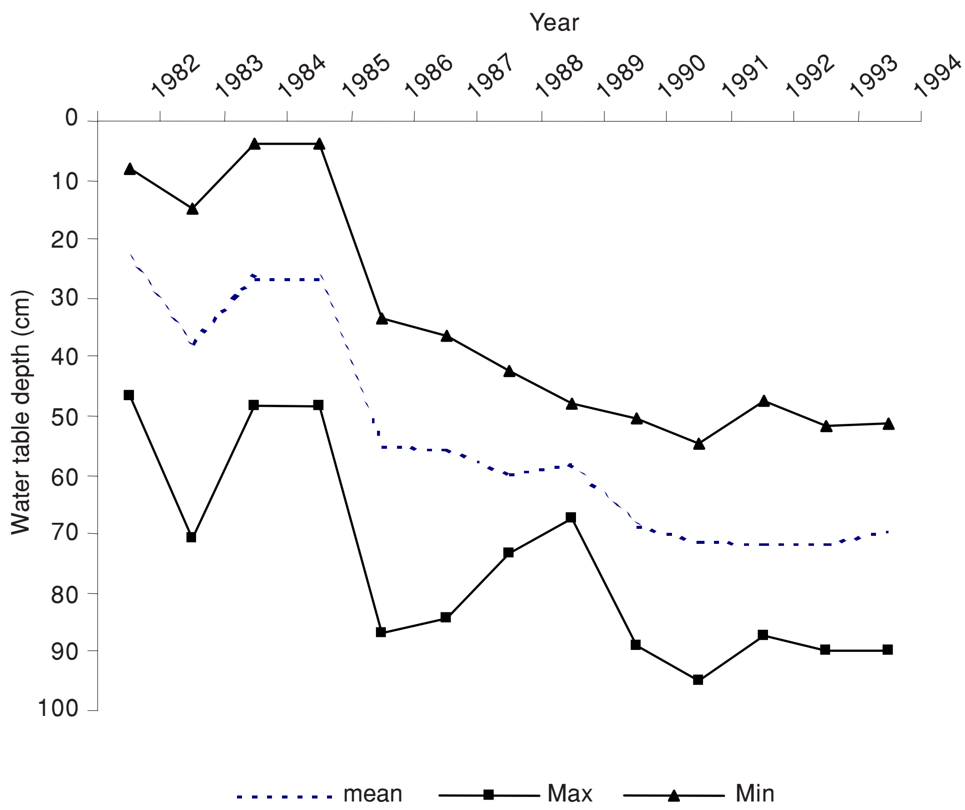

Figure 3 Mean annual water table depth showing a declining trend

that the evapotranspiration rate is the surplus of rainfall over runoff and can be estimated using a simplified water balance equation (Van Dijk et al., 1997 quoted by Schellekens 2000) as,

$$ET = P - Q \tag{4}$$

where P is the total rainfall and Q is the total runoff. Under the low water table condition most of the rainfall surplus is exported as subsurface runoff as the peat is almost saturated for much of the year.

3.2 Flow Duration Curves

The shape of the flow-duration curve gives a good indication on the characteristics of the catchment response to rainfall (Shaw, 1994). Since the primary concern in this study is to examine the temporal behaviour in flow regimes, the comparison of flow duration curves established from different period during drainage seemed relevant. It was intentionally used to extend our knowledge about the flow dynamics of the study area. As indicated in the immediate previous paragraphs, the runoff coefficients (runoff-rainfall ratio) for the watershed are large for all years. Recalled, the runoff coefficient was in the range of 0.30 to 0.97. This could mean that, generally, for this particular catchment , a high percentage of rainfall ended-up with stream flows. Inferences could be made here that the storage capacity of the study watershed was relatively small for all years because of the all year round low water table. As for comparison, the mean total runoff coefficient for a blanket upland peat catchment in the United Kingdom was about 0.70 (Evan et al. 1999).

To verify this finding further, differences in flow duration curves were used as the study tool. For a specific length of flow record, a flow duration curve was established to represent graphically the relationship between flows and the percentage cumulative frequency. The catchment's flow duration curve obtained from the whole periodic scale is presented in Figure 4. Figure 5 shows the magnified version of flow duration curves for different drainage period to be used for a closer inspection. From Figure 4, it can be seen that the curves have initially steep slopes. This shape of slopes is typical for duration curves generated from a small watershed (Shaw, 1994). A similar shape was obtained from a small peat watershed in the North America (Bay 1969; Spiekma, 1999). As a whole, the physical meaning of this finding shows that the flow regime of the study catchment experienced a relatively high variable flow during the specified periodic span. The catchment having had little storage whereby the stream flow reflects directly the rainfall pattern.

