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TABLE OF CONTENTS

WATER RESOURCES MANAGEMENT FOR DOMESTIC AND INDUSTRIAL NEEDS

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ABSTRACT

Ninety-eight per cent of water resources required for domestic, industrial, and other purposes is derived from surface water with naturally-defined watershed. Though the rainfall is considered abundant, due to uncontrolled land-use activities and unsustainable development coupled with poor land-use management policies/strategies, our precious water resource has been subjected to continuous degradation and other negative impacts limiting its utility. This has led to disastrous and/or catastrophic socio-economic events nationally. Hence, there is a need to seek and promulgate systematic management approaches/strategies that will support a sustainable balance between land-use activities and the need to protect our precious resource. This is critical in the long term considering the accelerated growth and the impending socio-economic development of the country against the growing demand and the rising expectation for adequate and sound water supply for domestic and industrial needs. This paper attempts to present and discuss current issues on water resource planning and management and the approaches/strategies required to confront present and emerging critical problems.

INTRODUCTION

Few issues have greater impact on our lives and on the life of the planet than the management of our most important natural resource: water. Today we have new appreciation of the role of water in our lives, our economies and our ecosystem. Water is our lifeblood. We also need water to develop and maintain a vibrant economy.

Today, 31 countries, mostly in Africa and the Near East, are facing water stress or water scarcity. By 2025, population pressure will push another 17 countries, including India, into the list. Although much of the world is trying to meet the growing demand for fresh water, the situation is worst in developing countries where some 95 per cent of the 80 million people added to the globe each year are born. In addition, the competition among industrial, urban and agricultural uses for water is mounting. In many developing countries, lack of water could impede future improvements in the quality of life (Hinrichsen, UN Population Fund, 1998)

Malaysia is gearing towards the status of an industrialised nation by the year 2020. The availability of water resource is one of the most important basic infrastructures needed to support the socio-economic growth and industrial development. Realising the negative impacts of unsustainable development on the environment and natural resources, under the Seventh Malaysian Plan, the Government has created the National Policy on the Environment. The objectives of the policy are:

- To achieve a clean, safe, healthy, and productive environment for both present and future generations;
- To conserve the country's unique natural resources and diverse cultural heritage with effective participation by all; and
- To promote lifestyles and patterns of consumption and production consistent with the principles of sustainable development

CURRENT AND FUTURE DOMESTIC AND INDUSTRIAL NEEDS

Water Supply Coverage

Water supply capacity in Malaysia is approximately 9,948 billion liter per day from 473 treatment plants. Based on the 1997 records it is shown that the national water coverage was ninety per cent, with the coverage of rural and urban areas of eighty-three per cent and ninety-six per cent respectively (JKR, 97/98). Table 1 below shows the percentages of water supply coverage by state.

Table 1: Urban and rural water supply coverages – 1998

State	Rural coverage (%)	Urban coverage (%)
Kedah	88	100
Perlis	91	100
Selangor	98	100
Pahang	87	98
N. Sembilan	97	99
Terengganu	84	97
Perak	90	98
P. Pinang	99	99.1
Melaka	99	100
Johor	99	100
Kelantan	52	85

Source : JKR (1997/98)

The total existing and projected water resource needs to support agricultural activities and socio-economic development are as depicted in Table 2.

Table 2 : Existing and projected water resource needs

Year	Irrigation (bil m^3)	Domestic, commercial and industrial (bil m^3)	Total (bil m^3)
1980 *	78	0.8	8.6
2000 *	10.4	4.8	15.2
2020 **	14.0	16.4	30.4
2040	17.6	43.2	60.8
2060	21.2	100.4	121.6

* JICA report on National Water Resources Study, Malaysia
** Projected data based on the JICA report on National Water Resources Study

Water Demand

The total water demand for the domestic and industrial needs in 1998 is about 5.1 billion litres per day compared to the current water supply capacity of about 9.9 billion litres per day. The national average of water consumed by the industries is 31% of the total domestic and industrial consumption, according to Table 3. Based on the JICA study in 1982 and the growth rate or trend towards achieving the national vision of an industrialised nation, it is projected that the water demand by the industries will increase to as high as 54% of the total demand by the year 2020 as shown in Table 4.

Table 3 : Ratio of annual domestic and industrial water consumption – 1998

State	Consumption by sector (m^3/y)		Percentage of total consumption	
	Domestic	Industrial	Domestic	Industrial
Johor	175,473,495	87,605,208	66.7	33.3
Kedah	93,651,846	24,295,434	79.4	20.6
Kelantan	33,379,786	9,970,585	77.0	23.0
Melaka	34,229,427	24,584,022	58.2	41.8
N. Sembilan	51,804,099	39,448,498	56.8	43.2
Pahang	84,970,513	21,242,628	80.0	20.0
Perak	131,919,484	39,426,774	77.0	23.0
Perlis	15,502,464	2,296,002	87.1	12.9
Pulau Pinang	111,891,259	86,146,367	56.5	43.5
Selangor	342,958,419	168,919,819	67.0	33.0
Terengganu	45,793,432	21,549,851	68.0	32.0
Sabah	56,610,412	11,064,916	83.6	16.4
Sarawak	18,585,709	10.095,941	64.8	35.2
Laku	19,351,145	16,684,506	53.7	46.3
Kuching	42,602,709	7,863,916	84.4	15.6
Sibu	10,571,097	6,248,469	62.8	37.2
Labuan	5,103,172	3,402,114	60.0	40.0
TOTAL	1,276,353,794	581,144,162	68.7	31.3

Source : JKR (97/98)

Table 4 : Projected water demand by sector

Year	Domestic (%)	Industrial/ commercial
1980*	63	37
1990*	62	38
2000*	59	41
2010**	54	46
2020	46	54
2030	40	60
2040	36	64
2050	32	68

* JICA report on National Water Resources Study, Malaysia
** Projected data based on the JICA report on National Water Resources Study

WATER RESOURCE – QUANTITY

Water Resource Status

The annual average rainfall in Malaysia is 2,400 mm for Peninsular Malaysia, 2,360 mm for Sabah and 3,830 mm for Sarawak. The total rainfall is about 990 billion m^3, of which 566 billion m^3 is surface water runoff, 64 billion m^3 goes to ground discharge and the rest returns to the atmosphere as evapo-transpiration (JICA, 1982). The detailed estimated water resource availability by state is as shown in Table 5.

Table 5 : Hydrological balance by state (billion m^3 per year)

State	Rainfall	Surface runoff	Groundwater recharge	Evapo-transpiration
Perlis	2	1	0	1
Kedah	23	12	1	10
P. Pinang	3	2	0	1
Peak	50	22	4	24
Selangor	18	7	1	9
N. Sembilan	14	5	1	8
Melaka	3	1	0	2
Johor	45	19	3	23
Pahang	80	33	4	43
Terengganu	43	22	2	19
Kelantan	39	23	3	13
Peninsular Malaysia	**320**	**147**	**20**	**153**
Sabah	194	113	14	67
Sarawak	476	306	30	40
Malaysia	**990**	**566**	**64**	**360**

Water Resource Imbalance

Ninety-eight per cent of the water resource required for domestic, industrial, and other purposes is derived from surface water — streams, lakes (impoundments) and rivers. Groundwater, which accounts for only two per cent of the raw water source, is not widely used due to its limited availability.

Although the overall figure of water resources convincingly denotes that there is an excess capacity as compared to demand by the domestic and industrial sectors, there are still some areas experiencing water shortage. As could be observed in Figure 1, the more developed states (western seaboard) receive relatively less rain (water resource) as compared to developing states (eastern seaboard).

The disparity warrants a delicate need to introduce and implement an effective water resource management approach/system to balance demand and supply inter-regionally.

Water Resource Catchment Area

Approximately half of Peninsular Malaysia constitutes water catchment areas as defined by the location of water supply intakes. These catchment areas provide the main source of raw water in fulfilling the domestic and industrial needs besides supporting the irrigation requirements and other uses.

The water catchment areas can be classified into three major categories, as follows:

- Urban catchment areas — catchment areas which contain developed areas such as towns, industrial zones, other economic activities/development, etc.
- Rural catchment areas — catchment areas which are predominantly covered by forests/wetlands and reserves
- Impounded catchment areas — catchment areas which impound water stored within reservoirs

WATER RESOURCE – QUALITY

River Water Quality Status

The Environmental Quality Report, 1997, as published by the Department of Environment (DOE, 1997), revealed a striking decline in water quality of the 119 monitored rivers of the nation. Table 6 shows the five-year profile of the Water Quality Index (WQI).

Table 6 : Malaysia – profile of water quality index for monitored rivers

	1993	**1994**	**1995**	**1996**	**1997**
Clean (%)	28	33	40	36	21
Slightly polluted (%)	63	55	46	53	58
Very polluted (%)	9	12	12	11	21

Source : Department of Environment ('93-'97)

Based on the Biological Oxygen Demand (BOD) and Ammoniacal Nitrogen Quality Index, the number of very polluted rivers was recorded to have significantly increased in 1997 as compared to 1996.

Impacts of Unsustainable Development

Major pollution impacting the quality of water resource has been identified to originate from agro-based industries, livestock farming, manufacturing activities, domestic wastes and land clearing activities.

Due to unsustainable developments/activities, the country has experienced major bitter incidences related to water resources as presented below:

- An increasing number of drinking water treatment plants have been and are on the verge of being abandoned one after another as a result of uncontrolled and extensive organic pollution along the water source irrespective of the upstream or downstream regime (the list includes Sg. Skudai, Sg. Damansara, etc.).
- Interruption of about 70% of the Melaka water supply source due to drying up of the Durian Tunggal impounded reservoir.
- Industrial spillage of 6,000 litres of diesel into Sg. Langat, immediately upstream of a 120 MGD Sg. Langat water treatment plant.
- Ammoniacal nitrogen contamination suspected to originate from incomplete sewage treatment – Sg. Langat.
- Spillage of 2,700 litres of diesel into a canal leading to the Sg. Dua Water Treatment Plant, Penang.
- Water supply rationing for about 1.2 million consumer and disruption of industrial activities within the Klang Valley related to watershed activities.

Impacts of Land Clearing/Logging Activities

Land clearing and logging activities contribute effectively to reductions in the quality of our water resources. The indicating parameter used by DOE to monitor the impacts from the land-use activities is suspended solids. This is evidently true by observing the river water quality profile based on suspended solids from 1993 to 1997. About 30–55 per cent of the rivers have been categorised as very polluted based on the suspended solids and WQI.

Some of the more serious events related to land-clearing/logging are as follows:-

- Extensive logging and land clearing have effectively forced some of the most economical treatment plants, for example, in Negeri Sembilan, to be abandoned at a substantial loss, whereas some have had to be upgraded technically incurring huge costs in order to maintain their utility in producing water subscribing to the established WHO standard. The list is as presented:

Treatment facilities (water treatment plant)	Capacity (MGD)	Abandoned	Upgraded
Pantai	5.0		λ
Sg. Ngoi-Ngoi	1.0		λ
Sg. Mahang	0.30		λ
Sg. Bangkong	0.30	λ	
Gunung Tampin	0.10	λ	
Ulu Bendol	0.40		λ
Gachong	0.13	λ	
Sg. Lui	0.12		λ
Pertang	0.24	λ	
Titi	0.29		λ
Terachi	0.80	λ	

- Premature silting up of the Old Pedas Dam by 52% of its useful storage within 25 years. This was attributed to rampant and uncontrolled logging activities immediately upstream of the dam. The dam, which was built in 1932, had to be replaced by another dam in 1988 at a significant cost.
- In 1998 the Pahang Government had no recourse but to reject at least 20 applications for logging concessions which were too close to water catchment areas in order to protect its water resources, from long-term impacts (Tan Sri Mohamad Khalil Yaacob, 1998).
- More than 800 ha of forest reserve at Kahang, Johor, had being illegally logged resulting in the serious reduction of the Sg. Kahang water level/flows.
- The increasing turbidity of Sg. Tengkil, Sg. Linggui in Kota Tinggi and Sg. Johor had been traced to mining/logging activities for many years.

Depletion of Water Resources

The direct impacts of unsustainable development such as urbanisation and industrialisation have resulted in a reduction of the suitability of our water resources as a source of drinking water with reference to the criteria set by the Guidelines on Water Quality Classification for Beneficial Uses. River water quality monitoring in 1995 had shown that about 57% of the water resources are not conforming to the Class 11A Guidelines. Further, considering that 50% of the water resources have to be devoted for other uses such as river maintenance, aquatic life support, saline protection, etc., and 20% as a margin of reserve, the effective resource available for use would then be a mere 97.2 billion m^3 in balance as enumerated in Table 7 below.

Table 7 : Impact of environment to water resources

Item	**Volume (bil m3)**
Total available water	566
57% not conforming to Class 2A	323
Balance of water resources available (43%)	**243**
50% devoted for other uses	121.5
20% reserve margin	24.3
Effective water resource available	**97.2**

By superimposing Table 2 (water resources projection demand) on Table 7 above, we should realise the fallacy of believing that there is an endless amount of effective water resource out there. Based on the current trend it is believed that there will be a doubling in the utilisation of water resources at the end of each 20-year period and this would lead to a point where we would just be wringing ourselves dry by the year 2053 if not earlier, unless we accord the proper value or worth to our water resources.

WATER RESOURCE – MANAGEMENT APPROACH AND STRATEGIES

Water Resource Planning

The call for a long-term planning for the purpose of regulating, allocating, and utilising water resources from and for different regions/states can no longer be ignored. The concept of interstate water resource transfer and the introduction of, perhaps, a national water resource grid should be pursued in the near future. The present interstate water transfer as presented below is a reality:

- Johor to Singapore
- Johor/Negeri Sembilan
- Perak to Kedah
- Pahang to Klang Valley and Negeri Sembilan

- Kedah to Penang
- Perak to Selangor

Recognising the importance of a systematic development of water resource to meet future demand, the Federal Government embarked on a comprehensive study in 1979 under the Japanese Technical Assistance Programme. In 1997, a second National Water Resource Study was commissioned with the objective of assessing and updating the national water resource availability and to formulate a masterplan for water resources management and development to the year 2050 (SMHB, 1998)

There is also a need to audit and explore the potential of developing ground water to meet water demand in conjunction with surface water holistically.

Development Planning

The Government and planners alike should seriously take into consideration the water resource availability in the planning of certain areas for various types of socio-economic development.

For example, from Table 4, it is envisaged that the demand for water supply by the industrial sector will grow at a tremendous pace in the future, especially, beyond the year 2020. Hence, superimposing this fact upon the water resources map should prudently direct us in strategically attempt to spread or to locate such sectors in water resource rich states or basins. Beyond this, the most obvious strategic approach would then be to introduce water-conserving processes, incentives, etc., for the industrial sector. The recycling of water should be seriously researched by the industries. Table 8 below shows the distribution of industrial estates by state.

Table 8 : Distribution of industrial estates developed by government agencies

State	No. of industrial estates	Total plan area (excl. housing) (hectares)
Johor	29	4,851.49
Kedah	19	1,279.52
Kelantan	7	602.4
Melaka	9	871.42
Negeri Sembilan	8	477.27
Pahang	16	6,596.85
Penang	14	2,472.24
Perak	26	1.659.04
Perlis	5	201.24
Sabah	13	222,48
Selangor	28	3,763.60

Sarawak	16	5,540.94
Terengganu	21	3,827.80
Kuala Lumpur	8	133.00
Labuan	2	214.23
TOTAL	220	32,713.25

Source : MIDA (1998)

Impounded Storage

Water authorities have developed more impounded storage facilities as a strategy to guarantee a consistent and sufficient water resource to meet future water demand. Table 9 shows the growth in the number of impounded reservoirs by state.

Watershed Protection

Protection is any measure, either structural or non-structural, with the objective of ensuring and maintaining the quality of the water resource suitable for its intended purpose by subscribing to a set of governing rules, regulations, and standards.

Watershed protection strategies and management must be undertaken immediatetly. All land within protected watershed must be gazetted to avoid negative impacts on its water resource. Towards this end, a systematic and practical approach in embracing the concept of sustainable development must be supported. As a reference, for example, the Catchment Management Plan (CMP) has been established and used effectively by the National River Water Authority (England & Wales), and the NORDEIFEL model has been created by Germany to meet such objectives, and locally the Negeri Sembilan State Government has implemented the ABC approach in reviewing and approving various activities within watersheds. This will be discussed subsequently.

Yet another concept founded on the importance of an integrated approach towards achieving a balanced use of catchment areas is the Total Catchment Management (TCM) approach.

TCM is defined as the co-ordinated and sustainable use and management of land, water, vegetation, and other natural resources on a water catchment basis so as to balance resource utilisation and conservation. TCM is a philosophy to promote co-ordinated and natural resource management on geographic catchment areas on a holistic basis, rather than on an administrative basis.

As mentioned above, the Negeri Sembilan State Government has adopted the ABC water catchment protection approach mooted by the State Water Supply Authority in 1987, with the rational objective of balancing the need to allow socio-economic development to continue within certain category of water catchment while sustaining the quantity and quality of its raw water source for human consumption. The approach in essence involves the mandatory gazettement of the Class B and C water catchments – rural catchments providing the source of raw water supply to subconventional treatment plants and impounded reservoir respectively, based on their extreme sensitivities to land use and development impacting upon the ensuing quantity and quality of the raw water.

Table 10 presents the various attributes of the watersheds within the confines of Negeri Sembilan. The conclusive points of the scenario can be summarised as presenting an inverse relationship between development and water quality. On an inclining scale, as the water catchment urbanises, the raw water quality declines. Consequently, as the raw water deteriorates, the more advanced a treatment is warranted and as such the cost of treatment increases.

While protection should be held sacred and a priority, it is important to determine the appropriate and the right amount of protection necessary. Too much protection would likewise be as detrimental as too little protection in the form of economic wealth foregone.

Table 9 : Growth of impounded storage facilities by state

State	1970	1980	1990	1998
Perlis	-	-	-	1
Kedah	1	1	3	3
Pulau Pinang	1	1	2	2
Perak	1	2	3	3
Selangor	3	4	6	7
Melaka	1	3	3	3
Negeri Sembilan	-	1	3	5
Johor	7	8	12	13
Pahang	-	-	1	1
Kelantan	-	-	-	-
Terengganu	-	-	3	3
Pen. Malaysia	**14**	**20**	**36**	**41**

Table 10 : Comparative assessment of development and water resource quality

Attribute	**Sg. Linggi (326 km^2)**	**Jempol (373 km^2)**	**Pantai (15.7 km^2)**
Raw water quality			
• Turbidity (NTU)	30 - 500 (163)	15 - 110 (30)	2 - 35 (6)
• Ammonia (mg/l)	<0.03 - 3.18 (0.67)	<0.05 - 0.57 (0.18)	<0.03 - 0.14 (0.04)
• COD (mg/l)	8 - 19 (15)	6 - 19 (10)	1 - 18 (7)
• Total coliform (counts/100ml)	348 - 300,000 (160,900)	100 - 240,000 (70,800)	33 - 2,400 (348)
• Faecal coliform (counts/100ml)	348 - 91,800 (38,800)	100 - 34,000 (10,900)	33 - 790 (100)
Treatment plant	Sg. Linggi	Jempol	Pantai
Capacity (MGD)	17.5	5.5	4.5
Type of treatment	Advanced (ozonation)	Conventional	Sub-conventional (disinfection only)
Cost (RM)/1000 gallons of treated water	0.90	0.60	0.15
Industry/sq. km	0.5	0.03	Forest Reserve
Population/sq. km	888	200	5

Source : Johari (1996)

Systematic Monitoring Tools

The traditional approach of monitoring, tracking and predicting water quality status must be revised. More accurate and systematic tools, such as water quality computer simulation models, catchment models and GIS, should be used to understand, enumerate and predict impacts of development and subsequently to implement mitigative control measures within catchment areas. Numerous models have been applied to simulate water quality conditions in streams, surface-water, impoundments, urban areas, aquifers and estuaries (Steele, 1984). The application of water quality computer simulation modelling has successfully being performed for the Sg. Linggi catchment in 1993 (Johari, 1993)

Legislative Approach

There are more than twenty legal provisions some of which are listed below, directly and indirectly related to planning, control, management and the abstraction of water resources. Most of these were enacted some time ago as either Federal Laws or State Laws.

Table 11 : Legal provisions for water resources

Function	Enforcement	Year
Function of Federal/State	Federal Constitution	1957, 1963
Property and conservancy on river	Water Act	1920, 1989
Land use	National Land Code	1965
	Town and Country Planning Act	1976
Water use	Mining Enactment	1929
	Water Supply Enactment	1932, 1957, 1998
	Irrigation Area Ordinance	1953, 1989
	Drainage Works Ordinance	1954, 1988
	Fisheries Act	1963, 1978, 1985
	Electricity Act	1973
	Electricity Supply Act	1990
Water quality/conservation	Forest Enactment	1935
	Land Conservation Act	1960
	Land Acquisition Act	1960
	Protection of Wild Life	1972
	Environment Quality Act	1974, 1985
	Geological Survey Act	1974
	National Parks Act	1980
	National Forestry Act	1984
	Sewerage Service Act	1993
Urban drainage	Street, Drainage, Building Act	1974
	Local Government Act	1976

For example, the Environmental Impact Assessment (EIA) is a pre-protection requirement which is legally enforceable under Section 34A of the Environmental Quality Act, 1974. As a planning tool, the EIA attempts to identify, predict, evaluate, and communicate information about the impacts on the environment of a proposed project. It is hoped that any predicted impacts can then be foreseen and addressed at an early stage of the project for mitigative measures.

Executively, however, there is a need to review our effectiveness in enforcing such provisions, especially for monitoring and deterrent purposes. Agencies, either government or independent, need to be strengthened and empowered to render any legal system effective.

Public Awareness

Recognising the importance of the role of the public in confronting issues related to water resource, the government has actively promoted a general awareness among the public through fora, campaigns, exhibitions, etc. Such programmes have also been organised by Non-Governmental Organisation (NGO's) and the private sectors. On this score, much more is needed to be done collectively and cohesively in building and moulding a society committed and sensitive to all issures related to water resource.

CONCLUSION

Water is the most valuable and important asset to humankind and the basic ingredient for continuous growth and development of our nation. Hence, a more holistic management and approach towards balancing the development and the protection of our water resources must be performed and initiated immediately.

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IMPACTS OF EXTREME CLIMATIC PHENOMENA ON WATER RESOURCES MANAGEMENT

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INTRODUCTION

Malaysian rainfall has strong seasonal characteristics which are under the influence of the Asian monsoons. It is also subjected to interannual variations which range from the well-known 24-month cyclic oscillation or quasi-biennial oscillation (QBO) to the much longer variations related to the 11-year sunspot cycle. In between lies the El-Nino Southern Oscillation (ENSO) which varies from 2 to 7 years and decadal changes. These interannual variations modulate the seasonal rainfall, producing in certain years drier than normal rainfall and in some years excessive amount. An understanding of the seasonal characteristics as well as the interannual variations of Malaysian rainfall is a key factor in ensuring an optimum water resources management.

FACTORS CONTROLLING INTERANNUAL VARIATIONS OF RAINFALL

Mean Monthly Rainfall Distributions

Annual cycles of the rainfall patterns for selected stations representing different regions in Malaysia are shown in Figure 1. The figure depicts their mean monthly rainfall distributions and the associated upper and lower standard deviations. In general, the west coast of Peninsular Malaysia has a semi-annual mode with two maxima coinciding with the two intermonsoon periods (April-May and September-October/November) whereas the east coast registers a single peak at the end of the year during the early northeast monsoon. Over East Malaysia, Sarawak in particular shows a U-shaped distribution with a peak at the beginning of the year as influenced by quasi-stationary monsoon disturbances whereas western Sabah has bi-modal pattern in June and October during the southwest monsoon period. Apart from the influence of relief, latitude and proximity to the South China Sea, the above distinct timings of peak wet seasons in different locations in Malaysia indicate distinct climatic regimes of rainfall (Grimm *et al.*, 1998) due to the two dominant southwest and northeast monsoons.

From Figure 1, it could be seen that rainfall fluctuation is large and significant for the east coast states of Peninsular Malaysia from November to January, and for western Sarawak from January to February. It is noted that in Tawau, the mean monthly rainfall exhibits relatively uniform distribution and associated standard deviation is small. Therefore, for effective water resources monitoring and management, it is essential to understand the mean monthly rainfall distribution and their lower and upper standard deviations as well as the probability of occurrence of a certain amount of rainfall (Table 1) for each climatic regime.

Table 1: Cumulative distribution of monthly rainfall for Petaling Jaya

Rank (m)	Rainfall (mm)													Estimated probability of occurrence, F = m/(n+1) where n equals to total number of data
	Jan	Feb	Mac	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Annual	
1	61	30	35	99	67	12	21	17	53	71	137	115	1830	0.033
2	78	54	140	157	76	12	59	41	69	108	178	118	1924	0.067
3	79	101	146	167	78	19	60	51	99	125	189	142	2025	0.100
4	86	106	149	171	82	51	66	55	108	125	192	143	2041	0.133
5	91	106	151	174	133	52	66	57	124	158	206	151	2111	0.167
6	95	107	160	201	149	56	69	59	128	160	213	158	2138	0.200
7	96	117	183	221	151	67	74	67	138	161	216	160	2300	0.233
8	138	128	191	241	154	71	78	102	138	177	220	177	2303	0.267
9	138	136	193	244	158	78	81	110	148	198	223	183	2402	0.300
10	145	140	194	254	162	83	84	113	152	228	242	195	2419	0.333
11	152	146	211	258	168	101	86	115	173	252	249	198	2427	0.367
12	152	147	217	265	206	103	97	118	185	257	251	216	2496	0.400
13	169	162	228	270	212	107	105	124	190	263	257	219	2545	0.433
14	188	174	234	276	213	120	121	125	194	269	261	225	2556	0.467
15	188	174	236	282	217	132	126	128	197	283	263	239	2572	0.500
16	195	175	244	282	236	147	134	158	198	298	275	248	2709	0.533
17	200	177	251	302	237	150	137	163	201	305	281	262	2742	0.567
18	203	179	283	307	245	152	148	171	204	308	298	288	2792	0.600
19	203	179	298	309	272	157	152	172	204	316	311	289	2825	0.633
20	206	185	298	326	277	161	156	203	210	322	323	308	2946	0.667
21	207	225	305	339	300	165	170	222	210	330	375	316	2976	0.700
22	216	257	324	363	306	181	184	223	211	376	409	319	2998	0.733
23	220	265	339	385	320	187	184	223	233	392	440	343	3018	0.767
24	232	268	351	405	348	192	188	239	238	395	441	369	3155	0.800
25	233	295	352	444	379	200	191	287	248	402	447	389	3205	0.833
26	246	298	402	451	381	221	235	288	294	413	461	434	3208	0.867
27	273	326	414	456	423	228	258	322	296	425	504	451	3221	0.900
28	274	332	496	480	457	251	269	406	328	484	635	454	3256	0.933
29	466	498	514	546	566	262	291	481	364	602	661	455	3668	0.967

Example:
The probability that August rainfall is less than 110 mm is 0.300; and greater than 110 mm, 1 - f = 0.700. The probability that it lies between 100 and 125 mm is approximately 0.17.

Interannual Variations of Rainfall

As an example, Kota Bahru (Figure 2a) and Kota Kinabalu (Figure 2b) normally receive much of their annual rainfall during the northeast and the southwest monsoons respectively. In 1982, both places received below-normal rainfall particularly in Kota Kinabalu. During the southwest monsoon of 1995, significantly above-normal rainfall fell in Kota Kinabalu. In general, a close scrutiny at Figures 3a and 3b shows that there are large year-to-year fluctuations of standardized rainfall departure or so-called seasonal rainfall index for the whole country. The standardized rainfall departure is defined as the departure from the appropriate 1961-90 base period mean standardized by the standard deviation of the mean. The fluctuations are more prominent during the southwest (May to August) and northeast (November to March) monsoon periods as compared with the two transition periods (April and September-October). It is also noted that significant positive standardized rainfall departure for both Peninsular Malaysia and East Malaysia occurs during November-March while the negative departure occurs during May-August for Peninsular Malaysia and during November-March for East Malaysia.