A close inspection to Figure 5 provide a further detail discussion on the dynamic of the flow regime of drained peat basin. Comparing the flow duration curves from three drainage period, it can be generalized that the curves had gone through a transition point (point A) at flow 0.10 m^3s^{-1}. All the duration curves started quite similarly until

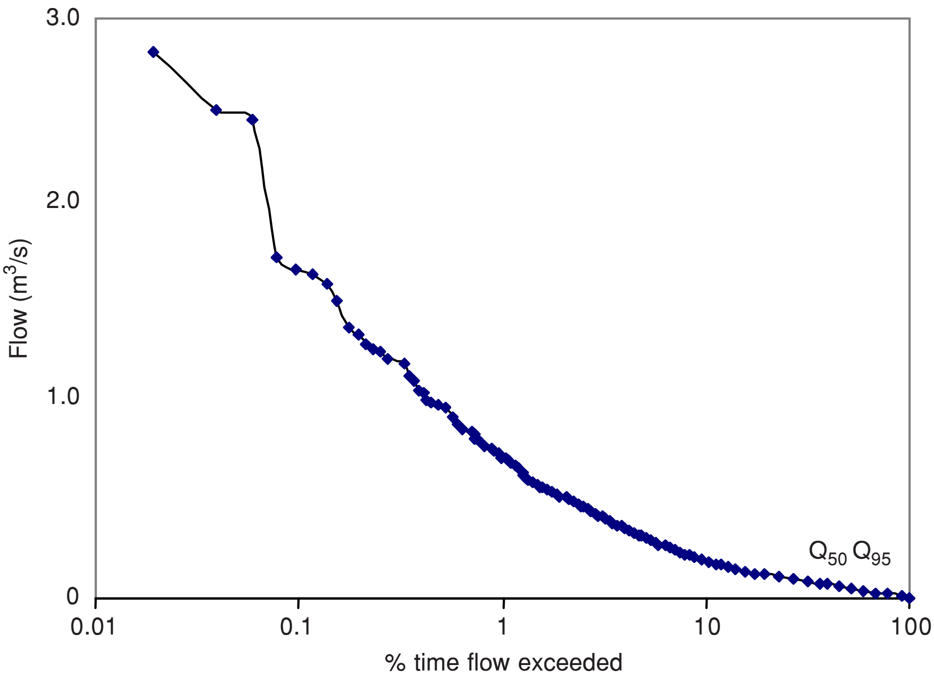

Figure 4 Flow duration curve at the study site

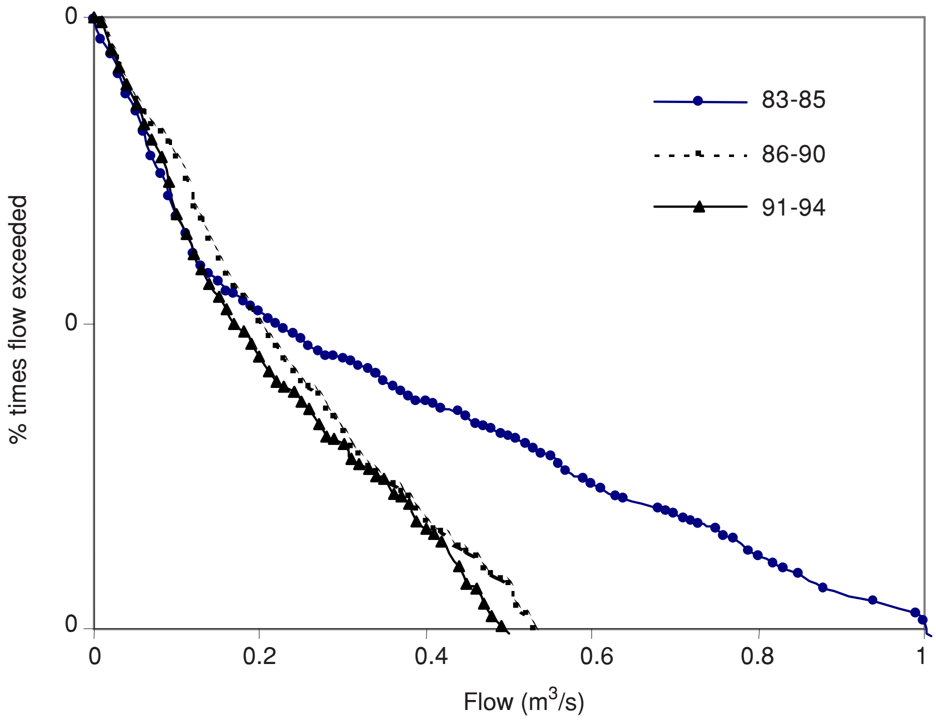

Figure 5 Close-up of the flow duration curve for different drainage period

a turning point at 0.10 m^3s^{-1} where the 1983-85 curve started to disperse from others. The 1986-90 and 1991-94 curves are almost identical. The different behaviour found from these curves could be a useful tool to describe the complexity or the hydrological variance of the drained peat catchment of the study site. It is wise to explore further processes affecting these curves and implications for tropical peat hydrology.