Obviously, rainfall in Malaysia is strongly dependent on the monsoons and their associated meteorological phenomena such as monsoon trough and tropical storm track. Above-normal or below-normal rainfall is often associated with variations in the strengths of the monsoons and the corresponding activity of monsoon trough and tropical storms. Modulation of monsoons could possibly be attributed to the effects or combined effects of the quasi-biennial wind oscillation (QBO), sunspot activity, decadal changes and the El-Nino Southern Oscillation (ENSO) (Subramaniam, 1993; Ooi & Lim, 1997).

EFFECT OF 30 HPA QBO

The quasi-biennial oscillation (QBO) is a major feature of the equatorial stratosphere. At pressure altitudes between 60 and 10 hPa, alternate spells of easterly and westerly winds are observed with periods of two years or slightly longer (Figure 4b). Theoretical studies have indicated that QBO is caused by an interaction between vertically propagating internal waves from the troposphere and the mean flow of the stratosphere. Certain studies appear to suggest that the phase of the oscillation at 30 hPa is related to the rainfall fluctuations in the monsoon region.

Tables 2a and 2b show the variations of the standardised northeast and southwest monsoon rainfall departures of 30 hPa QBO E(east) and W(west) phases in relation to El- Nino, La-Nina and normal years. There is no obvious relationship between the departures and the 30 hPa QBO E and W-phases.

Table 2a. Relationship of SOI, standardized southwest monsoon rainfall departure and stratospheric zonal wind

Period	SOI				Standardized Rainfall Departure												Stratospheric							
					East Malaysia				Peninsular Malaysia								Easterly				Westerly			
									East Coast				West Coast											
	May	June	July	August	May	June	July	August	May	June	July	August	May	June	July	August	May	June	July	August	Ma	June	July	August
1968	1.1	0.9	0.6	-0.1	-0.07	-0.10	0.23	0.62	1.59	0.01	-0.89	0.35	0.14	0.12	0.24	0.55	√	√	√	√				
1969	-0.6	-0.2	-0.7	-0.6	2.43	-0.87	-0.06	1.70	-1.00	-0.27	0.11	0.11	0.70	1.18	-0.65	2.08			√	√	√			
1970	0.1	0.7	-0.6	0.2	1.30	1.14	-0.99	0.49	-0.61	0.72	0.31	-0.09	1.07	-0.16	1.18	-0.24	√	√	√	√	√			
1971	0.7	0.1	0.1	1.3	0.51	-0.33	-0.95	1.68	0.32	-1.16	0.98	-0.08	-0.64	0.63	-1.32	1.08	√		√	√		√		
1972	-2.1	-1.1	-1.9	-1.0	-0.91	-0.73	0.06	-0.88	-0.30	-0.43	0.25	0.14	-1.82	0.14	-2.12	-1.10	√	√	√	√				
1973	0.2	0.8	0.5	1.1	0.36	1.41	0.86	-0.43	-1.48	1.18	0.50	-0.27	2.43	0.59	0.01	0.38			√	√	√	√		
1974	0.9	0.1	1.2	0.5	-0.95	0.33	-1.31	-0.57	-0.78	-0.17	1.07	-0.34	0.08	-0.03	-0.93	-0.31	√	√	√	√				
1975	0.5	1.1	2.1	1.9	-0.59	-0.11	0.27	0.20	0.78	1.90	-1.35	0.24	-0.30	-0.62	1.19	-1.07			√		√	√	√	√
1976	0.2	-0.1	-1.2	-1.3	-0.27	-0.53	-0.42	0.63	1.58	0.42	1.60	0.14	-0.93	-0.16	0.48	0.55	√	√	√	√				
1977	-0.9	-1.5	-1.5	-1.3	-2.04	0.19	-0.46	-0.23	1.00	-0.82	0.11	0.47	0.20	1.48	-1.53	0.87	√						√	√
1978	1.3	0.3	0.4	0.0	1.57	0.11	-1.06	-1.02	-0.14	1.23	-1.12	-0.03	0.31	0.08	0.06	0.42	√							
1979	0.3	0.4	1.3	-0.6	-1.99	3.57	1.92	-0.98	-1.13	0.44	-0.15	-0.28	-2.40	2.05	1.19	-0.54	√	√	√					
1980	-0.3	-0.4	-0.2	0.0	-0.02	1.00	-0.29	1.82	-0.05	1.00	0.36	0.05	1.30	-0.10	0.06	1.28			√	√	√	√		
1981	0.7	1.0	0.8	0.4	-0.94	-0.88	1.13	-1.90	-0.85	-1.98	-1.38	-0.51	0.19	-1.40	-0.54	-2.02	√	√	√	√				
1982	-0.7	-1.6	-1.9	-2.5	1.14	-1.63	-1.37	-0.91	-0.03	0.45	1.41	0.32	1.26	-1.17	1.33	-0.85	√	√	√	√				
1983	0.5	-0.3	-0.8	-0.2	0.34	0.77	0.32	1.02	-1.02	0.62	0.76	0.06	0.57	-0.34	0.87	0.92		√	√	√	√			
1984	0.0	-0.8	0.0	0.0	1.73	-0.43	2.16	-0.80	0.04	1.09	0.90	-0.05	-0.88	-0.34	1.41	-1.52	√	√	√	√				
1985	0.2	-0.9	-0.3	0.7	-0.64	-1.84	-0.37	-0.13	1.23	-1.90	0.01	0.32	-0.45	-2.15	-1.34	0.79					√			
1986	-0.5	0.7	0.1	-1.0	-1.09	0.26	0.28	-0.06	-0.07	-0.96	-1.80	-0.34	0.61	-0.78	-0.64	-0.95	√	√	√	√				
1987	-1.7	-1.7	-1.7	-1.5	0.46	0.12	-0.01	-0.25	-1.37	1.51	-1.16	0.02	0.87	-0.27	-0.64	0.27	√	√	√	√	√			
1988	0.8	-0.2	1.1	1.4	-0.18	-0.75	1.64	1.61	1.12	-0.69	-0.81	-0.06	-0.65	1.86	0.67	1.49		√	√	√	√			
1989	1.2	0.5	0.8	-0.8	0.46	-0.59	-0.46	0.00	0.50	-0.78	0.13	0.28	-1.39	0.97	-0.54	-0.05	√	√	√	√				

1990	1.1	0.0	0.5	-0.5	-0.31	-0.25	-0.34	-1.47	-0.07	-1.02	1.03	-0.45	-0.45	-1.40	-0.07	-1.34			√		√	√		√
1991	-1.5	-0.5	-0.2	-0.9	-0.58	0.09	-1.01	-0.02	1.06	-0.77	-2.04	-0.08	3.59	-0.48	0.81	0.17	√	√	√	√				
1992	0.0	-1.2	-0.8	0.0	1.24	-0.33	-0.61	0.06	-0.51	0.56	-0.10	0.01	0.75	-1.18	0.43	-0.48	√	√	√	√				
1993	-0.6	-1.4	-1.1	-1.5	-0.22	-1.80	2.78	-0.12	-1.29	-0.02	-0.69	0.27	1.04	0.51	1.49	-0.09		√	√	√	√			
1994	-1.0	0.9	-1.8	-1.8	1.13	2.04	-1.64	2.11	1.95	0.80	-0.71	-0.06	0.66	0.15	-1.57	0.00	√	√	√	√				
1995	-0.7	-0.2	0.3	-0.1	0.31	-0.20	1.08	3.26	-0.24	0.96	1.34	0.40	0.02	0.87	-0.26	1.99			√	√	√	√		
1996	0.0	1.0	0.6	0.4	-0.72	0.68	-0.79	0.31	-1.22	-0.53	-0.06	0.31	-0.53	0.02	0.61	2.14	√	√	√	√				
1997	-1.8	-2.0	-1.0	-2.1	-0.50	-1.44	0.26	-1.32	-1.74	-1.27	-2.11	-0.16	-1.97	-0.89	-0.52	-0.34				√	√	√	√	
1998	-0.1	0.7	1.3	1.0	-1.22	-0.06	0.27	2.54	-0.67	0.72	-0.28	0.03	1.27	-0.11	0.99	2.83	√	√						

NOTE: Standardized Rainfall Departure = Total Monthly Rainfall Total Monthly Mean (1961-1990)
Standard Deviation (1961-1990)

▨ El-Nino Year
░ La-Nina Year

East Malaysia: Kuching, Miri, Bintulu, Kota Kinabalu & Sandakan
East Coast: Kota Bharu, Kuala Trengganu Mersing & Kuantan.
West Coast: Alor Setar, Bayan Lepas, Ipoh Subang & Melaka.
Stratospheric: Easterly Component Wind over Kota Bharu at 30 hPa level.

Table 2b. Relationship of SOI, standardized northeast monsoon rainfall departure and stratospheric zonal wind

Period	SOI					Standardized Rainfall Departure															Stratospheric									
						East Malaysia					Peninsular Malaysia										Easterly					Westerly				
											East Coast					West Coast														
	Nov.	Dec.	Jan.	Feb.	Mar.	Nov.	Dec.	Jan.	Feb.	Mar.	Nov.	Dec.	Jan.	Feb.	Mar.	Nov.	Dec.	Jan.	Feb.	Mar.	Nov.	Dec.	Jan.	Feb.	Mar.	Nov.	Dec.	Jan.	Feb.	Mar.
1968/69	-0.5	0.0	-2.0	-1.1	-0.1	-0.69	0.03	-1.16	-0.69	-0.04	-0.76	0.91	-0.26	0.12	-0.81	-1.88	-0.03	2.96	0.11	0.78							√	√	√	√
1969/70	-0.2	0.3	-1.4	-1.6	0.0	2.13	0.92	-0.15	-0.38	-0.58	1.54	-0.59	-0.34	-0.87	-0.26	0.74	0.65	3.64	-0.63	0.36	√	√			√	√		√	√	
1970/71	1.7	2.1	0.3	1.9	2.1	-0.10	-0.81	0.83	1.72	-0.89	-0.51	0.50	1.46	0.19	0.39	-0.07	0.19	2.43	1.07	-0.11	√	√	√	√				√		√
1971/72	0.5	0.0	0.4	0.8	0.1	0.73	0.51	0.21	-0.18	-0.48	0.14	1.02	-0.82	-0.60	-1.04	-1.54	2.18	-0.02	0.35	-2.19						√	√	√	√	√
1972/73	-0.5	-1.6	-0.5	-2.0	0.2	-0.66	-1.23	-1.35	-0.80	0.26	-1.15	0.73	-0.04	-0.43	1.59	0.57	0.62	1.65	-0.16	-0.73	√	√	√					√		
1973/74	2.9	2.0	2.7	2.0	2.2	-0.05	2.76	-0.54	1.14	-1.12	0.43	2.03	-1.03	0.61	0.11	0.45	1.10	0.88	-0.53	-1.52			√	√		√	√			√
1974/75	-0.3	0.0	-0.8	0.6	1.2	-0.45	-0.76	-0.26	0.19	0.09	0.21	-0.77	1.93	0.76	0.36	1.10	-0.02	2.32	1.34	-0.66	√	√	√	√	√					
1975/76	1.3	2.3	1.5	1.6	1.3	0.19	1.09	1.06	-0.35	-0.46	1.25	-0.02	-1.07	-1.22	-0.45	-0.21	1.19	1.12	-1.29	0.75						√	√	√	√	√
1976/77	0.7	-0.6	-0.7	1.1	-1.3	-1.22	-0.33	0.14	3.54	1.56	1.38	0.36	-0.80	0.78	-0.88	-0.78	-0.09	1.00	0.54	-1.92	√		√							
1977/78	-1.6	-1.4	-0.4	-3.5	-0.8	-0.60	-0.10	-0.21	-0.77	0.14	0.06	-1.01	0.03	0.36	-0.43	-0.21	-1.36	1.66	-0.77	0.22										√
1978/79	-0.1	-0.3	-0.7	0.8	-0.5	0.17	-0.23	-0.88	-0.80	-0.42	-0.40	-1.12	-0.63	-0.07	-0.28	-1.68	-1.33	-0.03	0.47	-0.63	√				√			√		
1979/80	-0.6	-1.0	0.3	0.0	-1.2	1.40	-0.86	0.66	-0.72	-1.30	1.67	-1.70	-0.35	-0.68	-0.72	0.53	-1.78	0.69	0.06	0.66			√						√	√
1980/81	-0.5	-0.3	0.2	-0.6	-2.1	0.41	1.81	0.82	-0.10	-0.31	-0.43	0.28	-0.71	0.03	-0.94	0.18	-0.44	1.05	1.48	-0.93						√	√	√		√
1981/82	0.1	0.5	1.3	-0.1	0.1	0.80	-0.68	-0.08	-0.18	-0.75	-0.18	1.17	-0.70	-0.82	-0.37	-0.65	-1.70	-0.41	-0.64	1.05	√	√	√	√	√					
1982/83	-3.2	-2.8	-4.2	-4.6	-3.4	-2.12	-0.63	-0.38	-1.01	-2.03	-1.45	0.79	-0.60	-1.01	-1.11	1.59	-0.51	0.62	-0.91	-0.15						√	√	√		√
1983/84	-0.2	-0.1	0.1	0.6	-0.9	1.50	1.21	0.29	1.66	0.12	-0.91	2.12	0.61	1.11	0.46	-1.63	-0.19	2.36	2.33	1.98	√	√	√	√	√					
1984/85	0.2	-0.4	-0.5	1.0	0.2	-0.20	-0.30	-0.76	-0.54	2.02	-0.49	-0.39	-0.12	0.89	3.28	-0.34	0.86	0.40	1.01	1.67	√									

1985/86	-0.3	0.1	0.9	-1.6	0.0	-0.60	0.14	0.95	-0.39	0.49	-0.82	-0.63	-0.40	-1.17	-0.31	2.08	-0.02	0.97	-0.05	-0.17							√			
1986/87	-1.5	-1.8	-0.9	-1.9	-2.0	0.66	-2.08	-0.92	-1.43	-1.53	2.07	-0.98	0.53	-1.15	-0.25	-0.74	-0.37	0.63	-1.24	0.04	√	√	√	√	√					
1987/88	-0.1	-0.7	-0.2	-0.9	0.1	0.01	1.29	-0.71	0.04	1.14	-1.06	1.20	-0.49	0.08	1.94	0.31	0.87	2.33	1.92	1.12						√	√	√		√
1988/89	1.9	1.3	1.7	1.1	0.6	2.00	1.21	-0.24	0.25	-0.16	2.26	-1.03	-0.42	-0.89	-0.60	0.75	-1.09	1.46	-1.13	0.30	√	√								
1989/90	-0.4	-0.7	-0.2	-2.4	-1.2	-0.35	-1.09	-0.47	-0.92	-1.37	-0.81	-1.69	-0.08	-0.02	-0.43	-1.23	-0.20	0.93	-0.75	-0.46	√	√	√	√						√
1990/91	-0.7	-0.5	0.6	-0.1	-1.4	-0.62	-1.06	-0.66	-0.26	-1.67	-0.74	-1.00	0.53	-0.10	-0.37	-0.21	-0.57	1.28	-0.31	-0.08						√	√	√		√
1991/92	-0.8	-2.3	-3.4	-1.4	-3.0	-0.80	-0.04	-0.64	-1.08	-1.79	0.44	0.77	-0.24	-0.80	-0.89	-0.80	0.80	0.44	1.23	-0.71	√	√	√	√	√					
1992/93	-0.9	-0.9	-1.2	-1.3	-1.1	-0.46	0.01	-0.76	-0.89	0.84	0.66	-0.80	0.48	-0.71	1.07	-0.72	1.49	1.28	-0.44	0.70						√	√	√		√
1993/94	-0.2	0.0	-0.3	-0.1	-1.4	-0.88	1.14	-0.18	-0.57	4.10	-0.08	0.36	-0.50	-0.59	3.61	0.51	1.02	0.72	0.41	2.09	√	√	√	√	√					
1994/95	-0.7	-1.6	-0.6	-0.5	0.2	-0.36	-0.14	-1.00	0.16	1.15	2.89	-1.01	0.55	0.78	-0.47	0.85	-0.79	1.94	0.27	0.43						√	√	√	√	√
1995/96	0.0	-0.8	1.0	-0.1	0.7	0.27	0.35	0.62	1.57	-0.34	1.43	0.36	0.13	0.45	-0.27	0.14	1.18	1.62	-0.33	0.19	√	√	√	√	√					
1996/97	-0.2	0.8	0.5	1.6	-1.1	-0.32	0.53	-0.60	1.12	-1.97	-0.59	0.28	-1.15	1.39	-1.07	-1.20	0.60	0.83	0.62	-1.20	√	√	√							√
1997/98	-1.4	-1.3	-3.3	-2.7	-3.4	-0.70	-1.40	-1.19	-1.36	-1.12	-0.68	0.35	0.01	-1.20	-0.58	0.91	-0.08	1.19	-0.00	-1.36	√	√	√	√	√					

NOTE: Standardized Rainfall Departure = Total Monthly Rainfall Total Monthly Mean (1961-1990)
Standard Deviation (1961-1990)

▨ El -Nino Year
⬚ La-Nina Year

East Malaysia: Kuching, Miri, Bintulu, Kota Kinabalu & Sandakan
East Coast: Kota Bharu, Kuala Trengganu Mersing & Kuantan.
West Coast: Alor Setar, Bayan Lepas, Ipoh Subang & Melaka.
Stratospheric: Easterly Component Wind over Kota Bharu at 30 hPa level.

EFFECT OF SOLAR ACTIVITY

Sunspots are observed as vortex-like disturbances in the sun and are associated with large magnetic fields. The frequency of sunspots appears to exhibit quasi-biennial characteristics with an average period of 11 years. The solar sunspot record from 1950 – 1997 is shown in Figure 4a.

Using the limited data set, an attempt is made to investigate the relationship between the Malaysian rainfall and the ascending as well as descending phases of the 11-year sunspot cycle. The analysis as shown in Figure 5 does not indicate any relationship at all.

DECADAL CHANGES

On an average of every 10 years, climatological rainfall series seems to exhibit a peak or the so-called decadal changes. Analysis of the time series of filtered standardised departure of mean annual rainfall for selected stations in Malaysia (Figure 6) reveals an average of 6-to 9-year peak (dotted arrow) with low amplitude during 70s and 80s. The decadal peak over East Malaysia is found to lag about one phase behind that of Peninsular Malaysia. Such information could be helpful in preparing very long range rainfall outlook.

ENSO CYCLES

General Description

The surface ocean in the central and eastern equatorial Pacific is normally colder than that in the western equatorial Pacific. In some years, however, the ocean is especially warm. This warming typically occurs around Christmas time and lasts for several months. During these warm intervals, fish are less abundant. Fishermen along the coasts of Ecuador and Peru originally termed the phenomenon as "***El-Nino***" (Spanish for "the Christ Child").

Nowadays, the term El-Nino refers to the extensive warming of the central and eastern equatorial Pacific that leads to a major shift in weather patterns across the Pacific. Such episode occurs at irregular intervals of 2 to 7 years. In the eastern equatorial Pacific, the overlying air is heated by the warmer waters below, increasing buoyancy of the lower atmosphere and fuelling convective clouds and heavy rains. However, the air over the cooler western equatorial Pacific becomes too dense to rise to produce lesser clouds and rains. *In other words, dry conditions result in Indonesia and Australia while more flood-like conditions exist in Peru and Ecuador*.

During the past fifty years, twelve major El-Nino events have been recorded as in the following table, the worst of which began in March 1997 and faded away in June 1998. Previous to this, the El-Nino event in 1982-1983 was the strongest.

El-Nino events			
1951-1952	1953-1954	1957-1958	1965-1966
1969-1970	1972-1973	1977-1978	1982-1983
1986-1987	1991-1992	1994-1995	1997-1998

In contrast to El-Nino, ***La-Nina*** (the girl child) refers to the colder than normal ocean temperatures across the central and eastern equatorial Pacific. It occurs roughly half as often as El-Nino and seven major La-Nina events have been recorded in the past fifty years as tabulated below:

La-Nina events			
1950-1951	1955-1956	1970-1971	1973-1974
1975-1976	1988-1989	1998-1999	

In La-Nina years, monsoons are enhanced over Australia/Southeast Asia but the central equatorial Pacific becomes drier than normal (the reverse of El-Nino years). It is noted that a La-Nina does not necessarily follow hard on the heels of any current El-Nino. However, it has done so four times in the past 16 years. The strong El-Nino of 1982-1983 was followed by a weak La-Nina; the modest 1986-1987 El-Nino preceded a strong La-Nina; the moderate but extended El-Nino of 1991-1995 was succeeded by a weak La-Nina; and the moderate 1998-1999 La-Nina tailed behind the strongest 1997-1998 El-Nino.

It has been found that the cyclic warming and cooling of the eastern and central equatorial Pacific can be linked to changes to the surface air pressure. In particular, when the pressure measured at Darwin is compared with that measured at Tahiti, the differences between the two can be used to generate an "index" number termed as the Southern Oscillation Index (SOI) (Figure 4c). When there is a significantly positive SOI sustaining for at least 6 months, we have a La-Nina (or ocean cooling), but when SOI is significantly negative for at least 6 months, we have an El-Nino (or ocean warming).

Impact on Malaysia

From the discussion so far, it could be established that the El-Nino Southern Oscillation (ENSO) cycle has considerably stronger control over the interannual rainfall as compared with the other cyclical phenomena. Figures 3a and 3b show that the impact of ENSO on rainfall is significant over East Malaysia and becomes more prominent as season progresses towards the northeast monsoon.

The impact of ENSO cycle or specifically the El-Nino/La-Nina phenomenon on Malaysia is analysed through the use of the composite monthly percentile rainfall. In the case of El-Nino, it is found that the phenomenon exerts drier than normal rainfall particularly over East Malaysia during the northeast monsoon (Figure 7a). Over Peninsular Malaysia the impact is only noticeable in the northwestern states. However, during strong El-Nino, impact is expected to prevail throughout the country as evidenced by the strong 1997-1998 El-Nino. During the occurrence of this phenomenon, prolonged drought persisted in the neighbouring country, thereby inducing widespread and uncontrollable forest fire. Coupled with the favourable prevailing winds, smoke haze was being advected towards Peninsular Malaysia, reducing the amount of solar radiation. Through feedback mechanism, convective cloud development was suppressed, thereby reducing rainfall (Lim & Ooi, 1998). With respect to La-Nina, its effect is not clearly evident. Rainfall appears to be higher than normal over Sabah and Sarawak but does not show any clear trend over Peninsular (Figure 7b). Preliminary analysis of the moderate 1998-1999 La-Nina shows that the impact has led to the late onset of the northeast monsoon, resulting in below-normal rainfall over most of Malaysia except the northwestern states of Peninsular Malaysia until mid-December 1998. Since then till the end of January 1999, many places, in particular East Malaysia, registered normal or above-normal rainfall.

CONCLUSION

From the above, it is noted that phenomena such as QBO and sunspot cycle have relatively minor or negligible effect on the interannual variations of rainfall in Malaysia. The rainfall exhibits evidence of decadal changes but the amplitude appears to be relatively small. Large and significant fluctuations in seasonal rainfall anomalies particularly during the southwest and northeast monsoons can be linked principally to the influence of ENSO. Its impact is significant during the southwest monsoon for Peninisular Malaysia and during the northeast monsoon for East Malaysia. Therefore, through the use of composite percentile rainfall and prediction of the ENSO cycle issued by global climate centres such as the Climate Prediction Center in US, it is now possible to provide expected monthly rainfall trend throughout the country associated with the effect of El-Nino or possibly La-Nina. Such information would be particularly useful for water resources management and agricultural production planning.

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CHARACTERISTICS OF THE 1998 DROUGHT AFFECTING LANGAT VALLEY

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ABSTRACT

In the first quarter of 1998, Langat Valley folks felt the full impact of a drought in the wake of one of the strongest El-Nino episodes of the century. The effects of this drought in the form of unpleasant periods of disrupted water supply also reverberated in several areas in neighbouring heavily populated Klang Valley whose water supply is partly sourced from the Langat Valley. During such times, the ability to track the onset of an impending drought and trigger a Drought Response Plan, assess its progressing severity, and to determine the drought's eventual termination, is certainly useful for the concerned authorities. This paper makes use of the Herbst Method to identify and characterise past droughts including the recent 1998 drought in the Langat Valley, using monthly rainfall data from Ponsoon hydroelectric station. The paper then proceeds to show how the results of this analysis can be used for monitoring drought (tracking its beginning, progressing severity and eventual termination) and adopting subsequent water management measures.

INTRODUCTION

A low extreme in rainfall is often easily defined and recognised, but the lack of rainfall has varying implications. For instance, in arid zones devoid of rain for years, the flora and fauna have adapted to such conditions. However, the shortage of rainfall in countries of the humid tropics like Malaysia can result in serious water deficiencies, as happened in the Langat Valley and adjacent Klang Valley in the first quarter of 1998 thereby resulting in some periods of disruption of water supplies for domestic and industrial purposes.

Analysis of Malaysian drought characteristics such as onset and termination, duration and severity by Chan and Hong (1991), Hong and Mohd Noor (1992), and Ahmad Jamalluddin and Hong (1998) using the Herbst Method has been found to yield reasonable results. In this study, the Herbst Method, which is based on easily available monthly rainfall data, is employed to characterise the 1998 Langat Drought.

DROUGHT ANALYSIS USING HERBST METHOD

Herbst *et al.* (1966) used cumulative departures from average to confine the definition of droughts more specifically to periods in which rainfall deficits were in excess of average deficits. Sequences of dry months are identified beyond the shortfalls in monthly rainfall amounts that are normally experienced in some months of each year. An average monthly drought intensity over the period of a drought can be calculated as follows:

$$G = \Sigma \left[(E(t) - MR(t)) - MMD \right] / \Sigma\, MMD$$

$$MMD = \Sigma\, (MR(t) - R(t)) / n$$

$$E(t) = R(t) + D(t-1) \times W(t)$$

and $D(t) = R(t) - MR(t)$

where $W(t) = 0.1\{1 + (MR(t) / (\Sigma MR(t)/12)\}$

and $X = (MAD - MMMR)/11$

where

MR(t)= mean monthly rainfall
R(t) = actual rainfall for the same month
D(t) = deficit or excess for that month
W(t) = weighting factor
E(t) = effective rainfall
MMD= mean monthly deficit
MAD = mean annual deficit
MMMR = maximum mean monthly rainfall
X = monthly increment
G = average monthly drought intensity
P = period of drought in months

The Drought Severity Index is then given by G x P. The test for the onset of a drought is based on a comparison of the cumulative excess deficits from the point at which the test begins, with a sliding scale of twelve values calculated by linear interpolation between MMMR and MAD. The test to check for drought termination has to be applied to the month following the first month with a positive difference occurring after the start of the drought.

Monthly rainfall data from Ponsoon hydroelectric station at Ulu Langat for the period January 1947–June 1998 are used in the analysis. The results of the analysis, i.e. the details of onset, termination, intensity, duration, severity and ranking, and percentage of mean rainfall for the period of the identified droughts, are presented in Table 1. The onset, termination and drought duration are graphically illustrated in Figures 1a, 1b and 1c.

Table 1: Characteristics of identified droughts for Ponsoon hydroelectric station at Ulu Langat

	Onset	**Termination**	**Average monthly drought intensity**	**Duration (months)**	**Index of drought severity**	**Drought severity ranking**	**% of mean rainfall for period**
1	1 Dec 1997	30 May 1998*	2.25	6	13.5	6	43.7
2	1 July1992	31 July 1993	2.1	13	27.2	2	50.9
3	1 Nov 1989	28 Feb 1991	1.17	16	18.7	4	73.8
4	1 Oct 1988	31 May 1989	1.5	8	12.0	7	64.4
5	1 Jun 1986	31 July 1987	1.89	14	26.5	3	56.4
6	1 Sept 1976	31 July 1977	1.39	11	15.3	5	63.4
7	1 Nov 1951	31 Mac 1954	1.46	29	42.4	1	66.3

* Potential end of drought

A total of 7 droughts were identified, with the worst drought in Langat from November 1951 to March 1954 (Index of Drought Severity being the highest at 42.4) for a duration of 29 months. The second worst occurred for the period from July 1992 to July 1993 (Index of Drought Severity at 27.2) for a duration of 13 months. It can be observed that the identified droughts, having Drought Severity Index ranging from 42.4 to 13.5, have low rainfalls ranging from a high of 66.3% to a low of 43.7% of the mean rainfall period. The 1988–1989 drought happened to be the least severe drought identified, with a Drought Severity Index of 12.0.

The 1998 drought, though ranked sixth in terms of severity (Index of Drought Severity was 13.5), is, however, the most intense on record, with an average drought intensity of 2.25, of the shortest duration (6 months) and the lowest percentage, 43.7%, of the average rainfall for the 6-month period. Incidentally this 1998 drought coincided with one of the strongest El-Nino episodes (1997–1998) of the Century. It is apparent that the low severity but rather high intensity drought was sufficient to disrupt the tight water supply situation (already suffering intermittent plant shutdowns due to polluted riverwater at the intakes) in the Langat Valley in early 1998.

An accurate assessment of existing drought conditions can be made using the Herbst Method. For example, when the monthly rainfall at a chosen rainfall station begins to fall below average, the monthly difference can be computed and checked against the values of the sliding scale for the possible onset of any drought. If a drought is detected, its severity can be estimated by comparing the current and past identified short duration droughts for the station. When the monthly difference for the ensuing months becomes positive it can be checked whether the current drought is at the stage of being temporarily interrupted or terminated. If a long drought has set in then further investigations need to be carried out.

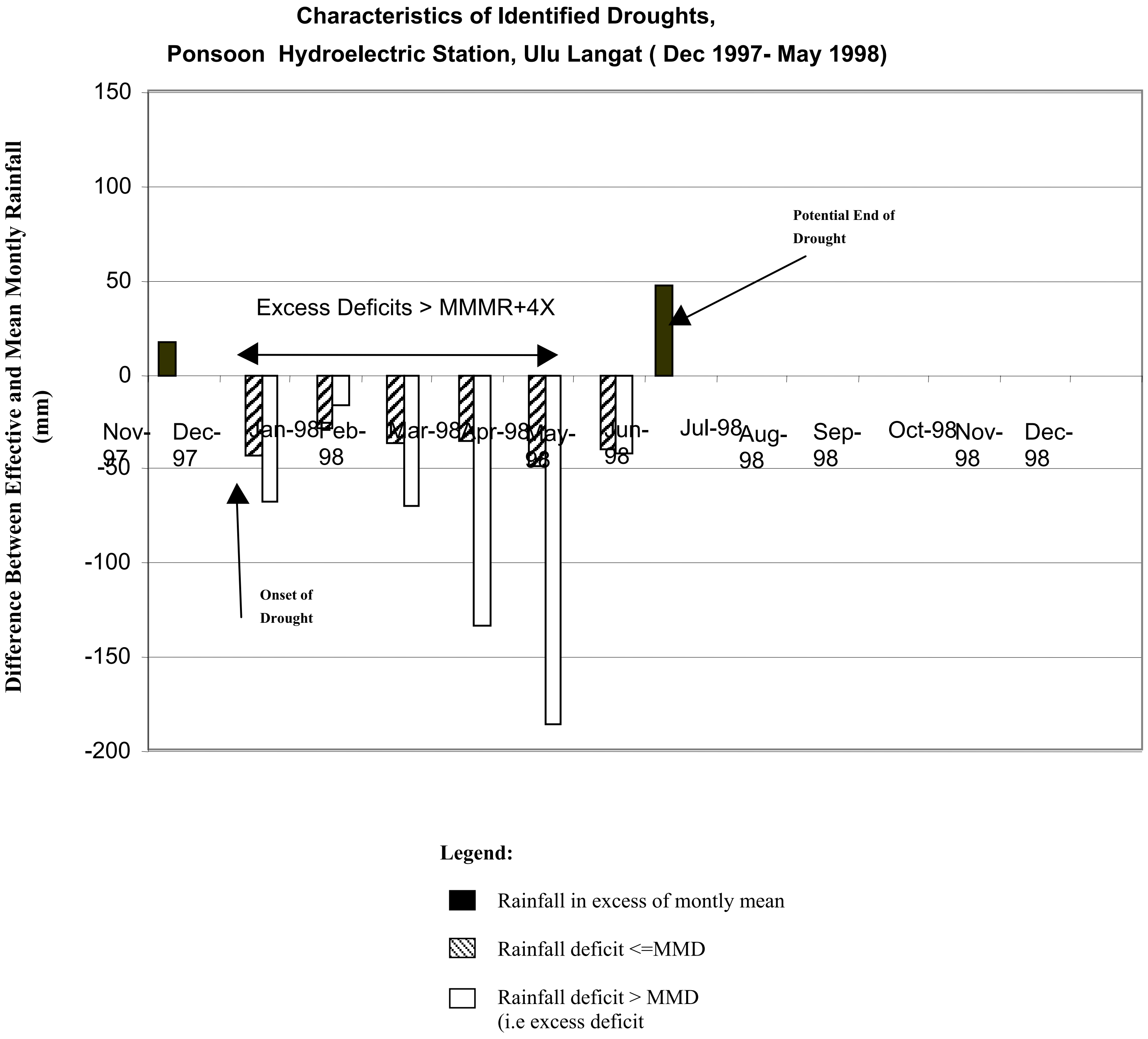

Figure 1a: Characteristics of identified droughts, Ponsoon hydroelectric station, Ulu Langat

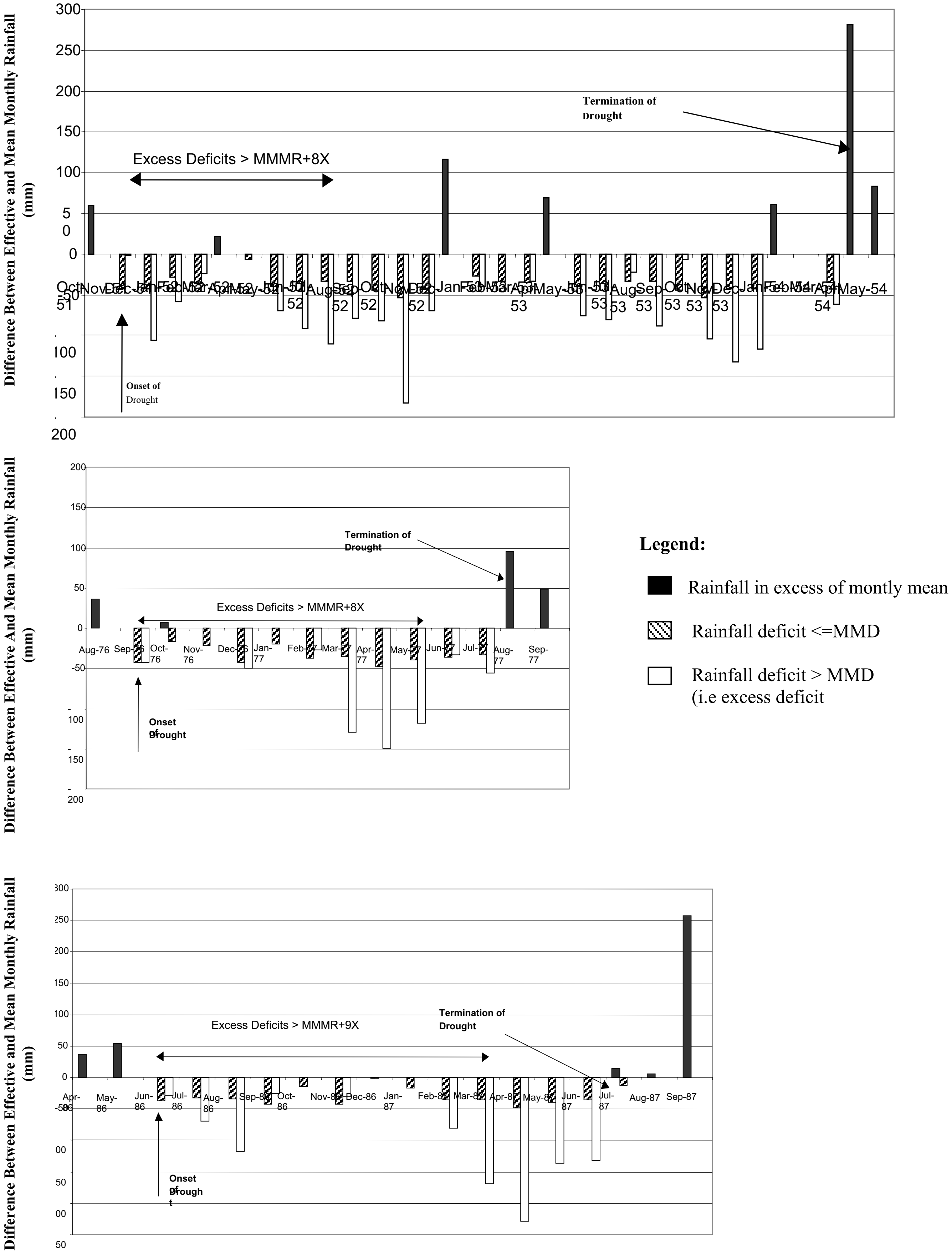

Figure 1 b: Characteristics of identified droughts, Ponsoon hydroelectric station, Ulu Langat.

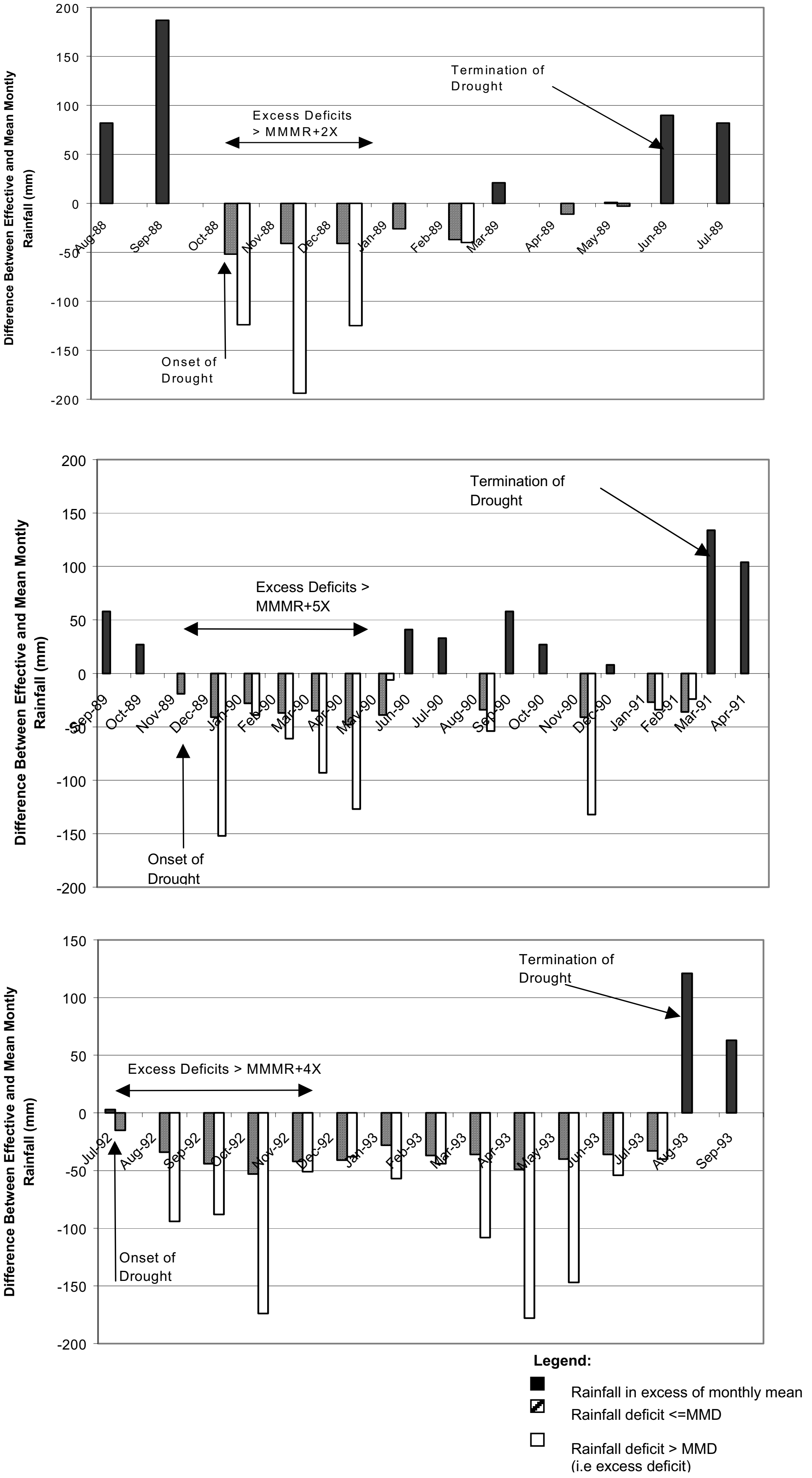

Figure 1c: Characteristics of identified droughts, Ponsoon hydroelectric station, Ulu Langat

Assuming an analysis of the rainfall data of the Ponsoon hydroelectric station at Ulu Langat was started in December 1997, then the analysis would have identified this month as a "potential drought starting month", although there was as yet no "true drought" then (as the excess deficit for December 1997 was smaller than MMMR). By March 1998, there was still no true drought occurring as the cumulative excess deficits then were smaller than MMMR + 3X of the sliding scale. This drought is then confirmed to have started in April 1998 when at the end of April the cumulative excess deficits were greater than MMMR + 4X. The above average rain in June 1998 resulted in a positive monthly difference indicating the potential end of the drought.

CONCLUSION

This analysis demonstrates the ability of the Herbst Method to characterise droughts in the Langat Valley. The Herbst Method could be incorporated into a drought monitoring system for the early detection of drought. Decision-makers could then make timely decision with regard to setting into motion drought response plans including allocation of precious water resources to those affected, thereby mitigating the impacts of the drought as much as possible.

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SELECTED ISSUES IN MOUNTAIN HYDROLOGY OF THE HUMID TROPICS

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ABSTRACT

With the exception of East Africa, there has been no long-term, controlled experimental studies that have been undertaken in the mountainous areas of the humid tropics. The work will therefore emphasize selected issues which require greater attention within the following topics, viz, precipitation linked with ‘occult’ precipitation in cloud forests, total evaporation, throughfall-stemflow, hillslope hydrology, the potential use of topographic-wetness models and possible impacts of various land-use conversions on catchment yield. As part of the discussion, the potential for extrapolation of findings from lowland forests with high, annual rainfalls is considered.

INTRODUCTION

Within the mandate of this paper, there is no accepted definition of ‘tropical mountain hydrology’ in terms of environmental factors such as elevation, climatology, pedology and ecology which influence the hydrology. If one follows the review of Bruijnzeel (1990) in terms of ‘Lowland’ tropical forest *vis-à-vis* ‘Montane’ forest within the framework of “total evaporation” (as defined by Ward & Robinson, 1990, p. 79) versus precipitation and elevation, then work undertaken on a controlled experimental catchment basis “is very limited” (Bruijnzeel, 1990, Tables 2 and 4). It is also widely recognized that the ecophysiology and related forest morphology adjust to elevation so that in general tree height decreases with consequential effects on horizontal interception of cloud droplets, rain interception, throughfall and stemflow. As highlighted later, available data to substantiate such effects are also limited (Hamilton, 1995; Hamilton *et al.,* 1995).

It is appropriate at this point to raise the management questions which pertain to tropical mountain hydrology. The central focus is anthropogenically induced change in land-use hydrology arising from the encroachment of mountain areas by socio-economic activities resulting in the conversion of forests to various land uses, and their consequential effects on the water balance.

A longer-term consideration is the impact of climate variability and change on the higher peaks whose rivers are fed by tropical glaciers whereby there have been recent reports of glacier contraction in selected areas such as Irian Jaya (Peterson & Hope, 1995, reported by Goss, 1995). It is beyond the scope of this paper to consider such aspects of tropical glaciology, but a major monograph on the subject is currently under preparation (Kaser & Osmaston, 2002). In a recent review of the impacts of climate change on tropical mountain biodiversity, Pounds *et al.* (1999) put forward the notion of rising sea surface temperatures (SSTs) which are encouraging enhanced evaporation from warm ocean surfaces. The resulting latent heat release from the condensation of excess moisture causes a change in the environmental (vertical) temperature lapse rates. The amplification of warming results in a decrease in the rate of temperature decline with elevation. Thus the freezing level is displaced upwards which encourages enhanced glacier melting.

In parallel with the above changes in lapse rate, the associated humidity profiles also adjust upwards which causes the condensation levels for cloud formation to be more elevated. Known as the *lifting–cloud base hypothesis*, the hydrology is altered "…by reducing critical dry-season inputs of mist (low-intensity windblown precipitation) and cloud water (non-precipitating droplets deposited onto vegetation" (Pounds *et al.,* 1999, p.611). Elsewhere when simulating climatic change under the *Last Glacial Maximum* (LGM) and for doubled atmospheric carbon dioxide (2 x CO_2) conditions, Still *et al.* (1999) observed a downward shift of tropical montane cloud forests (now referred to as TMCFs) under the LGM which conforms with paleo-data. Conversely, there is an upward displacement of TMCFs for the 2 x CO_2 scenario for reasons stated above. The impact on the hydrology is even more aggravated by a corresponding increase in total evaporation (principally dry canopy transpiration) due to rising temperatures and reduction in cloud contact (Still *et al.*, 1999).

Forest conversion potentially has impacts on "both" input and output variables of the water balance equation. As indicated, the more elevated, montane forests (i.e. TMCFs) have the unique distinction of being able to capture additional inputs of 'occult' precipitation, otherwise known as "horizontal interception", from the water droplets within passing clouds. Such occult precipitation is capable of adding a sizable proportion of the annual precipitation, although as later outlined, the accuracy of these estimates is not high because of the existing measurement techniques (Bruijnzeel & Proctor, 1995). Nonetheless these additional, 'occult' precipitation inputs are linked with the continued existence of forest which on conversion are potentially an immediate loss to the water balance (depending on the replacement vegetation) (Hamilton, 1995). Horizontal interception also enables montane forests to survive a protracted dry season as well as enabling the limits of these forests to extend into drier climates. For example, the outer fringes of the montane, closed forests of northeast Queensland (Bonell, 1991) are considerably dependent for their survival on 'occult' precipitation to supplement the very limited inputs from SE trade wind showers during the long dry season.

Forest conversion also radically alters the *total evaporation* component (*wet canopy evaporation* from interception plus *dry canopy transpiration*) and in the longer term, the surface infiltration and related soil hydraulic properties, especially if the land use involves less vegetal protective cover and surface compaction. The central focus is then on the changes in the runoff component in terms of total water yield and its constituents, quickflow (stormflow) and delayed flow (dry weather flow) (Bonell with Balek, 1993).

The above sets the framework of forest mountain hydrology, that is, the initial need for a comprehensive understanding of the baseline hydrology (including processes) prior to conversion and climate change. Because of the uncertainty and limited material on climate change impacts (Bonell, 1998a), the principal focus in this paper will be on anthropogenically induced impacts on the hydrology. The next stage is to evaluate the impacts of conversion on both quantity (as expressed in the water balance equation) and related adjustment in process hydrology, for modelling and prediction within the broad field of change in land-use hydrology. Land management is also moving towards restoration of degraded lands, including parts of montane areas. Thus land-use hydrology needs to consider the 'reverse' effects of rehabilitation, for example, through agroforestry and reforestation.

The preceding field of interest is far too broad for one paper to cover in the required detail. On the other hand, since the mid-1980s there has been a plethora of comprehensive reviews which intricately cover the overall effects of tropical forest conversion on the water balance (Hamilton, 1988,1990; Bruijnzeel, 1990) and some consideration was given to process hydrology (Bonell, 1993; Bonell with Balek, 1993; Bruijnzeel, 1996). Further updates within the context of climate change and variability (Bonell, 1998a) and forest hillslope hydrology (Bonell, 1998b; Bonell & Fritsch, 1997) have been presented by the author. Elsewhere the subject of the hydrology of tropical montane cloud forests (TMCFs) was presented as a state-of-the-art review by Bruijnzeel and Proctor (1995) as part of a monograph examining the ecology and management of these vulnerable ecosystems (Hamilton *et al.,* 1995). That review was recently updated by Bruijnzeel (2002) using more recent material from hydro-meteorological studies conducted in TMCFs in the Caribbean region. The issue of rehabilitation of degraded landscapes was also introduced by Bruijnzeel (1989) and Pereira (1991), and more recently given special attention as part of a multi-disciplinary workshop by Bonell and Molicova (2003).

It is thus more productive to outline what the author perceives as some of the "prime issues using selected examples only"*, based on the assumption that the reader is familiar with the above work. Thus it is not the intention for this paper to act as a comprehensive review.* Further it is beyond the scope to provide an overview of "all" the definitions of various processes and concepts. When concerning the latter, however, the working definition of tropical montane cloud forest (TMCF) is that set out in three detailed paragraphs by Hamilton *et al.* (1995, p. 2) which incorporates their floristic structure, climatology, physiology and pedology. Also following Bruijnzeel and Proctor (1995), TMCF are understood to include all forests which are frequently covered by cloud or mist whether they be lower montane rain forest (LMF), upper montane rain forest (UMF) or the "elfin cloud forests", associated with the higher elevations (Grubb *et al.*, 1963; Stadtmüller, 1987). Later discussions of runoff processes will rely on the *Glossary of Terms* set out by Chorley (1978).

Initially, issues related to the evaporation-interception, stemflow and throughfall process will be discussed. Subsequently attention will be directed towards runoff process hydrology linked with the interpretation of changes in catchment water yield following forest conversion. Particular emphasis will be given to the use of combined hydrometric-hydrochemistry studies in hillslope hydrology and the linkages with topographic-wetness models. Because of the existing broad field of coverage, the work will "not" include the complimentary aspects of hillslope erosion, and solid debris-dissolved load transport in organised drainage, except in connection with the use of environmental tracers. Finally the work will briefly review the impacts of various land-use conversions on catchment water yield.

EVAPORATION, OCCULT PRECIPITATION, STEMFLOW AND THROUGHFALL

Tropical Montane Cloud Forests, as previously indicated, are the least understood in terms of their hydrology despite the fact that they provide the most reliable potable water-supply to downstream users during drought periods from "a surface source" in the humid tropics. Available data indicate that cloud water (CW) inputs (or horizontal interception [*] known as 'occult' precipitation from cloud stripping in the absence of rainfall) is typically in the range of 5 to 20 per cent of conventional, annual rainfall. In certain situations, however, CW may even exceed rainfall during 'dry' seasons. Furthermore, dry canopy losses (transpiration) are low. Consequently, forest conversion potentially denies the continuation of a more surplus water budget, with serious consequences to water resources management (Bruijnzeel & Proctor, 1995). Such allegedly favourable water balances (associated with TMCFs) have been challenged more recently, due to the existence of enhanced wet-canopy evaporation (interception losses) arising from advected energy from adjacent warm oceans (Dykes, 1997; Schellekens *et al.* 1998).

The Measurement Problem

A key issue is gaining more precise estimates of occult precipitation. The traditional approach is either to use "fog catchers" or a comparison of the amounts of canopy drip measured within the forest (net rainfall or throughfall) as against the amounts of gross rainfall measured in the open (termed *the comparative measurement approach*) (see Schellekens *et al.*, 1998 for detailed description of instrumentation and methods). Neither of these techniques can be considered as providing the required precision for inputting "areal" estimates into the water balance equation (Bruijnzeel & Proctor, 1995; Juvik, 1999). Fog catchers are essentially representative (or unique) of the forest canopy being measured, that is, they are site (canopy) specific. As the forest canopy is morphologically spatially variable, then reliable extrapolation of results is not a practical proposition. Furthermore, the efficiency of the commonly used Girunew-type fog catcher is strongly sensitive by gauge exposure and windspeed (Schemenaur & Cereceda, 1994; Schellekens *et al.*, 1998). Consequently, the estimates of cloud water inputs by TMCF cloud stripping must be treated with caution. The principal contribution of this technique is to act as "an indicator" when cloud droplet interception is occurring. The second, comparative measurement approach is the more reliable, subject to wet canopy evaporation (from intercepted water) being accounted for, preferably by automated meteorological equipment as part of a micrometeorological investigation (Bruijnzeel & Proctor, 1995).

The preceding discussion leads into the complimentary issue of providing estimates of intercepted precipitation. As succinctly described by Bruijnzeel and Proctor (1995, p. 43-44), the conventional method of subtracting throughfall and stemflow amounts from incident rainfall is not practical because of the unknown, additional input of cloud water (CW) in TMCFs. Consequently, these writers urge the

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[*] Horizontal precipitation (HP) is also used and which includes horizontal (fog) interception plus wind-driven rain. However, estimates of HP are commonly undertaken in rainless periods (e.g. Schellekens *et al.*, 1998).

need for a more innovative experimental design that takes into account several factors, viz, both temporal and spatial variability in throughfall and stemflow coupled with the intensity and occurrence of fog or rainfall duration of canopy wetness, climatic factors to calculate evaporation rates from a wetted canopy, and time lag between the start of the fog occurrence and the commencement of fog (canopy) drip in relation to moisture status of epiphytic cover. "Epiphytes", in particular, pose a significant problem by complicating the procedure for obtaining estimates of intercepted precipitation (Bruijnzeel & Proctor, 1995).

Estimates of Cloud Water Inputs

Because of the aforementioned measurement difficulties, absolute amounts of CW inputs reported in the literature using fog catchers must be treated with caution. There is a wide range cited from less than 45 mm y^{-1} (1.4% annual precipitation, P) in the Blue Mountains of Jamaica to *c.* 1,450 mm y^{-1} (99% of P) in Honduras (Bruijnzeel, 2002). The amounts and proportion of P are also seasonally dependent (see Table 1, Bruijnzeel & Proctor, 1995). Exposure is one of the critical factors. For example, Cavelier *et al.* (1996) noted that in a transect study across the Central Cordillera of Panama, CW inputs were highest on the more exposed ridges to the prevailing winds and increased with increasing altitude; so that such horizontal interceptions ranged between 2.4 and 60.6% of P. Absolute amounts of CW ranged from 142 to 2,295 mm. Significantly seasonal variation in CW was different from rainfall patterns and there was no correlation between monthly (on annual) rainfall and fog interception (Cavelier *et al.*, 1996).

Throughfall Estimates (Neglecting Stemflow)

Throughfall estimates (TF) are also vulnerable to error because of the complex architecture of TMCF. Nonetheless TF provides an indirect indication of the importance of CW inputs. Bruijnzeel (2002) reported TF ranges for respectively LMF and UMF (including dwarf forest) as being similar at 55-130% and 59-125% of P (the Honduras case study was excluded). These figures contrast with the typical range of 65-80% of P for LMF where cloud stripping is negligible (Bruijnzeel, 2002). It is clear that not all sites in TMCF have TF in excess of P due to variable persistance in cloud cover, exposure to moisture bearing winds and different wet canopy evaporation (interception). Bruijnzeel (2002) also pointed out the critical role of epipyte biomass impacts on TF. Some of the lowest TF percentages were identified with tall TMCF in high rainfall areas which received not only substantial amounts of CW (175-875 mm y^{-1}), but also incorporated substantial epiphyte biomass. Such biomass (especially for the nonvascular epiphytes) are capable of absorbing rain and fog up to 4–5 times their dry weight, with subsequent losses by evaporation (Bruijnzeel & Proctor, 1995). Thus canopy interception storage (~5 mm) is up to an order of magnitude higher compared with lowland rainforest.

Rainfall Interception, E_i (wet canopy evaporation)

Bruijnzeel and Proctor (1995, Table 2) and Cavelier *et al.* (1997, Table 2) provide a summary of rainfall interception E_i, as a percentage of annual rainfall. At sites where TF exceeds P, negative percentages of E_i have been indicated which of course are a result of enhanced CW inputs masking the occurrence of wet canopy evaporation at other times. Otherwise the common upper range of E_i is *c.* 20%. Cavelier *et al.* (1997), for a particular site in Panama (Fortuna), recorded E_i as 37.2% of P which as they noted is the highest value reported for TMCF (c.f. 32% New Guinea: Edwards, 1982; 24.6% Colombia: Vis, 1986). Cavelier *et al.* (1997) attributed their high interception value to the very tall forest canopies (20-30 m) which are similar to those of the above New Guinea and Colombian studies. Conversely, TF was relatively low in the Panamanian study, being 62.4% of P (Cavelier *et al.*, 1997).

The above explanation contrasts with advected energy as a casual factor for enhanced E_i mentioned elsewhere (e.g. Schellekens *et al.*, 1998). Significantly, only 6 out of 140 of the rain events showed net precipitation (TF) exceeding gross rainfall; thus inferring that CW inputs are not an important water source for the Panamanian forest study (Cavelier *et al.*, 1997).