Shaw (1994) suggested that studying the slope of each flow duration curve component could provide some idea on the storage capacity of the soil reservoir. A very flat slope in duration curves indicates little variation in flow regime that is the result of the damping effects of large storage. Using criteria shown in Figure 5, the following discussion could be made. The storage capacities of the peat basin could behave quite similarly regardless of drainage flow rate until a point at 0.10 m^3s^{-1}. Beyond this point the magnitude of the runoff variation was larger during 1983-85 drainage period compared to the other two. In other words, the larger runoff variation occurred during the first drainage period and decreased with time after drainage. This has to be expected because when subjected to a continuous drainage process the catchment's water table depths are lowered and the peat material are more consolidated. Consequently, less storage capacity within the soil profile was available. Thus, the transfer of infiltrated water to the drainage channel became more rapid.

3.3 Low Flow Characteristics

When environmental issues associated with peat land drainage is our main concern, low flow analysis is often more important than peak flow analysis. The main aim of this analysis was to examine how the slow release of water from peat basin can sustain stream flow over long periods of drainage. In the old literature of the temperate peat studies, popular opinion holds that slow release of water from a storage-based watershed such as in low-lying peat basin can sustain river flow over long periods (Bay, 1969). This is in contradict with the recent literature. For instance, Evan et al (1999) found that baseflows are partly maintained in many peat catchments.

Low-flow characteristics of streams can also be clearly shown using flow duration curves. As shown in Figures 4 and 5 the steep slopes throughout the range of flow at the upper and lower ends indicate a negligible amount of permanent storage existed in the study basin. The exact value of low-flows suitable for a particular watershed system is difficult to define. It is a subjective value to indicate the performance of stream flow.

When comparing flow regimes between watersheds, hydrologists suggest using Q_{95} (or sometimes Q_{50}) as an index to the low flow condition. An index Q_{95} is defined as the flow that exceeds 95% of the time. As depicted in Figure 5.3 and 5.4, the Q_{95} for the study basin was extremely small of less than 0.05 m^3s^{-1}. The Q50 of the catchment was about at 0.10 m^3s^{-1}.

To compare the low-flow values between catchment, Q_{95} or Q_{50} might be expressed in terms of flow depth by dividing the catchment area. Hence for this particular study,

$Q_{95}/A = 0.05\ m^3s^{-1}$ per $1.84\ km^2$ ($0.027\ m^3s^{-1}km^{-2}$) which give 2.33 mm day^{-1} and $Q_{50}/A = 0.10\ m^3/s/1.84\ km^2$ ($0.054\ m^3s^{-1}km^{-2}$). These values are extremely low compared to non-peat catchment in similar locality of the tropics. Yusop (1996) in his study on the hydrology of a non-peat forested small catchment area in Malaysia found that Q_{50} was about 38 l/s/km or $0.38\ m^3s^{-1}km^{-2}$. In a hydrological study of a large undisturbed peat catchment in Sarawak, Braggs (1997) reported that during dry periods, the storm hydrograph indicated a sustained base flow between 0.2 and 0.8 mm day^{-1}. These values are much smaller than the present study. Two things can be thought from these findings. First, the drained peat basin could not sustain stream flow during prolonged dry period and secondly the base flow performance of peat catchment was improving upon drainage. A further debate could be made if drainage alters the general behaviour of low flow characteristics of peat catchment in the tropics.

3.4 Water Table Duration Curves

Figure 6 (a) is the water table duration curves of the mean daily water tables of the study catchment. Figure 6 (b) is the water table duration curves for different drainage duration. The 1986-90 and 1991-94 curves are almost identical, similar to that occurred in the flow duration curves of the catchment. It clearly shows the changing in probability for different drainage periods. For instance, taking 50% time exceedence as a common reference value, 1982-85 experienced the lower water table depth compared to 1986-1990 and 1991-1994 drainage duration. During 1982-85, the water table condition of the catchment was lower than 42 cm 50% of the time. During 1986-90 and 1991-94, the water table was dropped to about 65 cm from the surface 50% of the time. In overall, as shown in Figure 6 (a), the catchment's water table exceeded 60 cm during 50% of the time. The effect of long-term continuous drainage and other reclamation activities to the catchment’s water table regimes is obviously depicted from these plots. A remarkable water table draw down over time during drainage was observed.