Estimates of E_t

Even more scarce are good estimates of transpiration from cloud forests, but available evidence mainly using indirect (water budget) techniques suggest very low annual rates in the order of 280 mm y^{-1} exposed to frequent cloud. For TMCF of more limited cloud incidence, E_t is of the order of 600 mm y^{-1}. The sparse estimates from UMF (elfin forests) suggest even lower E_t, *c.*75 mm y^{-1}(Bruijnzeel, 2002).

The cause of such low dry canopy losses remains a source of debate and cannot be simply attributed to climatic reasons. For example, even in bright sunshine (Bruijnzeel *et al.,* 1993), low rates of transpiration were recorded in Gunung Silam (Malaysia). Other factors linking physiological responses with a high soil moisture regime, and the resulting shallow roots not being able to cope with occasional high evaporative demand, have been proposed by several writers. Certainly the leaves of TMCF have more of a 'xeromorphic' appearance in comparison with lowland closed forest (Bruijnzeel & Proctor, 1995; Hamilton, 1995).

Total Evaporation

Combining both wet (E_I) and dry (E_t) canopy losses, and taking into account additional 'occult' (horizontal interception) contributions brings the annual rates of total evaporation (wet and dry canopy losses) within the range of 570-695 mm y^{-1}, which is much lower than the 1,225 mm y^{-1} associated with fog-free montane forests (Bruijnzeel & Proctor, 1995). A more recent revision by Bruijnzeel (2002) provides total evaporation estimates in the order of 550-700 mm y^{-1} for TMCF subject to persistent cloud cover and *c.*1,000 mm y^{-1} for those TMCF which receive only modest amounts of CW (CW< 3% P). To gain a more comprehensive understanding of the causes of such low losses requires a multidisciplinary approach which should examine both physiological and pedological considerations (including soil nutrient uplake) as well as the broader aspects of hydrology (including micro-meteorology and soil physics).

The Effects of Incident Angle of Rain and Forest Structure

When considering other hydrological aspects, Herwitz's (1985,1986,1987) work in northeast Queensland montane forest highlights the need for closer attention being given to the effects of forest structure parameters and incident angle of rainfall due to persistent high winds (Herwitz & Slye, 1992; 1995) in the measurement and modelling of the interception, stemflow and throughfall process. Such observations particularly apply to the trade wind belt of the outer tropics.

Moreover, the above work demonstrated that the assumption of constant canopy/trunk storage capacities was an oversimplification, and more account needs to be taken of the *dynamic* changes in storage capacities, including differences between still-air and turbulent conditions. Significantly, bark storage capacity (2.7 mm over five species) could be higher than leaf storage (1.7 mm over five species) under still-air conditions. Under turbulent conditions, bark storage could be as high as 6.6 mm (Herwitz, 1985) and storm sizes had to exceed a critical threshold (> 8.3 mm) before leaves and bark became totally saturated. Herwitz (1986) also emphasized the important role of tree architecture, in closed-canopy, montane rain forest (annual rainfall, 6,570 mm y^{-1}) in terms of being able "to funnel" large volumes of stemflow to the base of trees. For example, he noted that localized stemflow fluxes could be as high as 314 mm min^{-1} when the rainfall intensity was 2 mm min^{-1}. Such fluxes were capable of developing infiltration-excess (Hortonian) overland flow immediately in the area around the base of the tree bole.

Even more problematical is the effect of an uneven forest canopy on the interception process under conditions of wind-driven rainfall which cause incident rainfall to be inclined from vertical paths. Under this type of conditions, prominent canopy tree crowns create lateral rainshadows. Moreover, the canopy tree crowns themselves intercept greater volumes of rainwater per unit projected crown area than less prominent neighbouring canopy trees under inclined rainfall conditions (see Figure 3 in Herwitz & Slye, 1992). The analysis of Herwitz and Slye (1995) is one of the first to calculate the C_e/C index (effective rainfall-intercepting crown area/projected crown area ratio) of each tree in a rain forest measurement plot; and subsequently show a significant correlation between C_e/C index values and measured net rainfall totals (after correction for tree interception storage capacities). Rainfall inclination angles in excess of 19^o occurred on more than 80 per cent of the raindays examined in the analysis of Herwitz and Slye (1992,1995).

Elsewhere Elsenbeer *et al.* (1994a) emphasised the role of rainfall intensity linked with throughfall and interception under primary terra firma rain forest in the Upper Amazon Basin of Peru for "small" (< 2.5 mm) rainfall events. Such emphasis was in recognition that the canopy storage *(S)* is not strictly a vegetation parameter with a fixed value. Following Bultot *et al.* (1972), Elsenbeer and co-workers provided supporting evidence that there is a distinction between potential and actual canopy capacity, with the former being the true vegetation parameter and the latter influenced by meteorological conditions notably rainfall intensity and wind. Equally the free throughfall coefficient *(p)* (defined as the fraction of gross rainfall that reaches the ground without hitting the canopy) is affected by meteorological factors for small events. For larger events, gross precipitation is the most appropriate predictor of throughfall using regression analysis, the latter of which was estimated to be 83.1 ± 8.8 per cent of gross precipitation. Under these circumstances, throughfall coefficient is controlled by free throughfall and canopy drip. Whilst Elsenbeer *et al.'s* (1994a) study was technically not in montane rain forest (it was geographically located in a valley of the western Amazonas Andes), the determined percentage of throughfall was comparable with the range of 81.7-87.6% determined further north in Colombian montane rain forest by Veneklaas and van Ek (1990).

The Importance of Advected Energy

An interesting observation that applies to both montane as well as lowland rain forests is that wet canopy losses (evaporation) can exceed net radiation; and there has been considerable debate on the sources of the additional energy to enhance higher evaporation (see review in Bonell with Balek, 1993, pp. 189-190). Several contributory sources have been proposed such as a negative sensible heat flux (downward) to sustain evaporation from the wet forest canopy (Blyth *et al.*, 1994); greater surface roughness to airflow from the forest inducing enhanced turbulence; the maintenance of "drier" air advection at the mesoscale; and even the addition of heat to the air from extra heat storage in the woody biomass. Additional relevant factors in mountainous areas are either the "additional" evaporative power to air gained from the latent head release during orographic uplift (Morton, 1984) or because of the penetration into drier air above a synoptic-scale inversion layer, commonly found in the trade wind belt (Giambelluca & Nullet, 1992; Bean *et al.*, 1994).

Some of the preceding mechanisms need to be linked with the potential for forests to exploit advected energy from warm oceans in coastal areas. The rain forest covered mountains of northeast Queensland, adjacent to the Coral Sea, regularly demonstrate impressive visual evidence of wet canopy evaporation in the form of ascending "stratus" cloud during long duration rainfall. The latter materializes immediately above the rain forest canopy and there is some indirect evidence for the preceding effect. For example, Gilmour (1975) in northeast Queensland (annual rainfall 3,900 mm) measured much higher wet canopy losses as a proportion of total evaporation (46%, 702 mm y^{-1}) in comparison with continental Amazonia (25%, 328 mm y^{-1}) (reviewed in Bonell with Balek, 1993, p. 190). Thus "identifying energy sources and processes connected with enhanced wet canopy evaporation is a major research issue".

More recent research has taken up this challenge and provided further support for the influence of additional advected energy from an adjacent warm ocean. In a lowland tropical forest study (mean annual rainfall 4,500 mm) in Brunei, Dykes (1997) measured mean annual rainfall interception losses, E_i, in the order of 800 – 300 mm. Such estimates are within the same range of Gilmour (1975). Dykes (1997) suggested that as an absolute value, 800 mm of interception loss is high; and attributed this high value to the advection of energy from the adjacent warm South China Sea. Elsewhere in the Luquillo experimental forested catchments of Puerto

Rico, Schellekens *et al.* (1998) noted enhanced wet-canopy losses at a lowland site (i.e. Bisley) and upland TMCF site (Pico de Este) of 1.25 and 0.35 mm h^{-1} respectively using the method of Gash (1979). Such estimates are approximately five times more than estimated by the Penman-Monteith equation (Monteith, 1965, 1973, 1981), viz, 0.24 and 0.13 mm h^{-1} respectively. Schellekens *et al.* (1998) attribute the respective difference of 1.0 and 0.2 mm h^{-1} to a five-fold enhancement of evaporation which is utilizing advective energy from the nearby Caribbean Sea.

RUNOFF HYDROLOGY

A common characteristic of mountainous, headwater basins adjacent to oceans is the high annual runoff coefficients associated with them (see examples in northeast Queensland, Bonell *et al.*, 1991; Q/P range 0.58–0.90), although the sparse rain gauge network and lack of horizontal interception (CW inputs) studies means that the calculations of such coefficients are prone to major error. In contrast, the more 'continental' East African Highlands (~ 2,000 metres a.s.l.) of lower annual rainfall (1,100-1,300 mm) have in turn, much lower runoff coefficients (Q/P, 0.22) associated with montane forests (Lørup, 1998). Horizontal interception is not a critical factor here. The prevailing, highly permeable volcanic soils also do not favour the occurrence of overland flow.

The high runoff coefficients connected with maritime montane environments, which are affected by rain producing perturbations of maritime origin (see Manton and Manton & Bonell, 1993), arise from a combination of high annual rainfalls supplemented by the described additions of 'occult' precipitation (Bruijnzeel & Proctor, 1995). Consequently, such basins are a prime water resources asset as suggested earlier (both in terms of quantity and as a supply of potable water) which highlights their scientific importance. Nonetheless, to date there are no reports of results from "comprehensive" hillslope hydrology studies undertaken within TMCFs, although the writer is aware of an on-going initiative in the Bisley experimental watershed in the Luquillo mountains of Puerto Rico. Even in environments that can be "loosely" categorized as belonging to the mountain group of intermediate elevation, the number of studies is still very limited (see reviews in Bonell, 1993; Bonell, 1998a,b.; Bonell & Fritsch, 1997). Amongst this group are the studies of Elsenbeer and co-workers (Elsenbeer & Cassel, 1990, 1991; Elsenbeer *et al.,* 1995b; Elsenbeer & Lack, 1996) in western Amazonia, and Malmer and Grip (Malmer, 1993, 1996; Malmer & Grip, 1990, 1994) in Sabah. In addition, Herwitz (1986) highlighted the role of stemflow as a major component in the runoff process within the lower slopes of Mt. Bellender Ker range, northeast Queensland. Even the possibility of using lowland tropical forests which experience high annual rainfalls (> 3,000 mm) as prospective reference points for extrapolation remains limited because of the lack of "detailed" investigations in these areas. Work in Babinda, northeast Queensland (east of the site of Herwitz (1986 above) by Bonell and co-workers (summarized in Bonell *et al.,* 1991, 1998; Elsenbeer *et al.*, 1994b, 1995a) and French Guyana (Fritsch, 1992; Molicova *et al.,* 1997) might be the appropriate examples. Even so, the total number of studies from this high annual rainfall-lowland closed forest group also remains too small to form any definite conclusions.

What becomes apparent is the *greater role of short-term rain intensities in being capable of producing overland flow in selected undisturbed forests*. Elsenbeer *et al.* (1994a, Table 1) provides a summary of descriptive statistics of rainfall variables, and the maximum rain intensities for a Western Amazonian study are not too dissimilar from similar information cited elsewhere (e.g. northeast Queensland, Bonell *et al.***,** 1991). The principal difference, however, is the "duration" of such high intensities which generally are much longer and more favoured in the outer tropics which experience more organized, cyclonic perturbations in contrast to the prevalent, convective storms of the equatorial areas (up to 8°N or 8°S) (Bonell with Balek, 1993). The median of average rain intensity, irrespective of geographic location, however, is lower (see Elsenbeer *et al*., 1994a) compared to short-term maximum rainfalls *which reflects the temporal variability of rainfall intensity during events*. Such variability also plays a major role in the changing preferred pathways of hillslope runoff. Thus *short-term rainfall parameters*, which are up to an order of magnitude higher than the humid temperate areas, have a more dominant role in the runoff generation process within the humid tropics.

The preferred stormflow pathways are also the result of the interaction between the short-term rainfalls and the topography, nature of forest floor and the spatial and vertical changes in soil hydraulic properties. Elsenbeer and Cassel (1991), for example, noted the multiple occurrence of saturation (saturation-excess) overland flow and infiltration-excess (Hortonian) overland flow (with the former more dominant), as well as subsurface stormflow (especially from pipes). Complimentary hydrochemistry work later published by Elsenbeer *et al.* (1995b) and Elsenbeer and Lack (1996) confirmed the above preferred pathways, but highlighted their complex, temporal as well as spatial variability in occurrence. Similar conclusions emanated from the Babinda study (Bonell *et al.*, 1998; Elsenbeer *et al.*, 1994b, 1995a) where saturation overland flow is dominant during the higher intensity components of major storms occurring within the cyclone-prone, wet season. Otherwise subsurface stormflow is the most persistent vector. This work also highlighted the occurrence of greater volumes of 'new' or 'event' water occupying the storm hydrograph (in comparison with temperate areas) which also has obvious implications for nutrient cycling studies in terms of rapid transfer of some of the input of elements.

One has also to view the preferred flow pathways as being a dynamic phenomenon both in space and time, which are closely linked with the movement of rain patterns of different intensities at the mesoscale (~10^4 km^2) (Bonell with Balek, 1993; see example in Bonell *et al.*, 1998). In the Babinda study, for example, during the passage of intense rain (of high equivalent hourly intensity) in the monsoon, saturation overland flow is the preferred flow pathway in terms of magnitude. When rain intensities relax, subsurface stormflow becomes more dominant, although saturation overland flow can continue in some areas (Bonell *et al.*, 1991).

The study of Herwitz (1986) within the nearby Bellender Ker range did not monitor the runoff process in detail, but measured soil hydraulic properties were in the same order of magnitude as those reported from the Babinda study. It was deduced that once again saturation overland flow prevailed in this environment during the monsoon season supplemented by infiltration-excess overland flow from concentrated stemflow at the base of trees. It is worth mentioning that the top of Mt. Bellender Ker (annual rainfall, 8,065 mm) holds the record 24 h measured rainfall for

Australia of 1,140 mm during tropical cyclone 'Peter' in January 1979 (Bonell, 1991). During the same event 205 mm alone was manually measured in one hour, and within the foothills below was observed "*a sheet of water (overland flow) of approximately 15 cm deep*" emanating from the forest (personal communication, Australian Telecom, 1979).

Recent work by L∅rup (1998) in the East African Highlands provides a significant contrast with the above. As indicated, overland flow is rarely observed on the steep forested slopes due to the existence of very porous and deeply weathered soils. Consequently there is no statistical correlation between rainfall intensities and the storm runoff (quickflow) coefficient. Thus on an annual basis, quickflow is only 3-5% of annual rainfall. More significantly, such quickflow percentages were closely correlated with the equivalent percentage of riparian areas of the three catchments investigated by L∅rup (1998). Further, the more accessible groundwater within these riparian zones is available to meet transpiration demand. A consequence is lower, annual delayed flow volumes from the forested catchment, compared with those converted to subsistence farming. On the upper slopes, actual total evaporation is limited by soil moisture deficits in both the forested and cultivated catchments. These volcanic soils are capable of storing volumetrically only 0.1–0.15 $m^3 m^{-3}$ of soil water between field capacity and wilting point. In addition, about 80% of tree roots are less than 0.8 m. in depth. As a result, the ability of even the forest to access the more deeper, permanent groundwater is also limited (L∅rup, 1998).

Overall the estimated water balances of L∅rup (1998) were very similar to those reported earlier by Blackie (1979) from elsewhere in the East African Highlands. Consequently, the results from the earlier studies may not be as "exceptional" or "atypical" (L∅rup 1998) as previously suggested (Blackie 1979, Bruijnzeel 1989).

Hydrochemistry-Hydrometric Linkages of Storm Runoff Hydrology

During the course of reviewing the hydrochemistry-hydrometric linkages of storm runoff hydrology in the Babinda and Peruvian studies, Bonell and Fritsch (1997) highlighted several issues. These studies belong to the minority of humid tropical investigations where hydrochemistry (use of environmental tracers) has been closely linked with a previous (or current) hydrometric investigation in order to develop the appropriate hypotheses as well as better understanding the mechanisms of hillslope storm runoff delivery to organised drainage. In addition, the question of the most appropriate modelling strategies was addressed, as well as close scrutiny being given to the problems of the commonly used assumptions implicit in the mass balance equations not being met (Bonell & Fritsch, 1997). For example, the appropriate rainfall signature (concentration of selected environmental isotope or non-isotope tracer) to be selected for inputting into the mass balance equation needs some *a priori* knowledge of delivery times of overland flow. When the temporal signature of rain (using environmental deuterium) graphically 'crosses' the corresponding stream signature for a selected time lag, the 'new' water contributions can exceed 100 per cent in the calculations which is, of course, physically impossible. In addition, temporal variability of soil water and groundwater concentrations were indicated as more significant than usually assumed (Bonell *et al.*, 1998) which immediately violates the assumption of constant concentrations in both these parameters within the two- and three-component mass balance equation (Bonell & Fritsch, 1997). Elsewhere Barnes and Bonell (1996) discuss an adaptation of a conceptual model, whereby the transfer processes between an upper and lower store can now be identified from a combined hydrometric-hydrochemistry approach, so that the storm chemohydrograph as well as the storm discharge hydrograph can be more satisfactorily modelled. Identification of the lower store as a deep, well-mixed groundwater body of equivalent storage volume in excess of 3,000 mm was especially significant (Barnes & Bonell, 1996). Moreover, this deep groundwater store is more connected with the surface hydrology (via macropore flow though the deep unsaturated zone) and participates directly in the storm runoff generation process (Bonell *et al.*, 1998). Consequently, this led to the suggestion that many rainforests (in regions with a marked dry season) are underlain by such permanent groundwater bodies of substantive volume to ensure their survival during drought (Bonell, 1998a). The study of L⌀rup (1998) provides an exception.

The above findings, however, are geographically very limited and our knowledge of the runoff process therefore remains rudimentary. The recent work in several experimental catchments by Malmer (1993,1996) and co-workers (Grip *et al.*, 1994; Malmer & Grip, 1994) in Sabah (annual rainfall 3,200-3,500 mm) serves to emphasize the need for such caution. For example, within the control (undisturbed) catchments, the occurrences of overland flow were more restricted during this study period and only accounted for 2.9 per cent of total rainfall in a wet year because of the high infiltrability of the soils and prevailing rain intensities. Paradoxically only 26-30 per cent of the total runoff occurred as baseflow from the control catchments and hydrograph responses to storms were rapid. Subsurface stormflow in the top 0.1 m of soil seemed to be the principal flow path (Malmer, 1996). As expected, infiltration-excess overland flow becomes important over disturbed soils (such as tractor tracks). When concerning selected environmental tracers in the control catchments, the lack of surface runoff contributed to the lack of differences in concentration of dissolved loads between quickflow and delayed flow, except for selected elements which were correlated to streamflow within the range of delayed flows (baseflow) (e.g. ammonia, positively correlated with baseflow due to high soil moisture contents leading to mineralisation and leaching; calcium, negatively correlated with baseflow through dilution during storms) (Grip *et al.*, 1994). Malmer (1996) argued that such correlations were indicators of the dependence of high baseflows on topsoil flowpaths with shorter transit times and vice versa. There were, however, changes in streamflow water quality (suspended and dissolved load) following various forest management strategies entailing disturbance as one could expect. Such changes were, however, complicated by the proportion of each catchment occupied by two distinct soil types (Haplic Aerisol and Gleyic Podsol) (Malmer & Grip, 1994).

Application of Topographic-Wetness Models

Within the context of runoff process hydrology, it is now well recognized that at a headwater drainage basin scale (≤ 10 km^2) both surface topography (Beven *et al.*, 1995) and bedrock or paleotopography (Cosandey & de Oliveira, 1996; McDonnell *et al.*, 1996), through gravity, exercise stronger control than soil heterogeneity in terms of the movement and spatial organisation of soil moisture (in the upper unsaturated zone) and groundwater (as represented by the lower saturated zone). Since the 1980s several developments in more than one version of topographic-wetness models (known as digital terrain models of runoff procedure) have emerged which, when linked with a digital elevation model (DEM) and a geographic information system (GIS) (including overlays of the geomorphology, soils and vegetation), provide a basic framework for understanding the spatial and temporal runoff sources, coupled with isolating the most sensitive areas to erosion arising from disturbance. In addition, such models provide a base for experimental design considerations.

Several detailed reviews of these digital models for runoff production, including their mathematical basis, have been presented elsewhere in several sources (e.g. TOPOG, O'Loughlin, 1990a,b; Moore *et al.*, 1991; Bonell with Balek, 1993; TOPMODEL, Beven *et al.*, 1995). More recently a special issue in *Hydrological Processes (1997), Volume 11 (No. 9)* was devoted to the applications of TOPMODEL, and included the field testing of the latter in tropical rainforest of French Guyana (Molicova *et al.*, 1997).

More recently, Vertessy and Elsenbeer (1999) used the data from the western Amazonas (Elsenbeer *el al.,* 1995b, Elsenbeer & Lack, 1996) to test TOPOG. Characterisation of the "fast" subsurface stormflow pathway, through soil pipes in particular, presented problems during their simulations. Furthermore, the representation of field decay of saturated hydraulic conductivity with depth was considered by Vertessy and Elsenbeer (1999) to require modification. Part of the problem is that the field characterisation of saturated hydraulic conductivity is undertaken at an inappropriate scale. One should not use data from soil cores when a representative estimate is realistically required at the hillslope scale at least (Bonell, 1998b). Such comments apply to both the studies of Molicova *et al.* (1997) and Vertessy and Elsenbeer (1999), and most other similar works elsewhere as reviewed by Bonell (1998b).

It is accepted, however, that the hydrological parameterisation of the majority of headwater catchments ranges from minimal to non-existent which preclude the application of the more sophisticated aspects of these models. Nonetheless with the availability of good topographic information, these models can provide primary attributes such as elevation and slope from which it is then practical to develop secondary (or compound) attributes and indices that describe the spatial variability of specific hydrological processes occurring in the landscape (Moore *et al.*, 1991). Such indices refer to the topographic index of TOPMODEL and the wetness index of TOPOG.

THE ROLE OF REFORESTATION OF DEGRADED LAND WITHIN THE CONTEXT OF A CONTROVERSIAL HYDROLOGY ISSUE

There is a growing realisation that, with the decreasing availability of 'virgin' tropical forest, more attention needs to be given to the rehabilitation (through reforestation) of degraded and/or former forested land. The area of such land continues to expand in response to escalating socio-economic pressures on the remaining tropical forest resource base. Allied with this land management issue is a controversial point in hydrology. There has been considerable publicity within the humid tropics focusing on the linkage between increased flooding and decreased 'dry' weather flow arising from forest removal. Such publicity is not supported by the existing, but limited in number, controlled experimental catchments in the humid tropics (Bonell with Balek, 1993). The linkages between the intensity of land degradation, infiltration rates and prevailing rainfall intensities were, however, put forward as requiring more detailed attention (Bruijnzeel, 1989; Bonell, 1993,1998a,b). Such aspects especially relate to landscapes of long occupancy which have so far not been investigated by controlled experiments (Bruijnzeel, 1989) using the traditional, paired catchment approach (Hewlett *et al.*, 1969). Sandström (1995, 1996, 1998), however, recently presented field evidence from the sub-humid, central East African Highlands of Tanzania (annual rainfall 807 mm y^{-1}) which reveals that the most vulnerable areas to deforestation were "steep slopes which consisted of fine textured soils that enhanced infiltration-excess overland flow during storms". The associated deep percolation to groundwater was reduced because of the loss of macropores (associated with forest roots) by the development of surface soil crusts from raindrop compaction and trampling from overgrazing. The latter drastically reduced infiltration, and induced erosion and land degradation from the enhanced occurrence of infiltration-excess overland flow, in the absence of soil conservation measures (Sandström, 1995, 1996, 1998).

It is suggested that two approaches should be implemented. Initially, a preliminary survey of soil hydraulic properties linked with various rainfall parameters should be undertaken on the lines described for the UNESCO IHP/Karnataka Forest Department/National Institute of Hydrology (Belgium) project in the Western Ghats (UNESCO, 1997; Bonell & Molicova, 2003). In this way the most appropriate hypotheses can be established in preparation for a multiple, controlled drainage basin experiment or second stage 'paired catchment' approach. This second stage is a reverse of the traditional 'calibrate, cut and publish' approach in favour of studying the long-term hydrological response to reforestation (using different tree planting strategies) of existing degraded landscapes on the lines called for elsewhere (Bonell, 1993; Bonell & Molicova, 2003). In this case, the 'control' catchment should continue to remain in degraded condition. As described by Bonell and Molicova (2003) the use of digital terrain models of runoff procedure would be an integral part of the second stage of field experimentation in terms of planning the most appropriate reforestation strategies as well as contributing to hydrological design considerations.

SUMMARY OF IMPACTS ON TOTAL WATER YIELD, QUICKFLOW AND DELAYED FLOW

Because there has been no controlled experimental catchment programmes within TMCF and also no comprehensive programmes of process-oriented studies; one can only infer some of the consequences of forest conversion on the streamflow components. As suggested earlier, the commonly held notion is that a combination of additional CW inputs (occult precipitation) and low total evaporation rates leads to a favourable water budget for downstream water supply (Zadroga, 1981). Thus forest conversion to agriculture or pasture would negate the continued additions of 'occult' precipitation and, therefore, reduce total catchment yields (Zadroga, 1981).

Such alleged beliefs are dependent on the ability of the "disturbed" soils to retain their previous infiltrability after forest conversion (see previous section), and the relative magnitudes of CW (horizontal interception) and the total evaporation associated with the new vegetation cover (Bruijnzeel & Proctor, 1995). Total evaporation from crops or grass in the montane tropics approximates the transpiration by forest (Bruijnzeel, 1990), "so the critical component is the magnitude of occult" (CW) precipitation (which is in the order of 5 to 20% of incident rainfall). At other less favourable locations, the hydrological impacts of tall forests (e.g. Cavelier *et al.*, 1997) and the absorbtion capacity of epiphytes (reviewed in Bruijnzeel & Proctor; 1995) produce much lower throughfall percentages of annual precipitation. An additional factor is the enhanced wet canopy losses from advected energy (Schellekens *et al.*, 1998) which potentially offset the overall impact of CW inputs.

The preceding considerations indicate that the alleged impact of TMCF conversion automatically leads to reduced total catchment water yields is too simplistic. One might suggest "with caution" that in selected TMCF where occult precipitation is high, a reduction in total water yield can be expected on conversion. In contrast, if 'occult' inputs are only relatively small to negligible then work in East Africa, for example (Blackie *et al.,* 1979), suggests that water yield will increase following savings in transpiration from the removal of the deeper-rooted forest. The latter is the traditional conclusion from controlled experiments (Bosch & Hewlett, 1982) whereby total water yield increases mostly due to corresponding increases in delayed (dry weather flow). Such notions are also dependent on the magnitude of land degradation linked with surface infiltration capacities (as was highlighted in the previous section), whereby increases in the quickflow component could dominate the change in the water balance. In addition, as noted by Malmer and co-workers (Malmer, 1996), the proportion of drainage basins compacted by roads and snig tracks during logging or forest conversion is a critical factor on whether the resulting infiltration-excess overland flow is of sufficient magnitude to influence the quickflow component. The latter is as much dependent on whether sound logging (or forest management) practices are adopted. Such conservation measures include the spacing of road drains and the planning of logging tracks. If the infiltration-excess overland flow is directed on to slopes retaining a high infiltrability, then the preceding steps will reduce the contributions from this overland flow component into organized drainage.

A recent study by Brown *et al.* (1996) in Honduras and Guatemala provides some evidence for a reduction in streamflow following forest conversion, although the period of record was only a few months. Moreover, there were indications of the deforested basins being more responsive to storms (Brown *et al.* 1996) due to changes in the surface infiltration properties, on the lines described above. As the authors acknowledge, however, these results are only preliminary and the fact that such comparisons cannot be made under controlled experimental conditions (using the paired catchment approach, Hewlett *et al.,* 1969) requires some caution. Another aspect is that Central America and South America are directly affected by climate variability phenomena such as the El- Nino Southern Oscillation (ENSO). Separating the effects of the latter from anthropogenically-induced land-use change impacts requires preferably long-term hydrological records before firm conclusions can be made.

CONCLUSION

Insufficient attention has been given to the establishment of long-term, controlled experimental catchments within montane rainforest (the UK - East African work is the exception, Blackie *et al.*, 1979) especially in the higher elevated areas where considerable additional inputs from 'occult' precipitation are received. These areas are a very important source of water supply of high quality for downstream users, and as part of any new initiatives, an integrated programme of process hydrology needs to be implemented for a better understanding of "within" drainage basin effects arising from forest manipulation or conversion. This work has outlined the key issues in process hydrology, some of which have been linked with spatial models. Finally the work has called for greater attention being given to the hydrological aspects of degraded montane lands and their rehabilitation.

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RAINFALL INTERCEPTION BY LOWLAND TROPICAL RAINFOREST IN AIR HITAM, SELANGOR, MALAYSIA

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ABSTRACT

A study of interception by lowland tropical rainforest was conducted at Air Hitam forest in Selangor, Malaysia. Tree stratification was analysed by profile diagram. Precipitation, stemflow and canopy drip were measured *in situ.* Fifteen species of trees with DBH (diameter at breast height) above 10 cm were identified with density of 540 ha^{-1}. The dominant species was *Shorea leprosula* (density 160 ha^{-1}). The stratification of trees was continuous. The forest floor was covered by about 48.5% of vegetation which comprised creepers, herbs, seedlings and climbers. Throughfall varied between 0 and 91.3% and stemflow between 0 and 34%. There was a significant correlation between rainfall and canopy drip, and between rainfall and stemflow. The interception varied between 0 and 71.7%. However, the increase in interception was happening only at the beginning of rainfall until interception became saturated. The canopy saturation point was calculated at 15 cm^3, whilst the point of equilibrium between interception and canopy drip was calculated at 45 cm^3.

INTRODUCTION

Two of the characteristics of tropical rainforest are the statification of trees and the high species diversity. Another characteristic is the rainfall interception by the tree canopy. Naturally, forest vegetation is an important factor to reduce soil erosion. Rainfall interception by the forest canopy reduces the kinetic energy and velocity of raindrops reaching the soil surface of the forest floor (Singh, 1987). The shape and size of the canopy together with its optic characteristics play an important role in the structure and function of ecosystems. These characteristics bring changes on the canopy atmosphere. Most of the processes occuring in the ecosystem, such as productivity, succession and changes in atmospheris ecosystems, are influenced by the architecture of the canopy (Hutchion *et al.,* 1986)

Rainfall on the canopy involves interception, canopy drip and stemflow. Interception is the total amount of rainwater that can be held by the forest canopy and eventually will determine the amount of water reaching the forest floor (Teoh, 1974). Rainwater that drops from the canopy to the forest floor is termed canopy drip (Yong *et al.,* 1984). The amount of water flowing through the stems is stemflow (Scatena, 1990). The total amount of rainwater that reaches the ground (N) is the summation of the canopy drip and stemflow. Total rainfall, P, minus N is the total interception by the canopy (Calheiros de Miranda & Butler, 1986).

Studies on interception, canopy drip and stemflow have been conducted by many workers. However, many of the published works were concerned with temperate forests (e.g. Aston, 1979; Florida & Saplaco, 1981; Calder, 1986; Pethak *et al.,* 1989). Although works on tropical rainforest have also been published (e.g. Clegg, 1963; Debral & Subba Rao, 1968; Jackson, 1975; Herwitz, 1985; Pudjiharta & Kudeng Sallata, 1985), works on the lowland tropical rainforest are scanty (e.g. Manokaran, 1979; Ahmad Shah *et al.,* 1992). Furthermore, no work has been published on the relationship between branching system and stemflow. Hence the aim of this study is to find, firstly, the percentages of rainfall interception, canopy drip and stemflow at a lowland tropical rainforest in Air Hitam, Puchong, Selangor, Malaysia; and secondly to find the relationship between size of the canopy, branching system and stem diameter with stemflow.

STUDY AREA

The study area was located at Air Hitam Forest Reserve, in Puchong, Selangor, Malaysia, at $101^{0}\,30^{'}$ - $102^{0}\,0^{'}$N and $3^{0}\,0^{'}$ – $3^{0}\,3^{'}$ E, 25 km southwest of Kuala Lumpur (Figure 1). The altitude of the study area is between 50 and 150 m above sea-level (lowland tropical rainforest), and the soil is sandy loam. The climate of the area is wet, with annual rainfall about 2,215 mm (Figure 2). The mean temperature is 27.8 ^{0}C with mean maximum is 32.7 ^{0}C and mean minimum is 22.5 ^{0}C. Mean sunshine is 5.9 h day^{-1} with evaporation about 4.2 mm and relative humidity is 95%.

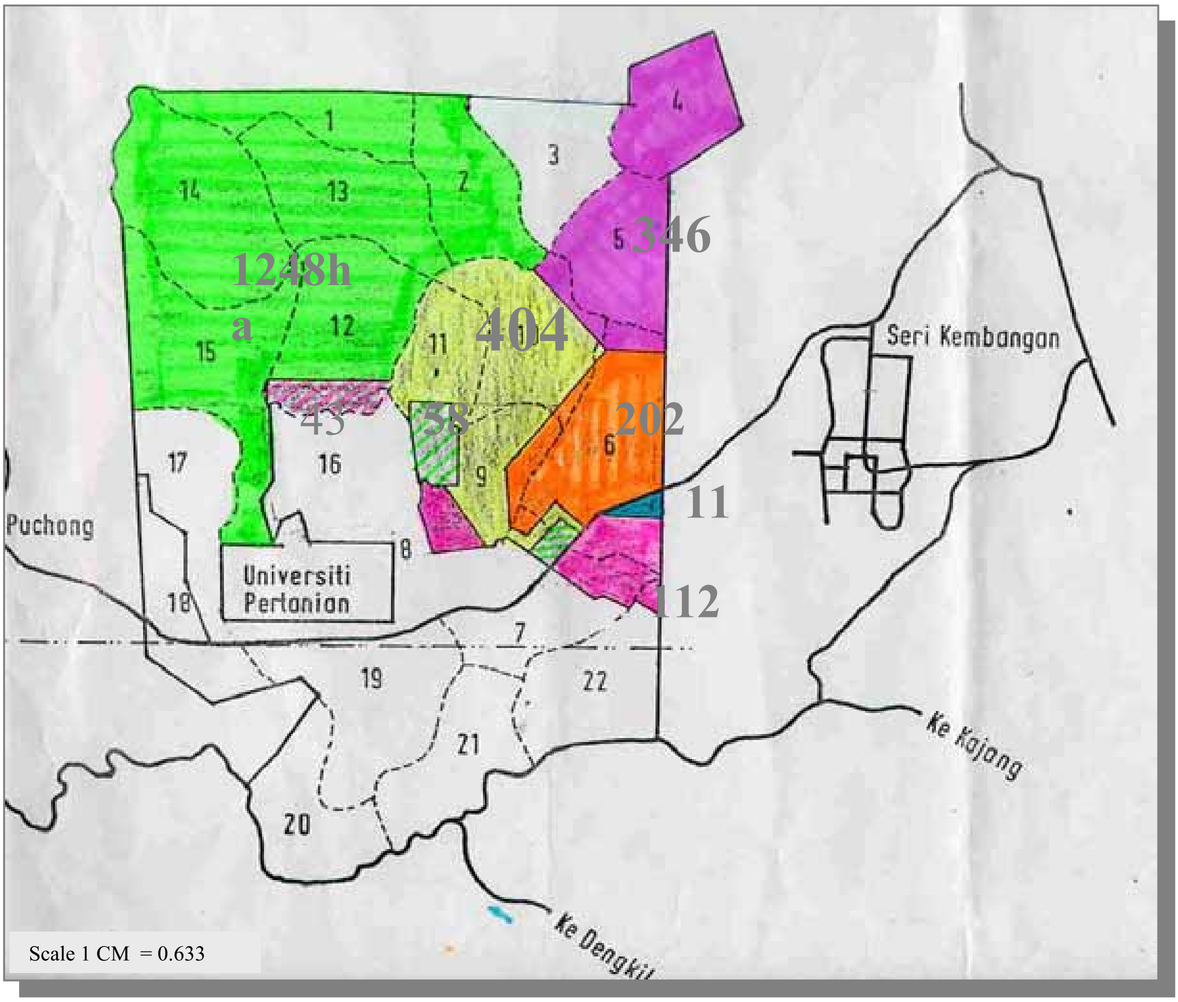

Figure 1 : Study area at Air Hitam Forest, Selangor, Malaysia

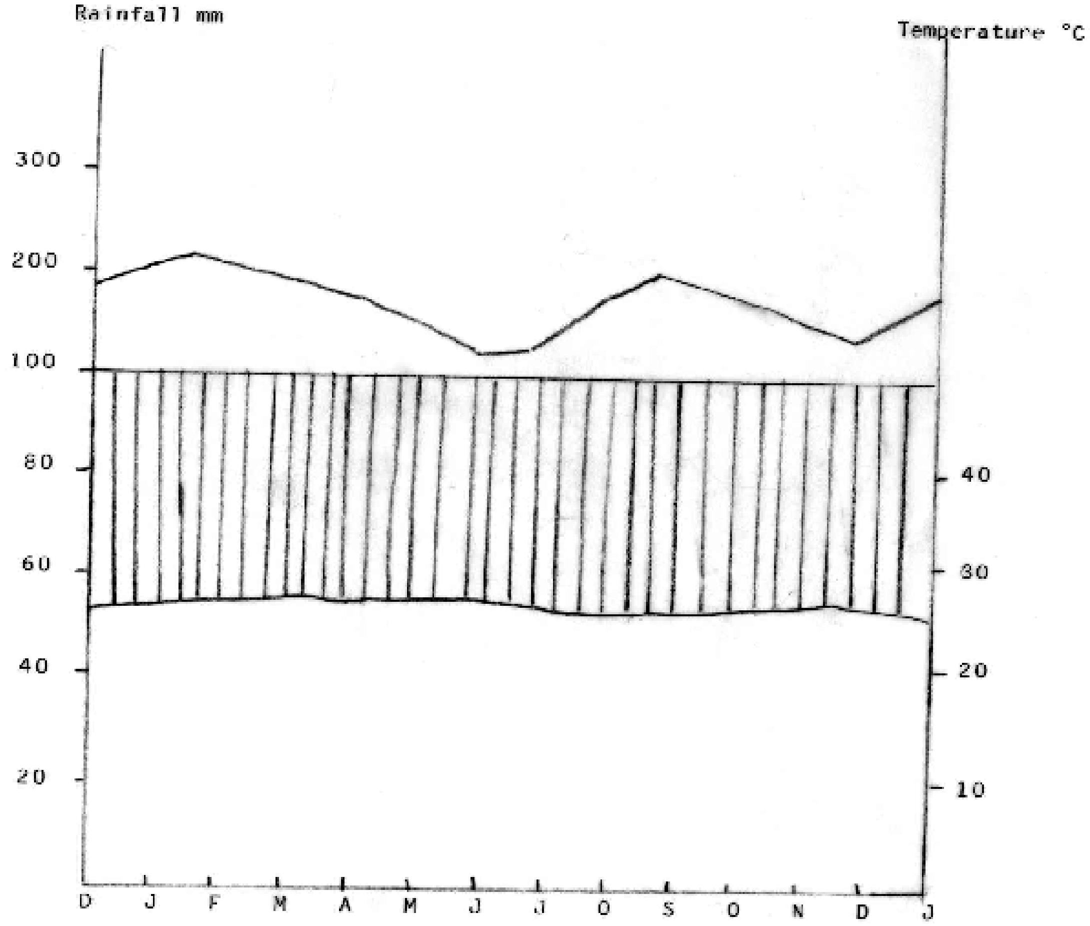

Figure 2 : Climatic diagram of the study area

MATERIALS AND METHODS

Vegetation Analysis: Tree Stratification

Five plots, each measuring 50 X 10 m, were chosen randomly at the study area. Each plot was divided into five subplots each measuring 10 X 10 m. Tree stratification was analysed by profile diagram described by Richards (1957). All trees having diameter at breast height (DBH) > 10 cm were identified and recorded. The height of each tree in esch plot was determined by a hagameter. Crown projection of each tree was measured based on the four ordinates on the ground.

Soil Edaphic Factors

Soils were sampled from each subplot. Each soil sample measuring 10 x 10 x 10 cm was sampled using hand shovel, brought back to the laboratory and used for the analysis of soil texture. Ground slope was also measured in each plot.

Measurement of Precipitation, Canopy Drip and Stemflow

Precipitation was measured using rain-gauge of Scatena (1990). The rain-gauge was placed in an open space at the study area. Precipitation per unit area was calculated by the following formula:

$$VG = V/L \times P \text{ cm}^3$$

where, V = volume of rainwater collected in the rain-gauge in cm^3
L = area of rain-gauge in cm^2
P = total area of the plot in cm^2

Canopy drip was measured using the apparatus described by Scatena (1990) with slight modification. Instead of a round funnel as suggested by Scatena (1990), we used a square funnel supported by a wooden frame. The funnel was fixed at 0.5 m above the ground and a plastic gallon container was placed underneath the funnel for collection of water. There were four canopy drip collections fixed in each plot. The amount of water collected was measured using a measuring cylinder. Canopy drip was calculated by the following formula:

$$VTF = Z/S \times P \text{ cm}^3$$

where, Z = the volume of rainwater collected by canopy drip apparatus
S = total surface area in canopy drip apparatus
P = the total area of plot

All trees having DBH > 10 cm were sellected for the stemflow study. The apparatus used in this study was based on Ford and Deans (1978), Yong *et al.* (1984) and Scatena (1990) with slight modifications. An alluminium collar of 10 cm width was fixed on the stem by means of silicon cement. The alluminium was fixed at an angle of 40^0 to the horizontal circumference and had an opening of 10–15 cm to the stem. The lower end of the collar was connected with an alluminium funnel and a rubber tubing leading into the plastic container. The mouth of the container was tightly covered to prevent water from outside entering the container. The amount of water collected was measured using a measuring cylinder. The total stemflow per unit area was determined using the formula:

$$VT = VS \times A/AS$$

where, VT = total volume per unit area
VS = volume of water collected after each rainfall
A = total study area
AS = canopy area of the tree concerned

Interception

The total volume of rainfall intercepted by plant canopy is termed interception. Interception can be calculated following the formula:

$IT = VG - (VTF + VT)$ (Debral & Subba Rao, 1968; Shahruddin, 1978)

where, IT = total volume of rainfall intercepted
VG = total volume precipitation
VTF = total volume of canopy drip
VT = total volume of stemflow

RESULTS

Vegetation Analysis : Tree Statification

Fifteen species of trees with diameter at breast height (DBH) > 10 cm were identified in the study area (Table 1). The tree density was 540 ha^{-1}. *Shorea* was the dominant genus with 5 species and the highest density among the *Shoreas* was 160 trees ha^{-1} for *S. leprosula*. *Ixonanthes icosandra* had the second highest density with 60 trees ha^{-1}.

Table 1: Density of trees recorded at the Air Hitam Forest

		Density (number / ha)
Famili:	Anacardiaceae	
1.	*Glutta elegens*	20
Famili:	Apocynaceae	
2.	*Dyera costulata*	20
Famili:	Burseraceae	
3.	*Canarium spp.*	40
4.	*Santiria levigata*	20
Famili:	Dipterocarpaceae	
5.	*Anisoptera spp.*	20
6.	*Shorea acumminata*	40
7.	*Shorea leprosula*	160
8.	*Shorea ovalis*	40
Famili:	Erythoxylaceae	
9.	*Ixonanthes isosandra*	60
Famili:	Leguminosae	
10.	*Ormosia parviflora*	20
Famili:	Olacaceae	
11.	*Ochanostachys omentaceae*	20
Famili:	Polygalaceae	
12.	*Xanthophyllum spp.*	20

Famili:	Rhizophoraceae	
13.	*Pllacalyx cardianus*	20
Famili:	Sapindaceae	
14.	*Pometia pinnata*	20
Famili:	Thymeliaceae	
15.	*Aguilaria malaesensis*	20
Jumlah		540

Tree stratification was studied by profile diagram method. Figure3 shows the profile diagram of trees at the study area as continuous. The first stratum was occupied by trees reaching the height of 30–40 m, i.e. *S. leprosula, S. accuminata* and *I. icosandra.* Many of these trees have monopodial crowns and straight stems up to the first branching (+ 18 m). The second stratum was occupied by trees with height of 20–30 m. Some of the tree species occupying this stratum was similar to the first stratum, i.e. *S. leprosula* and *I. icosandra.* Other species were *Anisoptera* sp.*, Dyera costulata* and *Omosia parviflora.* These trees have straight stems and monopodial crowns.

The third stratum was occupied by trees with height of 10–20 m. They were the young trees of the first and second strata species.

Precipitation, Canopy Drip, Stemflow and Interception

Figure 4 shows the precipitation, canopy drip and stemflow of the study area. The highest precipitation was measured in March and the lowest in August. Canopy drip varied between 0 and 91.3%, whilst stem flow varied between 0 and 3.42%. The interception varied between 0 and 71.7%. There was a significant correlation between rainfall with canopy drip, and between rainfall and stemflow. Increase in rainfall naturally increased the volume of water intercepted, until interception became saturated.

Figure 5 shows the relationship between the volume of water collected for rainfall with interception and with canopy drip. The point where canopy drip is saturated is known as *canopy saturation*, and it was at 15 cm^3 rainfall. The point where interception equals canopy drip is known as *point of equilibrium between interception-canopy drip,* and it was at 45 cm^3 rainfall. The mean interception of the area was 29.10%, stemflow 1.03% and canopy drip was 69.87% (Figure 6).

The relationships between diameter20 of trees, canopy area, the number of branches and the total volume of stemflow at the study area, Air Hitam Forest, are presented in Table 2.

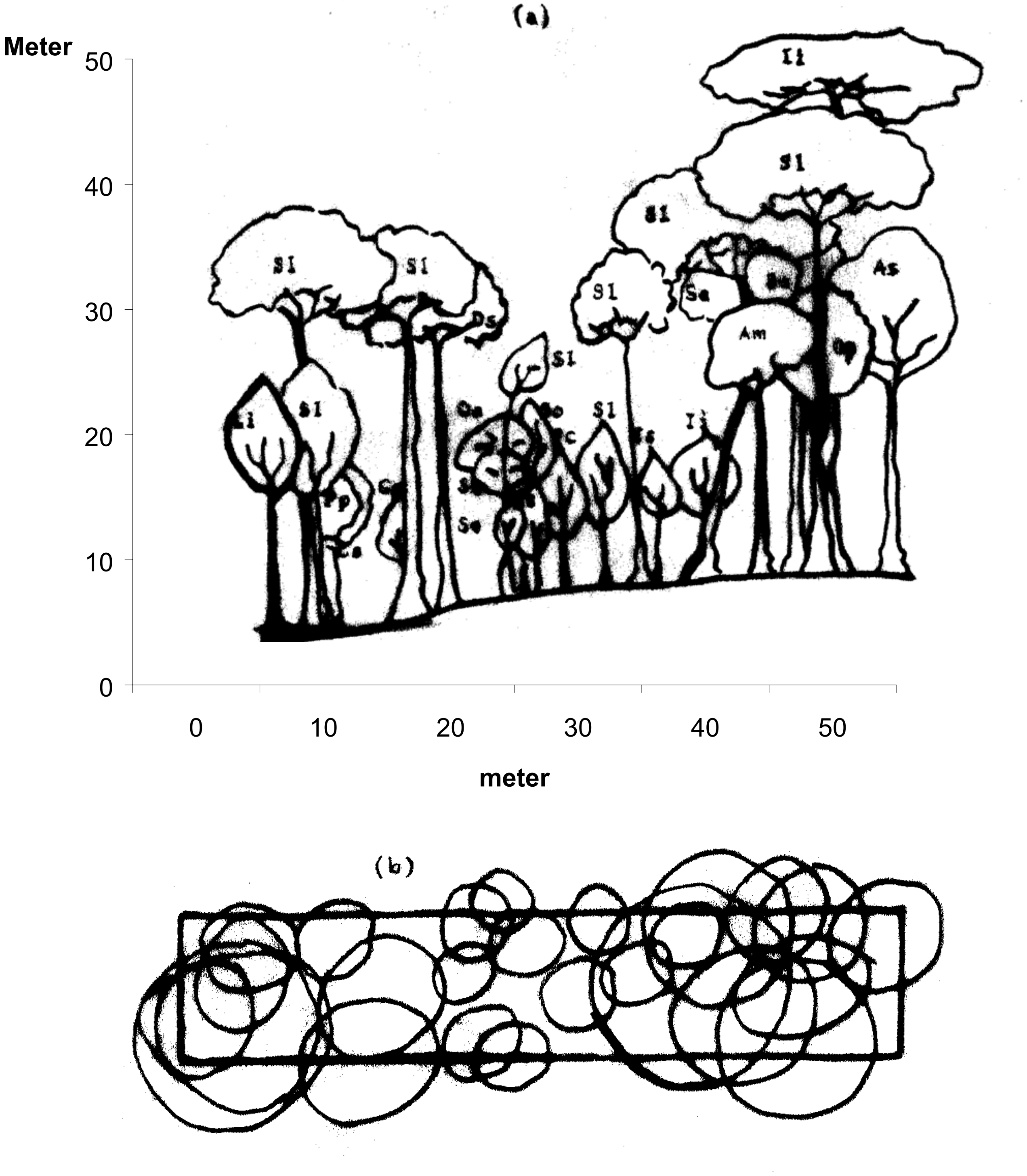

Figure 3. Profile diagram and crown projection of tree at Air Hitam Forest, Selangor, Malaysia

Am	Aquilaria malaccensis	As	Angioptera sp
Cs	Canarium sp.	Dc	Dyera costulata
Ge	Glutta elegens	Ii	Ixonanthes icosandra
Oa	Ochanostachys amentaceae	Op	Ormlosia parviflora
Pc	Pellacalyx cardianus	Pp	Pometia pinnata
Sa	Shorea acuminata	Se	Santiria laevigata
So	Shorea ovalis	Sl	Shorea leprosula
Xs	Xanthophyllum sp.		

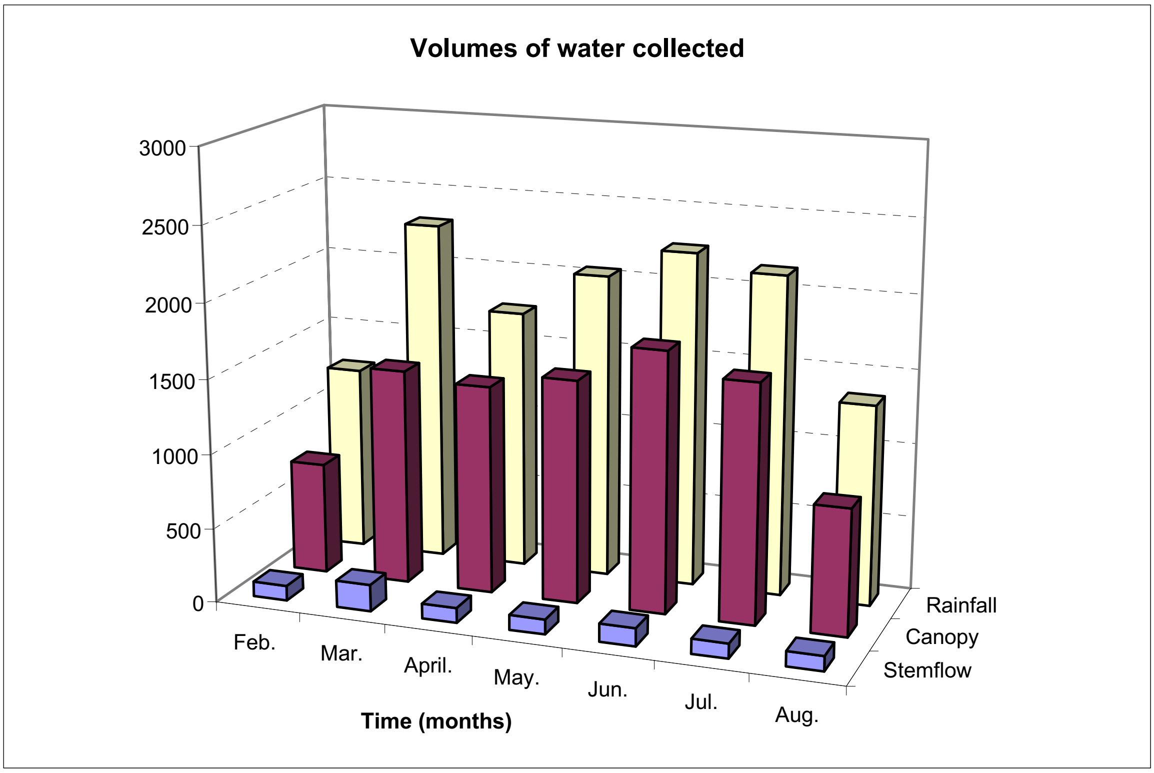

Figure 4 : The presentation of precipitation. Canopy drip and stemflow of Air Hitam Forest, Selangor, Malaysia.

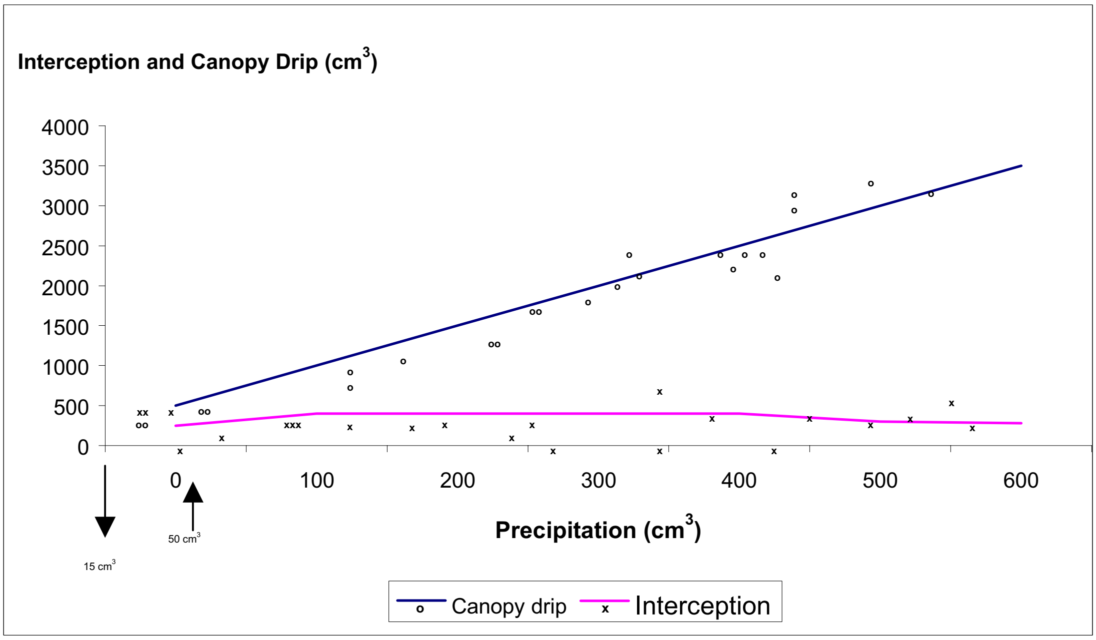

Figure 5 : Precipitation versus interception and canopy drip of Air Hitam Forest, Selangor, Malaysia.

DISCUSSION

The results show that the average values of interception, canopy drip and stemflow were 29.10, 69.87 and 1.03% respectively. These magnitudes are slightly higher than those of other lowland tropical rainforests. For example, Manokaran (1979) reported that the average percentage of interception at Pasoh Forest Reserve in Negeri Sembilan, Malaysia, was 21.80%, while Ahmad Shah *et al.* 1992) reported that the percentage of interception at Ulu Gombak Forest Reserve was 22.10%. The profile diagram (Figure 3) shows that the vertical structure of trees exhibits three layers of canopy, the emergent, main canopy and the lower canopy. These canopy layers could also increase interception (Ahmad Shah *et al.,*1992). If the first stratum is saturated with water, rain can be intercepted at the lower canopy (Calheiros De Miranda & Butler, 1986).