4.0 CONCLUSIONS

The quantitative analyses presented in the paper seek to establish the hydrologic mechanism responsible for storm flow generation processes that occurred in a drained peat catchment. The following conclusions are drawn:

(i) A drained peat catchment experienced a large variation in runoff coefficient, indicating that peat catchment has a highly dynamic hydrologic system.
(ii) The annual runoff coefficients are large, indicating that the peat catchment is highly permeable and flashy.
(iii) The low flow condition is too small, indicating that drained peat catchment could not sustain stream flow during prolonged dry period.
(iv) Peat catchment experienced a water table drawdown over time during drainage.

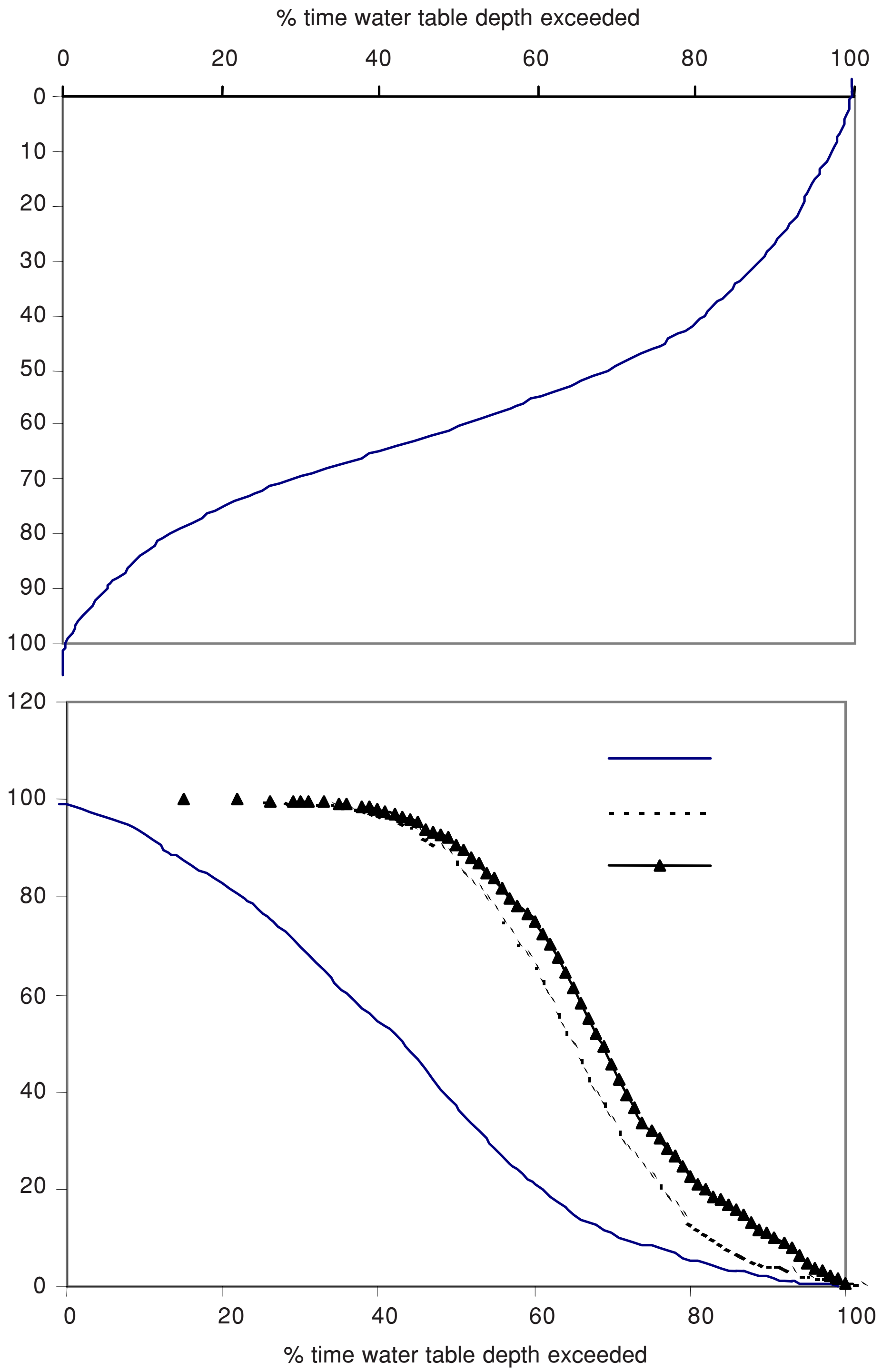

Figure 6 (a) Overall water table duration curve (b) Water table duration curves for different periods, showing the changing in probability in water table depth

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