Generally, interception in tropical rainforest is higher compared to temperate forest. For example, the interceptions for *Eucalyptus melanophloia* forest and maple plantation were 11.0 and 15.0% respectively (Pebble, 1980; De Miranda & Butler, 1986), i.e. about half the values reported for tropical rainforest. Low interception in

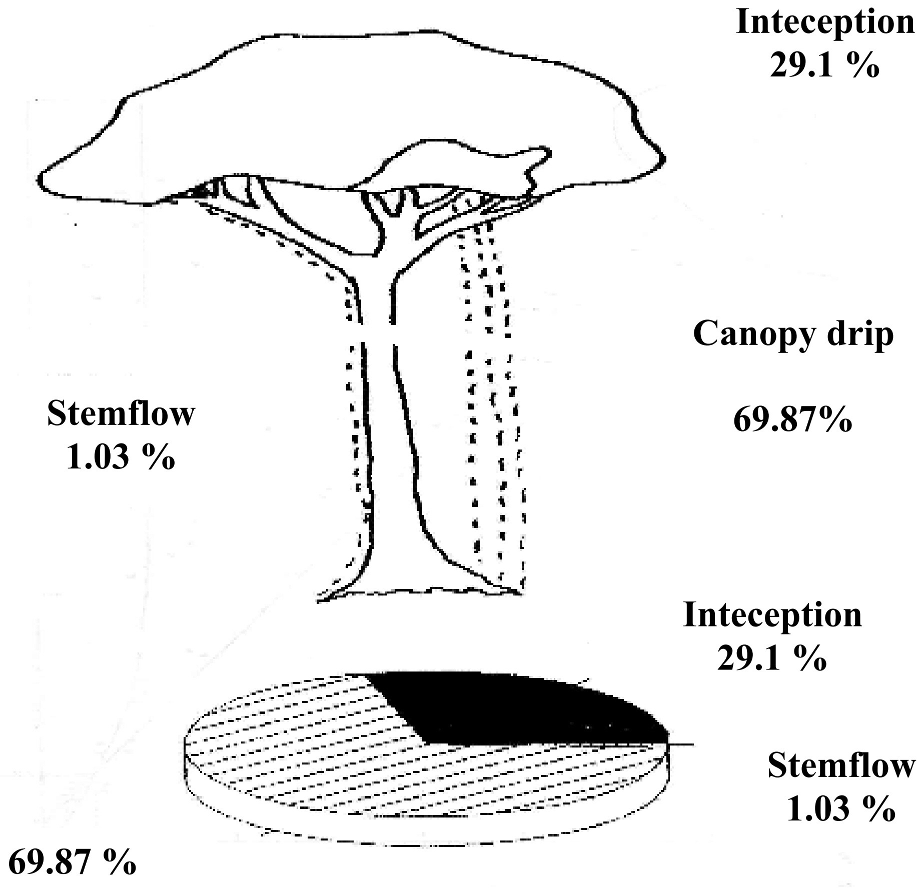

Figure 6: Percentage of interception. Crown drip (canopy drip and stem flow of the study area at Air Hitam Forest, Selangor, Malaysia

temperate forest is probably due to the temperate forest being less diverse with less vertical stratification (Scatena, 1990).

Branching system and size of tree have also been reported to be factors that influence interception. Bigger trees with massive branching systems increase the percentage of interception (Herwitz, 1985). *Shorea leprosula* was the dominant tree species in the study area; this species forms big and strong stems sending branches sideways to form a wide canopy (some parts of the canopy may reach more than 15 m in diameter). Ahmad Shah and Rieley (1989) reported that the morphology of plants, especially large canopy ones, also influences interception.

There was variation in canopy drip (between 0 and 100%). During heavy rainfall (March – April) canopy drip exceeded 80%. However, in February, when there was less rainfall, only 59.25% canopy drip was recorded. These results suggest that canopy drip is influenced by rainy seasons (Rowe, 1983). Canopy drip is also influenced by rainfall intensity, i.e. increase in rainfall will increase canopy drip (e.g. Zinanov, 1975; Pethak *et al.,* 1989; Scatena, 1990)

Jackson (1975) used the relationship between total volume of canopy drip and rainfall distribution to determine the canopy saturation point. In this study, the saturation point was at 15 cm^3 or 1.9 mm (Figure 5). This value is higher compared to other areas. For example, the canopy saturation point for Legeh Bisley in Puerto Rico was only 0.8 mm (Scatena, 1990); it was 0.89 for West Africa forest (Jackson, 1975). Throughfall was also influenced by the branching systems of trees at the study area. Massive branching systems form a very close canopy. Thus, during drizzle and light rain, water droplets on the canopy will be evaporated or absorbed by the plants before dropping. However, during heavy rainfall parts of plant leaves, branches, stems and boughs are saturated and all these plant parts can potentially produce canopy drip. *Shorea leprosula* has these characteristics, and this could be one of the reasons why the canopy drip of this area was considerably high compared to other forests.

The mean percentage of stemflow for the study area was 1.03%. Similar small percentages of stemflow have been reported for other vegetation types. For example, the stemflow was 0.6% for *Eucalyptus melanophloia* (Pebble, 1980), 2.0% for rubber tree (Teoh, 1975) and 2.0% for the coastal forest of New Zealand (Rowe, 1983).

There was positive correlation between the size of crown of *S. leprosula*, the dominant species of the study area, and stemflow (r = 81.83%). The crown of this species is monopodial shaped, and according to Scatena (1990), monopodial crowns contribute a substantial volume of the stemflow. Surface area of stems was also found to contribute significantly to the stemflow of *S. leprosula* ($r^2 = 0.85$). Surface area is directly correlated with stem diameter, the bigger the diameter the bigger will be the surface area. Increase in stem dameter will increase the surface area of the tree and this will increase the water flow from the canopy, branches, boughs and stems to produce a high value of stemflow.

CONCLUSION

The species diversity, stratification, surface area of the stems and the high intensity of rain contribute to the high interception of Air Hitam Forest Reserve in Selangor, Malaysia. About 29.10% of the rainfall was intercepted by the forest canopy, 69.87% of the water reached the forest floor via canopy drip and the other 1.03% flowed along the branches, boughs and stems as stemflow. From the analysis, interception, canopy drip and stemflow were positively correlated with rainfall.

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SUB-CANOPY RAINFALL AND WET-CANOPY EVAPORATION IN A SELECTIVELY-LOGGED RAINFOREST, SABAH, MALAYSIA

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ABSTRACT

Understanding the impact of the selective removal of trees from a tropical rainforest on the rate of wet-canopy evaporation and transpiration is critical to the assessment of the impact of so called 'sustainable forestry' on local climate, and the water resources potential of rivers. Accurate quantification of the changes in the wet-canopy evaporation component is, however, difficult given the extreme heterogeneity of the vegetation patchwork produced by commercial selective logging.

In order to address this issue for an area of lowland dipterocarp forest, selectively-logged some eight years prior to the study, a network of 450 throughfall gauges, plus 22 gross rainfall and 40 stemflow gauges, was installed within the 44-ha Baru Experimental Catchment (Sabah, Malaysian Borneo). Most of these gauges were located randomly within plots, themselves stratified according to the six canopy classes.

The results showed that more rainfall reached the forest floor beneath the undisturbed remnants of rainforest (i.e. the protected areas), than those patches of canopy subject to light or heavy impact. This may have been because the disturbed forest patches had a higher rate of wet-canopy evaporation (i.e. 12-18 % of gross rainfall) in comparison to the undisturbed remnants (i.e. 7% of gross rainfall). Alternatively, the difference may, at least in part, have been caused by the lower disturbed patches of vegetation being sheltered by the undisturbed forest remnants, leading to the receipt of less rainfall on their canopy surfaces.

INTRODUCTION

Wet-canopy evaporation (E_{wc}) or interception loss is the vaporisation of rainfall from wetted vegetation surfaces, and is an important component of the water budget of tropical catchments (Bruijnzeel, 1990; Black, 1996). Despite this, there is a dearth of studies on the impact of selective commercial forestry on rates and patterns of wet-canopy evaporation from tropical forests (Asdak *et al., 1*998). This study, therefore, aims to quantify the rates of wet-canopy evaporation and the remaining component of rainfall that reaches the ground as throughfall and stemflow (also called 'sub-canopy rainfall') within a lowland dipterocarp rainforest recovering from selective forestry.

RESEARCH SITE

The study area is the 44-ha Baru Experimental Catchment, situated near the Danum Valley Field Centre (DVFC) in the Malaysian State of Sabah, northeast Borneo (Figure 1). The catchment has an undulating terrain with an altitudinal range of 70 m.

The area was selectively logged in early 1989 using bulldozers and high-lead yarding, leaving the complex structure of regenerating forest patches, areas of protection forest and areas of highly damaged forest. The 'forest mosaic' within the

Baru Catchment has been classified into six categories depending on the level of forest disturbance and recovery rate (Bidin, 2001).

The study period, 1 May 1997 to 30 April 1998, coincided with the 1997/98 El-Niño Southern Oscillation (ENSO) drought. Not surprisingly, the recorded 1,520 mm of rainfall during this period was the smallest on record at the DVFC meteorological station from 1986 to 1999 (Figure 1). The longer-term average annual rainfall was 2,638 mm.

SAMPLING / INSTRUMENTATION NETWORK

The sampling network for this study includes a distribution of rain-gauges within canopy openings (min. diameter of openings was 40 m), and throughfall and stemflow gauges to measure the rainfall penetrating the forest canopy.

Rainfall Measurement

The rain-gauges installed within the 44-ha Baru Experimental Catchment are a subset of the larger network of rain-gauges within the 4-km^2 Sapat Kalisun Experimental Catchment (Bidin, 2001). There are 22 rain-gauges within openings in the Baru Catchment, comprising the 16 simple storage rain-gauges (Bidin, 2001), and six tipping-bucket rain-gauges (Figure 1).

Throughfall Measurement

Sub-canopy rainfall or net rainfall refers to the volume of rainfall that reaches the forest floor and comprises 'direct throughfall' (i.e. rainfall that falls through canopy gaps), 'leaf drip throughfall' and 'stemflow'. In this study the direct throughfall and leaf drip throughfall were measured together using 450 simple storage rain-gauges (Figure 1).

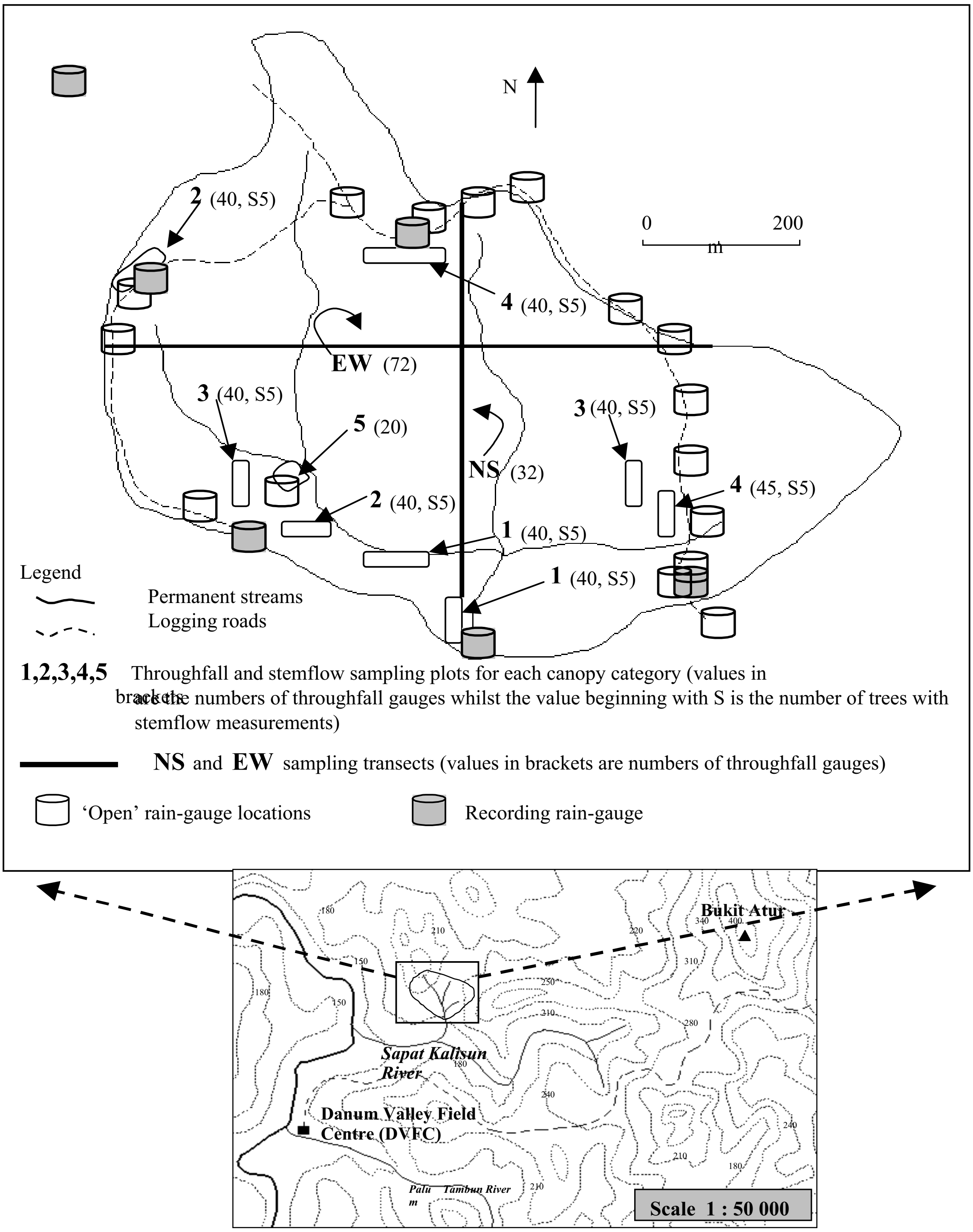

Figure 1: The 44-ha Baru Experimental Catchment (5^o 01' N and 117^o 48.75' E) showing the location of sub-canopy rainfall (throughfall and stemflow) sampling plots within canopy categories 1, 2, 3, 4 and 5. The cylinders represent the rain-gauges installed in the open canopy to measure gross rainfall (canopy category 6). See Bidin (2001) for canopy classification.

Most of the throughfall gauges were located within plots beneath clearly defined 'canopy categories'. These are (i) undisturbed forest canopy (category 1), (ii) moderately impacted forest canopy (category 2), (iii) vine-covered forest canopy (category 3), (iv) *Macaranga* spp. pioneer tree canopy (category 4), and (v) sprawler-covered canopy gap (category 5; see Bidin, 2001). Eighty to 85 gauges were installed in each of the canopy categories 1, 2, 3 and 4. Only 20 gauges were installed beneath the 'sprawlers' of canopy category 5. The sites for throughfall measurement beneath all canopy categories were located close to the five existing recording rain-gauges within the Baru Catchment (Figure 1). Two clusters (plots) of gauges (i.e. 40 to 45 gauges in each plot, except in canopy category 5) were installed for each canopy category (Figure 1). Plots were selected randomly within each of the stratified canopy categories, with the plot sizes ranging from 100 to 200 m^2.

Additional throughfall measurements were made with 105 gauges installed within mixed canopy categories found along two transects (North-South and East-West) across the Baru Experimental Catchment (Figure 1). Collectors were located approximately every 20 m along the 650-m 'North-South transect' and every 10 metres approximately along the 720-m 'East-West transect'.

The clusters of gauges within canopy categories 1, 2, 3, 4 and 5 were installed randomly at a fixed position beneath the forest canopies. Once installed, the location of all gauges within the region was surveyed using an electronic theodolite. The gauges were secured firmly in a 10-cm deep pit to keep them fixed and upright. Gauge relocation was not applied for three reasons. Firstly, the research involved a large number of gauges (typically 80 per canopy type), and therefore provided sufficient replication of experimental conditions (Hurlbert, 1984). Secondly, the forest canopies were recovering from selective logging, so throughfall characteristics may have changed with time (cf. Wong, 1991). Thirdly, geostatistical analysis of the long-term throughfall data was to be attempted, which requires a fixed location.

Stemflow Measurement

Exactly 40 trees and lianas were measured for stemflow. For canopy categories 1, 2, 3 and 4, eight trees and two lianas were measured for stemflow (Figure 1). The trees and lianas were selected randomly within each plot. Stemflow 'collars' were used to measure the stemflow. These collars were shaped out of aluminium plate, supported by 1-cm nails and sealed with a marine adhesive ('Mastik'). Silicon sealant was used to repair any leakage of the collars throughout the study period. Most stemflows were then collected volumetrically, though one gauge was continuously monitored with a datalogged 3-litre tipping-bucket device.

The total stemflow for the trees sampled is scaled to the whole plot using a survey of the basal area of all trees within each plot, i.e.:

$$\text{Total stemflow (mm)} = \frac{TA}{PA} \times \frac{SV}{SA} \qquad [1]$$

where TA = total tree basal area in plot (m^2)

PA = area of the plot (m^2)
SV = total stemflow volume collected from all sampling trees (mm^3)
SA = total basal area of sampling trees (mm^2)
(after Wong, 1991).

SPATIAL VARIABILITY OF THROUGHFALL

The spatial variability of the throughfall within each canopy category and between different canopy categories was examined.

Cumulative Throughfall at Each Gauge

Figure 2 shows the cumulative catch in throughfall measured at each of 20 collectors located along the East-West transect (Figure 1). Some sub-canopy gauges collect considerably more than the average gross rainfall for the catchment, due to some gauges being located beneath 'drip points' where branches and leaves have focused the intercepted rainfall (e.g. Rutter, 1963; Anderson *et al.*, 1969; Lloyd *et al.*, 1988; Herwitz & Slye, 1992; Black, 1996). Additionally, some of the cumulative curves cross, which indicates that the canopy characteristics change with time, due to perhaps movement by wind, growth of vines, branch fall etc.

Throughfall Variability within Each Canopy Class

Within each canopy category, the coefficient of variation (CV) in annual throughfall catch ranged from 16.2% for canopy category 1 to 30% in canopy category 5 (Table 1). The standard error in the catch was, however, small due to the large number of gauges used. The standard error can be seen to reduce exponentially as the number of randomly sampled gauges increases (Figure 3), comparable with that observed by Lloyd and Marques (1988). There were significant variations between the different canopy categories. For example, category 1, the undisturbed forest, only required 10 gauges to constrain the uncertainty (i.e. standard error) to 5%, compared with 20, 30, 16 and 35 gauges for canopy categories 2, 3, 4 and 5 respectively (Figure 3). The highly heterogeneous transects required 40 gauges for 5% sampling uncertainty. The pattern of throughfall along the East-West Transect across Baru Catchment is shown in Figure 4. The different number of gauges required to constrain uncertainty to 5% for different canopy covers suggests that throughfall in logged-over forest was much more variable than in remnants of undisturbed forest. Canopy category 5 was the most variable, followed by categories 3, 2 and 4 respectively. The lowest uncertainty for the disturbed forest blocks was for canopy 4, due to the fact that almost 80% of the trees within the plot were *Macaranga* spp. pioneer trees.

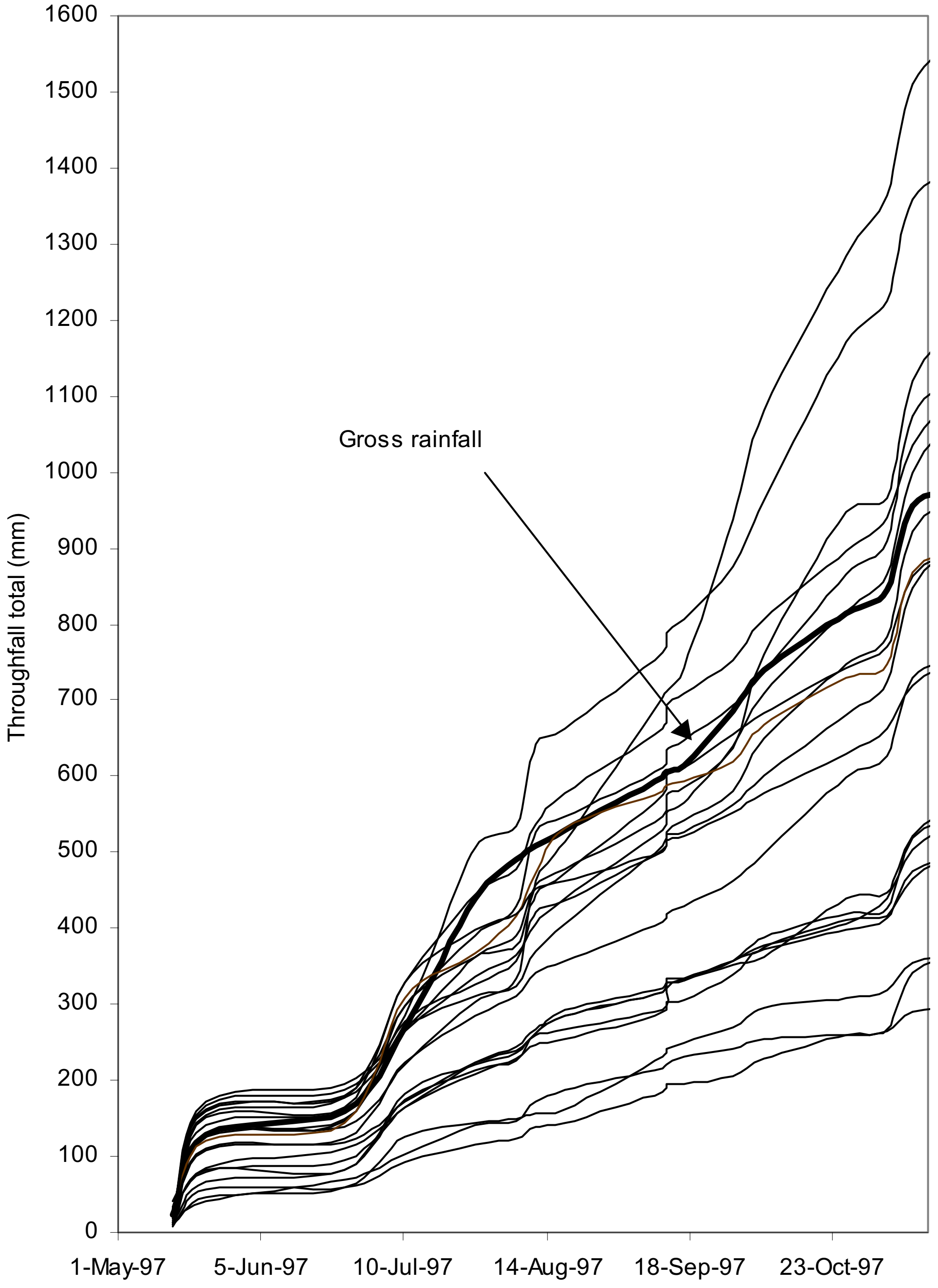

Figure 2: Throughfall mass curves for 20 gauges in the East-West transect, Baru Experimental Catchment

Over the year, the standard errors in throughfall catches were only 1.8, 2.6, 3.3, 2.0 , 7.1 and 2.7 % for canopy categories 1, 2, 3, 4, 5 and the transects respectively (Table 1).

Table 1: Sub-canopy and gross rainfall (Canopy 6) of the five canopy categories and transects in Baru Catchment during 12-month period of monitoring, 1 May 1997 to 30 April 1998. The non-parametric, Mann-Whitney U-test was used to estimate significance of mean difference.

	Canopy category					**Transects**
	1	**2**	**3**	**4**	**5**	
Gross rainfall (Pg) – canopy 6						
N	3	3	6	8	2	22
Total (mm)	1398.0	1431.0	1417.7	1417.9	1453.3	1413.0
σ (mm)	138.6	22.7	58.4	94.5	19.2	100.1
CV%	9.9	1.6	4.1	6.7	1.3	7.1
σ_x (mm)	80.0	13.1	23.9	33.4	13.6	21.3
Diff. In mean^1	-	Ns	ns	ns	ns	ns
Net rainfall (Pnet)						
Throughfall						
N	80	80	80	85	20	105
Total (mm)	1285.9	1150.2	1157.1	1241.9	1205.6	1201.3
σ (mm)	208.0	262.5	340.0	234.2	383.3	335.0
CV%	16.2	22.8	29.4	18.9	30.0	27.9
σ_x (mm)	23.3	29.4	38.0	25.4	85.7	32.9
Diff. In mean^2	$P < 0.001$					
Diff. In mean^3	$P < 0.001$	Ns				
Diff. In mean^4	$P < 0.1$	$P < 0.1$	$P<0.05$			
Diff. In mean^5	ns	Ns	ns	ns		
Diff. In mean^6	ns	Ns	ns	ns	ns	
%Tfall (%)	92.0	80.4	81.6	87.6	83.0	85.0
Stemflow						
N	10	10	10	10	-	-
Total (mm)	15.0	27.0	14.0	5.9	14.0*	15.5**
σ_x (mm)	2.4	6.2	4.6	1.9	3.8*	3.8**
%Sflow (mm)	1.1	1.9	1.0	0.4	1.0	1.1
Pnet total (mm)	1300.9	1177.2	1171.1	1247.8	1219.6	1216.8
σ_x total (mm)	25.6	35.6	42.6	27.3	89.5	36.6
Comparison of gross and net rainfall						
Diff. mean (Pg vs Pnet)	$P < 0.1$	$P<0.05$	$P<0.005$	$P<0.05$	ns	$P<0.05$
Pg - Pnet (mm)	97.1	253.8	246.6	170.1	233.7	196.2
$\sigma_{compound}$ (mm)	249.9	263.5	344.9	252.5	383.8	349.6
Diff. Pg – Pnet^2	$P < 0.05$					
Diff. Pg – Pnet^3	$P<0.001$	Ns				
Diff. Pg – Pnet^4	ns	Ns	$P<0.05$			
Diff. Pg – Pnet^5	ns	Ns	ns	ns		
Diff. Pg – Pnet^6	ns	Ns	ns	ns	ns	
%Pnet (%)	93.1±7.5	82.3±3.1	82.6±4.4	88.0±4.2	83.9±6.9	86.1±3.9
Tfallgauges > Pg (%)^7	28.8	13.8	20.6	23.1	20	34.7

Cont.'d…

Notes:
[1] level of significance for difference with canopy category 1
[2] level of significance for difference with canopy category 2
[3] level of significance for difference with canopy category 3
[4] level of significance for difference with canopy category 4
[5] level of significance for difference with canopy category 5
[6] level of significance for difference with transect canopy
[7] throughfall gauges recorded rainfall totals more than gross rainfalls
^{ns} not significant at $P < 0.1$
* estimated value – assumed as that of canopy category 3 (corresponding error mean of canopy 1 – 4)
** estimated value – assumed as an average of canopy category 1 to 4 (also corresponding error)

The percentages of throughfall catches that exceeded the gross rainfall were 28, 14, 20.6, 23, 20 and 35% for canopy categories 1, 2, 3, 4, 5 and the transects respectively (Table 1). This was consistent with the 29% for undisturbed Amazon rainforest (Lloyd & Marques, 1988), but larger than the 13% observed by Wong (1991) during the wet period 1989/90 at Danum Valley.

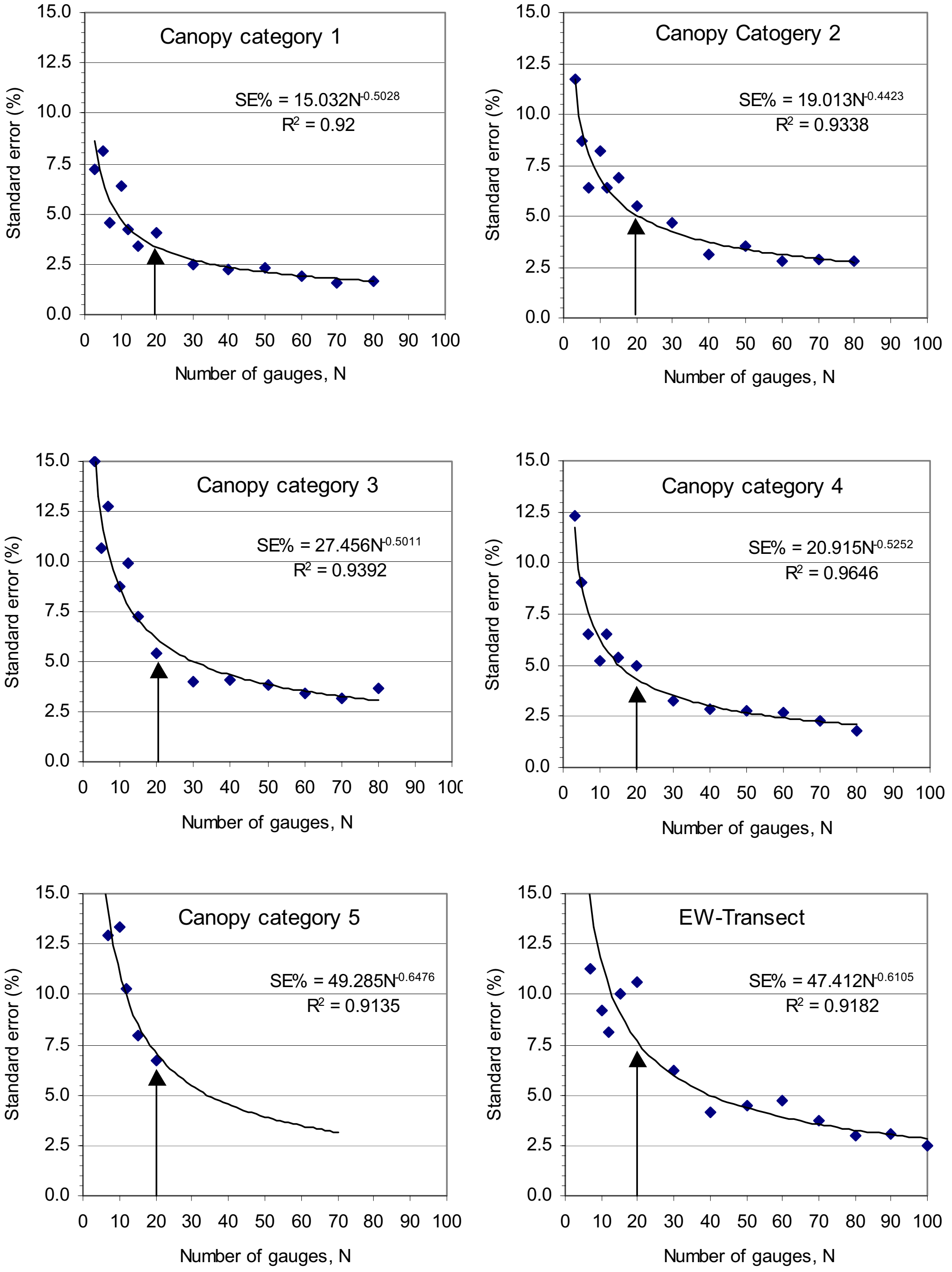

Figure 3: Uncertainty in throughfall measurement produced by different number of gauges under different canopy categories. An arrow on each plot shows the standard error in the catch where 20 rain-gauges were used under that particular canopy category.

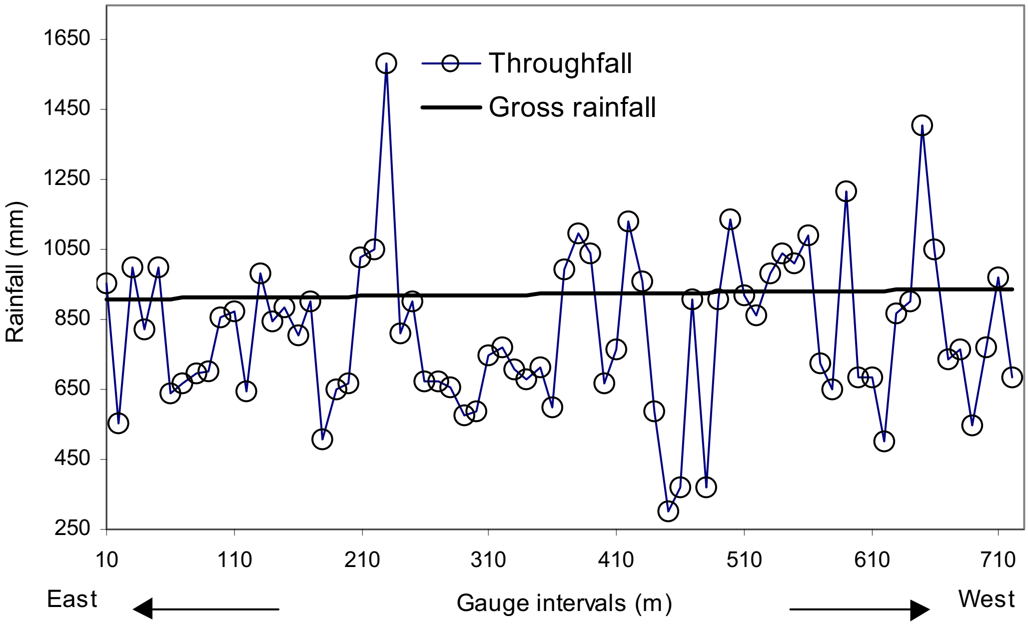

Figure 4: Throughfall totals for the period, 1 May 1997 to 30 April 1998, along the East-West transect of collectors in the Baru Catchment. Gross rainfall was measured by single gauges at each end of the transect.

Difference in Annual Throughfall between the Canopy Types

No statistically significant differences were observed between plots of the same canopy category (Table 1). In contrast, the differences in mean catch of canopy category 1, the undisturbed forest, and both canopy 2 (moderately impacted forest) and canopy 3 (vine-covered, highly disturbed forest) were highly significant ($P < 0.001$). Canopy category 3 was also significantly different to canopy 4 (*Macaranga* spp. trees) ($P < 0.05$). On average, canopy 1 allowed 1,286 mm of rainfall to reach the forest floor compared with 1,150, 1,157, 1,242, 1,206 and 1,201 mm for canopies 2, 3, 4, 5 and the transects respectively. These figures suggest that disturbed canopies allowed less rainfall penetration than undisturbed canopies. There are several possible reasons why less rainfall reaches the forest beneath disturbed canopies of selectively logged lowland forest. These relate to possible differences in: (i) gross rainfall intercepted by the canopy, and (ii) canopy surface characteristics.

(i) ***Gross rainfall intercepted by canopy*****:** The higher canopies of virgin forest patches within selectively logged forest may shelter the lower disturbed canopies, and hence lead to reduced rainfalls received in the lower disturbed forest patches (Hayes & Kittredge, 1949; Aldridge, 1975; Ford & Deans, 1978; Barry & Chorley, 1982, p.300; Herwitz & Slye, 1992). Herwitz and Slye (1992) termed the process 'the differential interception of inclined rainfall' and produced a model to illustrate the process within their tropical rainforest in Queensland. Ford and Deans (1978) explained that when rain falls at an angle, the leading shoots at the top of a canopy tree present a greater intercepting area than its vertically projected crown area. Thus if patches of undisturbed forest canopy receive more gross rainfall, then greater throughfall volumes would be expected

if wet-canopy evaporation rates are the same or smaller than those of the disturbed forest patches.

(ii) ***Canopy-surface characteristics:*** There are two aspects of canopy surface that may have contributed to lower throughfall in disturbed canopy. Firstly, qualitative field observation shows that there is an increased density of leaves on the outer surfaces of the disturbed upper canopy, as a result of the expansion of the woody climbers. This outer surface experiences the highest temperatures and rates of net radiation, thus may be subject to higher rates of potential E_{wc}. Additionally, some of the disturbed canopy appeared to contain more dead leaf and woody matter, turning parts of the canopy a darker colour and hence reducing the albedo. The increased leaf density and reduced albedo in this part of the canopy may, therefore, have had a disproportionate effect on the whole canopy E_{wc}. Secondly, selective removal of the upper canopy trees during the logging operations increases the roughness of the forest surface. This could increase the 'atmospheric conductance' and lead to a net increase in evaporation rate (Dingman, 1994; John Gash, pers. Comm.). Indeed, Klaassen *et al.* (1996) found that windspeed tended to increase around forest gaps, generating more turbulence, thus promoting E_{wc}.

Amongst the canopies in disturbed forest, canopy category 4 (*Macaranga* trees) recorded significantly higher throughfall (i.e. $P < 0.1$ and $P < 0.05$ relative to canopies 2 and 3 respectively). This is probably because the *Macaranga* trees at Danum have a very open canopy structure and low leaf area index (LAI, cf. Pitman, 1989) allowing much rainfall to penetrate. Additionally, the smooth bark of the *Macaranga* trees will not promote storage and subsequent evaporation from the tree trunk (cf. Herwitz, 1985).

VARIATIONS IN STEMFLOW BETWEEN DIFFERENT CANOPY TYPES

Uncertainties in sampling and calculation of stemflow are usually very high (Lloyd & Marques, 1988), though it normally constitutes only a very small proportion of sub-canopy rainfall. These small, but highly focused inputs can, however, become significant, for local erosion and mineral leaching (Herwitz, 1993) and in the moderation of local water stress (Navar, 1993).

The annual totals of stemflow for each of the canopy categories 1, 2, 3 and 4 were 15, 27, 14 and 6 mm respectively (Table 1). The very low stemflow beneath canopy 4 was expected, due to the branching architecture of the *Macaranga* spp. and the spar sity of vines within these forest blocks. The highest stemflow rates observed were beneath canopy 2 where there was a higher proportion of *Aporusa* and *Mallotus* trees which have small branching angles (Bidin, 2001).

The stemflows expressed as a proportion of gross rainfall were 1.1, 1.9, 1.0 and 0.4% for canopy categories 1, 2, 3 and 4 respectively (Table 1). The 1.1% stemflow within the undisturbed forest remnants (canopy category 1) was slightly smaller than the 1.8% reported by Lloyd and Marques (1988), 1.9% by Sinun *et al.* (1992), and 1.4 % by Asdak *et al.* (1998). This may be due to the fact that this study was undertaken during an ENSO drought.

ESTIMATION OF WET-CANOPY EVAPORATION

Subtracting the combined throughfall and stemflow totals from local measurements of gross rainfall gave annual wet-canopy evaporation (E_{wc}) percentages of 7, 18, 17, 12, 16 and 14 % from the canopy categories 1, 2, 3, 4, 5 and the transects respectively (Table 1).

An estimate of the catchment-average E_{wc} was calculated by weighting the canopy-specific rates by the estimated proportions of the catchment covered by that canopy type (cf. Bidin, 2001). This gave an average E_{wc} for the Baru Catchment of 13.6% (Table 2). Encouragingly, this rate is comparable with that from the mixed canopies along the two transects within the Baru Catchment (Table 3).

Table 2: Upscaling wet-canopy evaporation (E_{wc}) from proportional contributions of each canopy category (Bidin, 2001) during different periods of monitoring in Baru Catchment. See Table 1 for statistical details in the estimates.

	Canopy category						Baru total %E_{wc}[d]
	1	2	3	4	5	6 (Open)	
Area prop[b]	0.182±0.04	0.248±0.03	0.300±0.03	0.102±0.03	0.098±0.03	0.07±0.03	1±0.18
Sw monsoon							
E_{wc} (%)[a]	8.4	16.1	21.6	12.2	17.0	-	
Area weighted[c]	1.5	4.0	6.5	1.2	1.7	-	14.9
NE monsoon							
E_{wc} (%)[a]	5.2	19.6	12.6	11.8	14.9	-	
Area weighted[c]	0.9	4.9	3.8	1.2	1.5	-	12.3
12 months							
E_{wc} (%)[a]	7	18	17	12	16	-	
Area weighted[c]	1.3	4.5	5.1	1.2	1.6	-	13.6

Notes:

[a] E_{wc} as a proportion of gross rainfall for individual canopy categories.

[b] area occupied by individual canopy categories as a proportion of Baru Catchment area.

[c] E_{wc} of each canopy multiplied by the proportional area occupied by that category, including area only uncertainty.

[d] upscaled value from contributions of each canopy category.

Table 3: Mixes of disturbed and undisturbed forest +mosaics E_{wc} rates representing Baru Catchment measured by different combinations of throughfall gauges, showing no significant difference in the values. However, the upscaled value of E_{wc} is slightly lower, as this approach considered the area covered by roads and gaps, producing 0% E_{wc}.

Measurement of throughfall and calculation approach	**No. gauges**	**Annual**		
		Rainfall (mm)	**Sub-canopy rainfall (mm)**	**E_{wc} (%)**
1. Arithmetic mean of gauges in transects across catchment	105 (s)	1413	1217	13.9
2. Arithmetic mean of gauges in plots of different canopy categories regardless of the area covered by each canopy	345 (s)	1424	1225	14.0
3. E_{wc} values from plots of different canopy categories considering of proportional areas covered by each canopy	345 (s)	1424	1230	13.6
4. Arithmetic mean of gauges in 1 & 2 regardless of the area covered by each canopy	450 (s)	1422	1223	14.0

Rate of Wet-Canopy Evaporation within Undisturbed Lowland Rainforest

The E_{wc} value of 7% for undisturbed forest blocks in this study is amongst the lowest rates for tropical rainforests (Table 4) but within the range of reliable values defined by Bruijnzeel (1990). If one considers the errors with some other studies (Lloyd *et al.*, 1988), then the rate is comparable to the 9% for undisturbed Amazonian terra firma rainforest reported by Lloyd and Marques (1988) and the 11% reported for Kalimantan rainforest by Asdak *et al.* (1998). These uncertainties include (a) the ±1 % reported standard errors, (b) admissions of gauge overflows during extreme events (cf. Asdak *et al.*, 1998), and (c) the distance between throughfall collectors and the rain-guages measuring gross rainfall (cf. Lloyd, 1990). Given that this study was undertaken during an ENSO drought year, differences may have resulted from this longer-term temporal cyclicity (Chappell *et al.*, 2001). The smaller annual rainfall is probably associated with less rainfall being delivered as wind-driven, inclined rainfalls (Herwitz, 1985; Herwitz & Slye, 1992) giving reduced potential for wet-canopy evaporation. Tsukamoto and Ishigaki (1989) have also reported increased E_{wc} with increased gross rainfall. Indeed, Table 2 shows that the slightly smaller rates of E_{wc} were observed during the northeast monsoon, in comparison to the southwest monsoon, and Bidin (2001) shows that the northeast monsoon had typically lower rainfall intensities.

Table 4: Pertinent studies presenting annual rates of E_{wc} measured in undisturbed secondary rainforest

Reference	**Location**	**No. gauges**	**…….Annual………**	
			Rainfall (mm)	**E_{wc} (%)**
Calder *et al.*, 1986	West Java	2^b (s)	2850	21
Walsh, 1987	Dominica	Nk^c	5204	27
Lloyd *et al.*, 1988	Amazon	36 (m)	2805	9
Baharuddin, 1989	West Malaysia (central)	4^a (s)	3786	27
Sinun *et al.*, 1992	East Sabah	40 (m)	2824	17
Asdak *et al.*, 1998	Central Kalimantan	50 (m)	2199	11
Current study	East Sabah	80 (s)	1398	7^+

Notes:

[a] 0.7 m^2 trough
[b] plastic sheet
[c] not known
s stationary
m moved
\+ undisturbed patches with logged-over forest

Effect of Selective Forestry on Wet-Canopy Evaporation

Depending on the integration procedure, the catchment average E_{wc} for the Baru Catchment ranges from 13.6 to 14.0% of the incident rainfall (Table 5). This rate is comparable with those observed by Asdak *et al.* (1998) for the ‘closed canopy’ logged forest at their Kalimantan site, and for the disturbed lowland forest at Bukit Tarek in Peninsular Malaysia (Zulkifli, 1996). There is, however, considerable variability in the rates reported for disturbed tropical forests.

Table 5: Pertinent studies presenting annual rates of E_{wc} measured in disturbed secondary rainforest

Reference	**Location**	**No. gauges**	**…….Annual………**	
			Rainfall (mm)	**E_{wc} (%)**
Abdul Rahim *et al.*, 1997	West Malaysia (central)	11^a (s)	nk^b	27
Scatena, 1990	Puerto Rico	22 (m)	5745	39
Zulkifli, 1996	West Malaysia (central)	Nk^b	2723	13
Asdak *et al.*, 1998	Central Kalimantan	50 (m)	3563	15**
Current study	East Sabah	265 (s)	1427	13.6-14.0

Notes:
[a] 0.7 m^2 trough
[b] not known
s stationary
m moved
** Arithmetic mean of three different disturbed canopy types (excluding open canopy) provided by the authors.

CONCLUSION

The 1997/8 water-year studied turned out to be a severe ENSO drought. During this period, the remnants of undisturbed lowland dipterocarp forest studied allowed 93.1 ± 7.5% of the rainfall through the canopy to the ground, giving wet-canopy evaporation rate of approximately 7% of gross rainfall. This figure is towards the lower end of the range of wet-canopy evaporation rates observed for undisturbed tropical forests. The low rate may relate to the expected lack of storminess during the 1997/8 drought (Bidin, 2001).

Selective harvesting of the forest generated patches of moderately-impacted forest (canopy category 2) and more heavily damaged areas, now with the remnant climax trees covered by vines (canopy category 3). Much smaller volumes of sub-canopy rainfall were observed below these forest patches (i.e. 82.3 ± 3.1% and 82.6 ± 4.4% respectively). This result could be explained by (1) these (on average) lower forest canopies receiving less incoming rainfall due to sheltering by the undisturbed remnants, or (2) the changed canopy surface characteristics. The surfaces of the disturbed canopies often have a greater surface density of leaves, which may have a disproportionate effect on rates of wet-canopy evaporation. Further, the more uneven surface of the disturbed canopy patches may increase atmospheric turbulence and thus increase the rate of evaporation. These two phenomena may also account for the unexpectedly high estimates of wet-canopy evaporation from the areas of sprawlers and shrubs (canopy category 5).

Taking into account the area covered by the six canopy categories (Bidin, 2001), the catchment-wide estimate for wet-canopy evaporation from the selectively-managed forest (following eight years of recovery) was 13.6% of the gross rainfall. This figure was almost identical to the 14.0% wet-canopy evaporation rate calculated from the two transects of mixed canopy types. The study, therefore, suggests that the rate of wet-canopy evaporation may significantly increase as a result of selective logging. It then becomes important to know whether these extra losses are offset by reductions in the rate of transpiration, and also to know what is the resultant impact on the water yield of the river (Bidin, 2001).

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HYDROLOGICAL IMPACTS OF FORESTRY AND LAND-USE ACTIVITIES: MALAYSIAN AND REGIONAL EXPERIENCE

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ABSTRACT

Water stresses or shortages experienced in major cities of this country and other places have spurred heighten debates on the potential impacts of forestry and land-use practices carried out in upstream catchments. On a global perspective, the issue of adequate water supply vis-à-vis human activities has been a cause of concern and intensely discussed at numerous international meetings. Despite many years of experience in managing water resources and more than three decades of watershed-related research, this issue is still relevant today. In fact, many countries in this region are already grappling with water quantity and quality problems associated with land-use practices. Partly, rapid pace of development and the tremendous increase in urban population in the last three decades have compounded the water resource problems.

It has been accepted that forests play many important roles in the environment other than their economic values. Those benefits or services provided by forests include regulation of water cycle and watershed protection, soil stabilisation, maintenance of local climate and carbon sequestration. Therefore, in quantifying the hydrological impacts, reference to specific activities of forestry and types of land-use practices should be fully ascribed and discussed. The level of disturbance and, thus the magnitude of impacts, tend to vary according to different types of activities and stage of land-use development Commercial selective logging normally produces a measurable increase in water yield. However, greater changes in water yield and runoff responses are associated with forest conversion to other land uses. Depending on the extent of forest network, sediment yield from forest road and extraction may increase by two to ten times. Impairment of water quality usually occurs immediately after logging or forest clearance. Nevertheless, sediment loads and water quality may be stabilised within a few years after forest operation or after crop establishment.

Much adverse impacts can be minimised with ameliorative measures, including proper road planning, which thus facilitate recovery process. This paper also highlights the role of forests in managing watershed resources and its linkages to other environmental issues.

INTRODUCTION

In the 21st Century, water is likely to be one of the most scarce commodities in the world. The present trend of water consumption all over the world seems to confirm this concern. Water use has been growing at more than twice the rate of population increase during this century. According to the recent report on the “Comprehensive Assessment of the World’s Freshwater Resources”, about 20% of the world’s population in thirty countries face water shortage or stress, largely due to increased demands from a growing population and unsustainable human activities (UNCSD, 1997). Further, the report observes that the amount of water avilable and its quality are directly related to such activities as urban development, industrial growth, and agricultural and forestry activities.

On a larger perspective, the subject of water supply and land-use activities, including forest harvesting, has been frequently discussed at many fora and scientific meetings all over the world. Despite past experience in managing water resources and more than three decades of watershed-related research, we are still grappling with water shortages and environmental problems associated with land-use practices (McCulloch & Robinson, 1993). The question is whether or not land-use and forestry activities and water supply are at all compatible to the extent that either one should prevail.

With all these uncertainties about the impacts of forestry and land-use changes on the environment and downstream areas, a detailed understanding on the hydrological role of the forest becomes necessary in order to sustainably manage watershed resources. It has long been recognized that forests play many important roles in the environment other than for timber or other economic values. Therefore, the impacts of their removal or disturbance in land development activities on water and other natural resources become a great concern. Furthermore, most of the logging activities are located in hill forests which largely comprise the head water catchments for many of the river basins.

This paper attempts to review and synthesize available information on the effects of forestry and land-use activities on hydrological variables based on local and regional studies. The paper also highlights the role of the forests in managing watershed resources and its linkages to other environmental issues.

WATER RESOURCES PROFILE IN ASEAN

Due the wet equatorial climate, the region receives an abundant supply of rainfall of about 3,800 km^3 annually (Table 1). Accordingly, the water resources of ASEAN are generally self-contained by not depending on river flows from other countries with the exceptions of Thailand, Vietnam and Singapore. Considerable seasonal variations occur particularly in river flow, which are strongly influenced by the northeast and southwest monsoons as well as the occurrence of typhoons. However, within a country, there is considerable spatial variation. For example, in dry parts of central Sabah, the annual rainfall is about 1,730 mm, whereas in the mountain areas of Sarawak, rainfall could exceed 5,000 mm per year.

Annual internal renewable water resources per unit land area range from 2,200 to 14,000 m^3 /ha throughout ASEAN (ESCAP, 1995). However, on per capita basis, there are substantial variations mainly due to differences in population density. On the other hand, water withdrawal in ASEAN is about 120 km^3 annually which constitutes less than 10% of the usable water resource supply. Nevertheless, with the rapid pace of development in ASEAN over the last decade, water withdrawals have risen substantially to about 15% of available water supply. This level of water withdrawal is still below the acceptable threshold value of 33%, except for Singapore and Thailand, whose values have reached 32 and 29% respectively. Over the next one or two decades, the water requirements for the megacities in ASEAN are forecasted to increase tremendously, such as in Bangkok, Jakarta and Manila. The average domestic consumption of water in ASEAN is about 62 m^3/year or 170 liters per day. However, there is significant variation among countries, the highest being in Malaysia (Table 1).

Table 1. Freshwater resources availability and withdrawal in ASEAN

	Annual renewable water resources (km^3)	Annual withdrawal (km^3)	Per capita domestic use (m^3/y)
Indonesia	2530	16.6	12
Malaysia	456	9.4	121
Myanmar	323	29.5	85
Phillippines	0.6	0.2	74
Thailand	110	31.9	23
Vietnam	376	28.9	56

Source: First ASEAN State of the Environment Report, 1997

Malaysia is very fortunate to have an ubiquitous amount of available freshwater resources. The total annual water demand of all major uses, i.e. domestic, industrial and irrigation, amounted to 11.6 bil. m^3 or about 2% of the total surface runoff (JICA, 1982). The above demand is projected to reach 15.2 and 20.0 bil m^3 by 2000 and 2020 respectively. The percentage of the population accessed to safe drinking water has increased from 47% in 1970 to 89% in 1995.

LAND USE AND FOREST RESOURCES

Land use in the ASEAN region has drastically changed over the years. From 1980 to 1990, forest and woodland areas in ASEAN has decreased by 9% while croplands increased by 13%. Compared to entire Asia, ASEAN's land-use patterns have changed much more rapidly. For the same period, Asia's forests were reduced by 4.9% and croplands expanded by 10.8%. Unplanned conversion is one of the major factors influencing land-use changes. Further, encroachment by settlers and shifting cultivation have opened large areas of forests, leaving them without much protection.

The extent of forests in ASEAN countries has also decreased from 182 mil. ha in 1980 to 156 mil. ha in 1990 with an annual deforestation rate of about 1.4%. The rate has somewhat slowed down in recent years with reduced dependence on timber-based export industries. The growing population of the region continues to exert tremendous pressure on the forests for various uses in the form of increased fuelwood requirements, expansion of agricultural land, clearing for settlement and commercial logging. In addition, forests are also susceptible to natural disturbances, such as fires, landslides, insects and diseases.

Table 2. Forest areas in ASEAN countries, 1995

	Forest area (ha)	Percentage %	Forest per cap. (ha)	Cropland per cap (ha)
Indonesia	109.8	60.6	0.6	0.12
Laos	12.4	53.9	2.5	-
Malaysia	19.2	58.4	0.9	0.26
Myanmar	27.1	41.3	0.6	-

Phillippines	6.8	22.7	0.1	0.14
Thailand	11.6	22.8	0.2	0.36
Vietnam	9.1	28.0	0.1	0.10

Source: First ASEAN State of the Environment Report, 1997

Tropical rainforests of ASEAN are repositories of diverse biological resources. A quarter of the world's plant species can be found in the forests of Southeast Asia. More importantly, three of the 12 "megadiversity" countries in the world are in ASEAN: Indonesia, Malaysia and the Philippines.

Heightened environmental awareness and public pressure have continued to have impacts upon all aspects of the forestry sector: forest management, harvesting and post-felling operations and trade. Realising that forests should be managed in such a way that their productive functions, environmental services and social benefits are sustained has led to efforts to develop criteria and indicators for sustainable management (FAO, 1997). There is a concerted trend towards managing forests as ecological systems with multiple economic benefits and environmental values; conservation of biological diversity is given increased priority in management objectives.

Upstream and Downstream Interactions

Upstream and downstream interactions of any hydrological system or watershed are complex and elusive. The type of land use and land cover of the area would largely determine the magnitude and extent between upstream and downstream interactions and accordingly the degree of degradation to the environment. In order to quantify or assess the interactions fully, one has to consider interactions at several spatial levels, namely local level, intermediate and macro-levels or 'catchment cascade'. However, due to limitation of quantitative information, the assessment seldom covers the whole sequence of spatial levels.

Land-use, socio-economic and biophysical considerations all affect the relationship between upstream and downstream watershed interactions. While the upstream area possesses a beneficial resource base for the people, it also receives high-intensity but short-duration to long-duration rainfall with extreme variations in land formations. Given such a scenario, upstream areas hold a delicate balance on the productivity and prosperity of the interactions. Hence, this highlights the need for a fuller understanding of the interactions which rely on the quantitative data gathered from within the region.

A pertinent issue to be discussed is the role of forest upstream with respect to annual water yield, water regime and flooding downstream. What happens when the original forest cover is removed or transformed to another land use? In this instance, it is helpful to distinguish the terms water yield and flow regime. The former refers to the total volume of streamflow discharge over a certain duration whilst the latter relates to the seasonal f0luctuations of the streamflow in the channel at a particular time (Bruijnzeel, 1990).

EXPERIMENTAL WATERSHED RESEARCH

Experimental watershed approach has been adopted in most of the research to document and quantify the effects of forest cover manipulation or removal on interested variables of water balance. While there are many variations to conducting this type of research, the paired-watershed method is the most common one and being used in many countries including Malaysia. From the practical point of view, a manageable size of a watershed ranges from 100 to 200 ha, beyond which it would be impractical to apply 'treatment' uniformly. Therefore, most of the present information regarding hydrological changes resulting from forest logging or forest conversion is based on experiments usually conducted on relatively small watersheds of less than 250 ha in size (Hewlett, 1982). However, a recent study used a large watershed of more than 2,000 ha. One of problems associated with the catchment study is the leakage problem, especially those in small headwater catchments (Bruijnzeel, 1990).

ROLE OF FORESTS IN THE ENVIRONMENT

The inter-relationships between forests and the local hydrology are complex, yet the beneficial effects to humankind can be easily appreciated and described. The presence of trees in an undisturbed environment generates numerous interesting activities from their root system, branches, and leaves to their canopies. In photosynthesis tree leaves use sunlight to make carbohydrates for energy. By evapotranspiration great amounts of water are pumped from the ground into the air. With the ample supply of energy in the tropics, tropical forest transpires much more water than other vegetation, amounting to more than 1,000 mm per year. Thus, large quantities of water are recycled back into the atmosphere as vapour through this process.

The multi-layer canopy and forest litter intercept falling rain, thus protecting the tropical soil from erosion and compaction while holding the soil mass. The litter layer on the forest floor buffers the impact of raindrops on the top soil. This role is especially critical in the humid tropics such as Malaysia where large raindrops are possible with intense storms. The spongy litter of forest floor plays an equally valuable role in absorbing surface runoff resulting from heavy storm. It has been shown that infiltration capacity of forest soil is much higher than that of other soils by a factor of ten (Bruijnzeel, 1990).

Due to the efficient buffering and filtering effects of forest ecosystems, minimal soil erosion takes place and hence a high quality of water is usually generated from such forested catchments. Sediment yield from rain forested catchments may be as low as 0.25 t/ha/yr in stable areas underlain by deep permeable soils (Douglas, 1967). Similarly, forest cover invariably influences the regional and local climate or microclimate. A dense forest canopy efficiently modifies climate near the ground, especially air temperature, humidity and soil temperature. This would tremendously help the physiological processes in the forest floor such as germinating of seeds and other microbial activities.

From the global climatic scenario, forests also play a pivotal role in the present and future carbon balances, for they store about 80% of all above-ground and 40% of all below-ground terrestrial organic carbon in addition to photosynthesis and respiration processes (Dixon *et al.*, 1994). Depending on the extent and nature of activities undertaken, forests may act as either carbon 'source' or 'sink'. The rate of carbon uptake varies depending on forest types and forest practices as seen in Table 3.

Table 3: Rate of carbon either uptake under various forest types

Forest type and condition	T/ha/y
Selectively logged rainforest (Brazil)	2.9
Selectively logged rainforest (RIL Project) (Sabah, Malaysia)	3.1
*Pinus caribea (*Brazil)	5.1
Pinus elliota (Brazil)	3.9

Sources: Nabuurs & Mohren (1993); Moura-Costa (1996)

Although ample scientific information documenting forest functions is available, quite often some misconceptions or myths still persist as 'common knowledge', even among foresters. Likewise, some of the benefits of forest cover as claimed can be achieved, but some can only be achieved under certain conditions while others are questionable and fail to survive the scrutiny of scientific research. One of such misconceptions relates to the 'sponge effect theory'.

Level of Forest Disturbance

Forest removal and clearance may take place in several forms—some are more destructive than others. For the ease of assessment of impacts, Bruijnzeel (1990) classified them into three levels of disturbance, namely low, intermediate and high intensity disturbances. Low intensity disturbance is usually associated with a natural cause such as mortality or tree fall. The other levels of disturbance are associated with human induced activities, ranging from selective logging or shifting cultivation to forest conversion to forest plantation or permanent agriculture crops respectively. Therefore, we must be more precise in describing forestry and land-use activities before evaluating the hydrological responses of each. On the other hand, commercial forest logging may cause detectable changes in hydrological variables, depending on the intensity of disturbances and cover removal. By the same token, forest clearance and forest conversion to other land uses are expected to cause greater impacts on hydrology and erosion processes. Even in commercial selective logging, differences have to be made between common logging practices and improved harvesting methods, such as Reduced Impact Logging (RIL). The latter may include conservation measures, such as retention of buffer strip, installation of cross drain and properly designed forest road and road maintenance.

EFFECTS OF FOREST CONVERSION AND FOREST LOGGING ON WATER YIELD

The question of hydrological changes upon forest removal or land-use changes has been extensively assessed and reviewed in many parts of the world, both in temperate and tropical countries (Bosch & Hewlett, 1982; Oyebande, 1988; Bruijnzeel, 1990; Bonell with Balek, 1993; Bruijnzeel & Proctor, 1995; 1997). The main objective of these investigations was to determine the effects of vegetation and natural cover removal or modification on hydrological variables including water yield and flow regime. This issue has assumed greater importance as forestry and land-use changes take place in upstream catchments which serve as an important source of water supply for downstream users.

The forest generally utilizes much more water than other types of vegetation such as agricultural crops and grass, mainly due to its canopy structure and species composition. This is particularly true of the tropical rainforests. Consequently, the conversion of forest to other types of land use is usually accompanied by increases in streamflow discharge as a result of a reduction in evapotranspiration demands.

Based on results from studies in temperate regions as well as the tropics, it can be inferred that almost every well-designed experiment has shown increases in water yield as a response to forest cutting and in general the increase is proportional to the amount of canopy removal (Abdul Rahim, 1988; Bruijnzeel, 1990; Table 3; Abdul Rahim & Harding, 1992). Removing up to 40% of the standing trees caused increases in water yield ranging from 113 to 188 mm/y or 59 - 85% per year. In other words, removal of forest cover generally leads to increased streamflow totals, and afforestation or reforestation with fast-growing species on cleared lands leads to a decline in water yield (Oyebande, 1988). This increase may be permanent when converting tall forest to grassland or shallow rooted agricultural crops, or temporary in the case of conversion to tree plantations. With much effort given to reforestation in many developing countries in view of diminishing forest areas, more detailed attention should be focused on this issue in future (Bonell, 1997; Bruijnzeel, 1997)

However, the above responses are generally applied to forests located at elevations lower than 1,000 m asl which comprise lowland and hill diptercocarp forests in humid tropics. Floristically, beyond that altitude, different forest types can be found, namely upper dipterocarp, oak-laurel and montane-ericaceous forests (Burgess, 1969) which are also known as tropical montane cloud forests.

During the regeneration or recovery period, the time taken to recover to pre-logging level is rather irregular depending on the level of disturbance and year-to-year variability of rainfall. Nevertheless, detailed information in this respect is still limited and sometimes contradictory. Based on the Berembun study, water yield increment began to decline after seven years of selective forest harvesting which extracted about 40% of commercial stocking (Abdul Rahim & Zulkifli, 1994). Similarly, Malmer (1993) working in Sabah, did not observe any trend in annual evapotranspiration for five years after forest clearing. On the other hand, Kuraji and Paul (1994) claimed that logging activities in Sabah attained the pre-logging yield after 3-5 years. Under temperate conditions, it may take much longer to return to the pre-clearing level of streamflow. Table 4 shows the results from some of these studies.

Table 4: Changes in water yield and stormflow response following logging (adapted from Bruijnzeel, 1990, 1992)

Location	Type of logging	Changes in water yield (mm/yr)							Changes in stormflow volume	Changes in peakflo discharge	References
		1	2	3	4	5	6	7			
Sg. Tekam(A), Malaysia	Dipterocarp forest to cocoa plant.	+110 (117)	+706[a] (157)	+353 (94)	+263 (158)%					280% increase	Abdul Rahim (1988)
Sg. Tekam, Malaysia	60% conversion of forest to oil palm	145 (85)	155 (142)	137 (97)%					19 to 37% increase in 1 first three years	38% increase after logging/burning	DID (1989) Abdul Rahim (1988)
Mendulong (1) Sabah	Clearfelling rainforest to *Acacia mangium*[b]	+397	+522	+89							Malmer(1993)
Mendulong (4) Sabah	Clearfelling rainforest to *Acacia mangium*[c]	+197	+170	+80							Malmer (1993)
Mendulong (5) Sabah	Clearfelling rainforest to *Acacia mangium*[d]	+460	+262	+468							Malmer (1993)
Berembun (C1) Pen. Malaysia	Selective logging removing 40% of the commercial stocking	165 (70)	142 (55)	175 (72)	188 (85)	161 (73)	168 (67)	113 (59)%	Sign. ($p<.10$)	ns[e]	Abdul Rahim (1992)
Berembun (C3) Pen. Malaysia	Selective logging removing 33% of the	87 (37)	70 (28)	106 (44)	102 (46)	53 (24)%			ns	ns	Abdul Rahim (1992)
Lien-Hua-Chi, Taiwan	Clearcutting of mixed evergreen hill forest; regeneration	+448 (58%)	+204[f] (51%)						ns	48% increase	Hsia & Koh (1983)
Babinda, Queensland	Light selective logging	+264 (7.0%)	+323[g] (13.4%)						ns	ns	Gilmour (1977)

[a] 100% clearance
[b] non-mechanical, burning, no wood extraction
[c] manual log extraction, no logging
[d] ns. Not significant at <0.05
[f] dry year
[g] wet year
(   ) percentage

EFFECTS OF FOREST REMOVAL ON FLOW REGIMES AND FLOODING

In some places, dry-season flow is an important issue to the water supply manager particularly when the demands are high due to a protracted period of no rain. During this period, the baseflow and reservoir storage become the only sources of water to meet the consumptive requirements, viz, irrigation, domestic and industries. In addition, a low-flow period is also critical from the water quality point of view in terms of pollutant concentrations. Hence, the impact of forest operations on dry-flow conditions becomes a major concern not only to the forest manager but more so to the water supply engineer.

Evidence of the effects of forest clearing on dry season flow in the tropics seems, at first, contradictory and ambiguous. On the one hand, there were reports of greatly diminished flows whilst on the other significant increases have been observed as well. This is so because forest conversion has two opposite effects on the water. First, it tends to increase runoff and decrease infiltration of water into the ground, mainly due to ground compaction and disturbance which would lower the water table (Bruijnzeel, 1990). Second, replacement of forest with shallow rooting vegetation and lower transpiration rate tend to reduce ground water loss and hence raise the water table. Nonetheless, in interpreting the above contrasting results one has to take into account the prevailing climatic, pedological and hydrological setting of the area as well as the way in which conversion and subsequent land use were carried out (Bruijnzeel, 1989).

Results based on hydrological studies on selective logging in Peninsular Malaysia clearly enforce the observation that increases in water yield following forest removal are largely associated with baseflow augmentation. This is so mainly because of minimal disturbances occurring in the ground and stream channels except along forest roads and skid tracks. This, in turn, leads to surface infiltration remaining unaffected. Eventually, a greater recharge to the groundwater may occur resulting from reduced evapotranspiration, ultimately being able to sustain a larger baseflow.

There has been a protracted debate and popular belief regarding the role of forest within catchments, that forest cover in the upstream will prevent floods downstream. Quite often forest logging has been blamed for causing disastrous flooding downstream. For instance, monsoonal floods in the Ganges and Indus have been attributed to tree cutting in uplands (World Water, 1981). Controversies arise mainly due to the misunderstanding of the biophysical relationships involved. Among pertinent questions are, for example, whether the perceived increase in flooding that follows forest clearing is due to the removal of tree cover itself or is due to abusive land use. Further, are both upstream and downstream features affected?

Scientific evidence supports a link between deforestation and flooding only at a local level – within a drainage basin of less than 50,000 ha (Bruijnzeel & Bremmel, 1989). In small watersheds, increases in water yield resulting from forest conversion translate directly into increases in stormflow. Individual sub-watersheds will tend to flood in sequence, as storm passes over rather than simultaneously. It has been shown that after forest clearance, peak discharge and stormflow volume significantly increase due to the effect of increase in soil wetness. However, in the case of selective logging, the effects on peak discharges related to soil moisture would be less significant.

Much of the evidence discussed is essentially based on small-scale catchment studies or on-site effects. In this relation, Bruijnzeel (1997) suggested that the hydrological response of small catchment to rainfall depends on an interplay between climatic, geological and land-use variables. Key parameters include hydraulic conductivity, rainfall intensity and duration and slope morphology. This highlights the importance of keeping minimum soil disturbance during forest clearance and logging operations. However, much more work is required in order to answer questions on the effect of forest clearance on larger-scale or off-site effects.

EFFECTS OF FOREST REMOVAL ON SOIL EROSION AND SEDIMENTATION

In discussing the impacts of forest removal on soil erosion and sedimentation, it is instructive to make a distinction between on-site erosion and off-site or downstream effects. The former involves a smaller spatial scale such as a field or hillslope which produces a much faster effect while the latter affects a larger area further downstream. This downstream effect may take a long time to be reflected in a large watershed (Pearce, 1986). The eventual effect, when eroded soil particles are washed downstream, is to reduce the life of reservoir and irrigation systems, diminish their efficiency and thus increase the costs of maintenance.

Interesting results have been synthesized by Wiersum (1984) on surface erosion under various tropical forests and tree crops. Ground cover, rather than canopy extent, is the main factor of surface erosion. Removal of the under-storey vegetation may lead to slightly increased erosion rates, but soil erosion increases remarkably upon removal or destruction of the forest litter layer. When trees are harvested, their removal requires trails, skid tracks, and roads, which if not planned and constructed properly would cause serious erosion and sedimentation problems. In many instances, erosion impacts of land-use change may be the result of associated road construction rather than the land-use change itself. In Malaysia, the amounts of soil erosion arising from forest roads and skid tracks in the first year after logging are 13 ton/ha and 10 ton/ha respectively. However, the rates of erosion are drastically reduced to 3 and 2 ton/ha/year respectively in the second year (Baharuddin, 1995).

The effects of selective logging in Berembun catchment, Negeri Sembilan, showed minimal increases in sediment yield concentration and thus sediment yield for both types of logging methods, namely commercial and supervised commercial logging (Baharuddin, 1995). This was because of the low logging intensity as prescribed in the selective logging system coupled with the institution of conservation measures. On the other hand, forest logging in Ulu Sagama, Sabah and Hulu Langat, Selangor, produced much higher sediment yields (Douglas *et al.*, 1993; Lai, 1993; Table 5).

To fully assess the impact of land-use changes from forest to other types, it is necessary to evaluate the link between induced erosion and sedimentation. This depends on two factors—sediment delivery ratio and background level of sedimentation (Chomitz & Kumari, 1996). Essentially, only a portion of eroded soil ends up into stream channels and rivers; the reminder is trapped or redeposited down the slope. Sediment delivery ratio varies inversely with the catchment size and a ratio 0.3 is assumed for basin on the scale of hundreds of square kilometres. The background sedimentation varies remarkably depending on the local geology and the state of land use on site. This relates to the existing practice, human settlement, extent of road area and also topographical features.

EFFECTS ON WATER QUALITY AND NUTRIENT BUDGET

Water Quality

Forest disturbances affect stream water quality by way of physical, geo-chemical and biological processes. Removal of forest cover, especially the undergrowth and litter layer will not only induce erosion but also enhance leaching of chemicals and other solutes. Additional sources of organic matters in the form of logging trashes, coupled with greater sunlight exposure will also enhance microbiological activities, leading to higher rates of decomposition, mineralization and nitrification

Local studies on the impacts of forest conversion and harvesting on water quality were reported at three sites, namely Sungai Tekam, Pahang (DID, 1989), Berembun, Negeri Sembilan (Zulkifli *et al*., 1993), and Mendolong, Sabah (Malmer, 1993). The Berembun study provides valuable information on the impact of selective logging. The stream water was sampled during both lowflow and highflow conditions and analysed for 22 parameters. Commercial logging resulted in increases in pH, electrical conductivity (EC) and hardness. The largest increases were observed for suspended solids and turbidity, raised 12- and 9-fold respectively, in the first year after logging.

Increases in chemical concentration were also observed, particularly for alkalinity, silicate, Fe, K and Na. Recovery periods were attained between three and five years but the increases in Fe and K tended to prolong. Nitrate and colour were also elevated initially, but decreased rapidly to background levels within six months. The logging impact on water quality was most obvious during and immediately after storms.

Table 5: Impacts of forest conversion and logging activities on sediment yield

Location		Type of land-use change	Area (ha)	Annual rainfall (mm)	Sediment yield (mt/ha/y) (before)	Sediment yield (mt/ha/y) (after)
1.	**Sungai Tekam, Pahang**					
	- Catchment A	- Secondary forest to cocoa	47	1916	0.17	0.50 – 1.05
	- Catchment B	- Secondary forest to oil palm	96		0.42	1.05 – 4.14
2.	**Berembun, N. Sembilan**					
	- C1	- Selective logging, 40% extraction	12.9	2032	0.12	0.27
	- C3	Selective logging, 33% extraction (supervised)	29.7	2070	0.12	0.19
3.	**Ulu Segama, Sabah**					
	- Sg. Stesen Baru	- Selective logging	490	2642	0.6	6.6
4.	**Hulu Langat, Selangor**					
	- Sg. Batangsi	- Selective logging (on-going)	1980	2305	0.54	28.26
	- Sg. Chongkak	- Recently logged	1270		0.54	24.7
	- Sg. Lui	- Logged-over	6880		290	0.90
5.	**Ulu Segama, Sabah**	- Forest to *Acacia mangium* (manual felling/tractor)	18		0.24	2.53

Sources **:** 1. DID (1989), 2. Baharuddin (1988), 3. Douglas *et al.* (1993), 4. Lai (1993), 5. Malmer (1993)

Amongst the parameters investigated, Fe, suspended solids and turbidity are the most critical to water supply. The turbidity, for example, far exceeded the 5 NTU level for drinking water standards. Similarly, Fe concentration surpassed the recommended limit of 0.3 mg/l (DOE, 1986). Concentration of Fe was naturally high and exceeded the standard even before logging. Fe is easily leached from lateritic soils which are common in the tropics. While the Fe concentration was still manageable and could be easily removed by aeration process, the higher solids and turbidity are expected to increase the treatment cost.

Clearfelling, approximately 60% of a logged-over forest at Sg. Tekam, Pahang, resulted in increases in EC by two folds and was sustained at this level for three years. The higher EC reflects an overall increase in the ionic concentrations. However, due to the limited samples, especially during high flow, the study was not able to capture the full impacts. The only noticeable increases were for Fe and K during land preparation and planting stages. Bared ground, especially roads, was the major sources of Fe. On the other hand, K might be released from soil minerals and decomposing biomass. Considering the extent of disturbances that involved clearfelling, burning and land preparation, such activities are expected to show more intense hydrological impacts (Bruijnzeel, 1990).

At Mendolong, Sabah, considerable increases in EC and K were observed following forest plantation establishment (Malmer, 1993). The concentration of K in a clearcut catchment but with the biomass left unburnt was lower than in a nearby clearcut and burnt area. This suggests an accelerated leaching of K; thus over a long run this may lead to K depletion especially when burning is to be repeated during the next rotations. The Sabah study also found a large but short-term increase in nitrate.

Although water quality degradation due to forest operations is inevitable, it is possible to reduce the impact to a manageable level under well-planned logging and strict adherence to conservation measures. Proper road alignment and buffer strips are the main considerations for reducing logging impact (Hamilton & King, 1983). In the case of clearfelling, avoiding biomass burning will contribute less impact on water resources.

Impact on Nutrient Loss

Tropical rainforests are particularly sensitive to site disturbance and the delicate structures important for conserving nutrient may be partially or completely destroyed during forestry operations, causing accelerated losses of nutrient. The magnitude of nutrient loss varies from undetectably small in the case of ‘low intensity of disturbance’, such as natural gap creation by wind, to serious and permanent reduction in site nutrient capital as a result of ‘high intensity of disturbance’, such as converting rainforest to pasture (Bruijnzeel, 1990). Nutrient removal occurs via biomass harvest, surface erosion and enhanced leaching to ground water.

Losses of major nutrients following commercial logging at Berembun increased from 70% to more than 200%. Conversely, the ‘supervised’ catchment showed modest increases in solute losses, ranging from 13% for Na to 66% for NO_3. Beside trapping sediment, buffer strips are also effective in filtering and absorbing back nutrients before entering water courses (Brouwer, 1995)

Interesting studies examining the effects of different methods of establishing forest plantation on forests previously struck by fire, and forests that had been selectively logged were conducted in Sabah (Malmer, 1993; Nykvist *et al.*, 1994). After two years of calibration, four of the six catchments were treated involving: i) clearing of secondary vegetation, burning and planting (W1 and W2); ii) clear-felling, crawler tractor extraction, burning and planting (W5), and iii) clear-felling, manual extraction, no burning and planting (W4). The losses of major solutes were consistently higher from the 'normal practice' treatment (W5) compared to manual site preparation with residuals unburnt (W4). It is also interesting to note that, within the short time-span (2.8 years) after treatment, the hydrologic losses of K and Fe had exceeded losses via stemwood even for the manually extracted and unburnt catchment, W4.

On an annual basis, loss of nutrient seems to be small but over a long term, the total loss might be significant. Forested catchments depend on atmospheric deposition (mainly rainfall) and weathering for the inputs. Zulkifli *et al.* (1998) attempted to estimate the time-span needed to compensate loss through biomass and enhanced leaching by quantifying nutrient deposition in rainfall and weathering sources. To get a reliable long-term nutrient input, rainfall chemistry from several remote sites was considered. Depending on the chemistry of the rainfall, the time-span needed to compensate nutrient losses following harvesting ranged from 25 to 90 years for Ca, 20 to 35 years for Mg and 10 to 50 years for K. The slower recovery rate for Ca can be attributed to the much larger quantity of Ca required for the formation of woody biomass compared to Mg and K. The implication of this study is that nutrient sustainability could be attained if logging is carried out over 50 years rotation but not for the shorter 30 years rotation.

IMPLICATIONS TO WATERSHED MANAGEMENT

Activities in upstream catchments, be it forestry or other land uses, may cause great concern to the public as well as downstream users. In the past, watershed degradation could be largely associated with clearing of forests for intensive agriculture or other land-based development activities in upland areas (Abdul Rahim, 1988). Disturbance caused by selective logging operation assumes a different magnitude compared to that of forest clearance (Bruijnzeel, 1992). This study and others clearly show that selective logging operation with proper conservation or ameliorative measures may not cause significant long-term effects on water regime and water quality. Although some degradation of water quality was experienced, it was in fact short-lived and recoverable. From the forest and watershed management point of view, such findings would be helpful in prescribing management strategies. This is crucial because future logging activities would involve a similar type of environment, if not a more difficult terrain.

Effective supervision of logging operations becomes a central issue in order to ensure all regulations are well-adhered to during the operations. Recognising the physical constraints and manpower shortage of enforcement agencies in developing countries, this requires the full cooperation and support at all levels particularly of the workers on the ground, namely the tree cutters and bulldozer operators. In real life they are the people who ultimately decide the fate of the operations. Hence, not only their competency in handling machinery is important, but also an adequate exposure to the basic principles of environmental conservation is relevant.

Though the above study of Bruijnzeel (1992) deals mainly with the on-site impacts of logging, some immediate policy implications could be formulated or otherwise reinforce the existing procedures. For example, the extent of forest removal in selective harvesting should be limited to 40% of the stocking while a minimum buffer strip of 20 m from both sides of the stream should be strictly imposed. Minimum disturbance to the soil should be observed. With regard to streamwater quality, avoiding logging operation during rainy season would certainly be helpful in minimising the adverse impacts because pollutants resulted from logging activities are mainly conveyed to stream channels by surface runoff, especially when the soil is wet.

The above results pertained mainly to the `on-site impacts' and little to the `off-site impacts' on downstream users. The latter impacts could not be fully explained as adequate studies have not been undertaken. From a larger perspective, the `off-site impacts' are more important because the cumulative effects of logging upstream would be captured over time downstream which might cause economic implications such as siltation of reservoirs, impairment of water quality, and altering aquatic life and recreation attributes of water. This points to the need for a holistic approach in assessing the overall effects of land-use development using a watershed unit approach. Such an approach allows a quantification of upstream and downstream interactions which encompass various levels, including local, intermediate and macro-levels.

RECOMMENDATIONS

In view of the important role of upstream watersheds and their interactions with downstream users vis-a-vis increasing water demands to meet the increasing population and future developments in the country, the following considerations are recommended:

i. *Delineation and gazettement of priority watersheds*

Sensitive watersheds and other landscapes in headwater zone that serve certain intended uses downstream should be readily delineated and classified. In this instance, those forested watersheds within the Permanent Forest Reserve can be classified into appropriate functional categories as required by the National Forestry Act, 1984. Accordingly, the classification scheme for these watersheds should consider other potential uses of water in addition to other biophysical factors such as slope, elevation, erosion potential, and unique forest types such as cloud forest. Similarly, riparian areas along perennial streams, lakes, wetlands should be delineated and subsequently be subjected to a certain level of management regimes as they serve important ecological and hydrological functions. Once classified and delineated under appropriate categories, management prescriptions should be prepared in line with the intended uses. Therefore any land-use development in the catchment must be strictly controlled.

ii. *Integrated approach in management of river basin*

The basic premise is that any human actions or activities in any part of a river basin can profoundly affect downstream users as well as the environment. Recognising that a river basin or watershed, besides providing water, may accommodate various types of land uses ranging from forestry in the upper reaches to agriculture, industrial centres and residential areas downstream, an integrated approach must be adopted. Essentially, water management should take into account a wide range of ecological, economic and social aspects and needs. In addition, this approach calls for a better coordination and cooperation among relevant agencies involved in water resources. Subsequently, this would lead to a greater transparency in the decision-making process and allows constructive public participation in the process. There is a need for planners at all levels to understand water issues and problems.

iii. *Water as resource having an economic value*

For too long, water has been considered a free good and thus must be accessible to all. In fact, water use has a cost either in terms of its development or foregone cost. The cost of using or misusing water does not disappear; somebody has to pay. Thus, a proper and affordable price mechanism should be instituted so that a certain level of efficiency can be achieved in water resource development. It is also important to see that there is full cost recovery for the provision of water.

iv. *Develop incentive and awareness programme for sustainable water use*

A concerted effort should be made in formulating incentive programmes and public awareness programmes to promote sustainable water use and conservation among users at all levels. Enhanced understanding and promotion of commitment among the general public would lead to better appreciation and a keen interest in water conservation. The public should be taught to use water wisely and not to degrade it. For this, the involvement of individuals and NGOs is strongly encouraged.

v. *Integrated research on upstream and downstream interaction in identified river basin or catchment cascade concept*

As emphasised by this year's theme of the World Day for Water – 'Everyone lives downstream', scientific studies should be conducted involving all related disciplines in evaluating the interactions of upstream activities with downstream uses. In effect, assessment is needed of the off-site impacts of upstream activities within watersheds according to the catchment cascade concept.

Conclusion

The influence of forest cover on the hydrological characteristics and water resources in any watershed depends largely on several biophysical factors, including soil, geology and rainfall regime, in addition to the method and extent of forest transformation. Although the effects of forest removal on water resources and hydrological characteristics are context-specific, several general inferences can be elicited from the findings. Based on some of these findings, appropriate policy options or management regulations can be formulated to ameliorate the potential impacts of forestry and land-use activities on hydrology and the environment.

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RUNOFF ESTIMATE FROM THE NORTH SELANGOR PEAT SWAMP FOREST

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ABSTRACT

Runoff from the North Selangor Peat Swamp Forest was estimated from the hydrogen ion concentration. The technique assumes that the runoff from the peat swamp and the diverted flow from the upper Bernam Catchment have completely mixed once reach the Main Irrigation Canal. The peat swamp water was the most acidic (pH 3.77), followed by the water in the Main Irrigation Canal (pH 5.88) and that in the feeder canal (pH 6.02). Hydrogen ion concentration $[H^+]$ was strongly correlated against the volume ratio of peat swamp and non-peat swamp water. The peat swamp contributed about 11% of the total water production. The remaining 89% was diverted from the Bernam River. During low flow conditions, runoff from the peat swamp made up about 8% of the total water but increased to 17% during high flow. The existing log extraction canals could have facilitated the water outflow, particularly during storms. Based on rather limited data for water balance analysis, the runoff amounted to 146 mm/y or about 6% of the annual rainfall. The corresponding values for ground water recharge and evapotranspiration loss were 29% and 65% of the rainfall respectively.

INTRODUCTION

Concern over the rapid depletion and degradation of wetland ecosystems has reached an unprecedented level. Despite this, there is still a considerable lack of knowledge on the roles of wetlands in maintaining the hydrological, geochemical and biological functions of ecosystems and their surrounding areas. The hydrology is probably the single most important factor for the development and maintenance of specific types of wetland and the various processes that take place within it (Mitsch & Gosselink, 1993). The interplay between hydrological regimes and abiotic activities influences soil anaerobiosis processes and nutrient availability. Peat swamp forest is one of the important landscapes that fall under the wetland definition conceived during the Convention on Wetlands of International Importance, or often known as the Ramsar Convention 1989.

In Peninsular Malaysia, large tracts of peat swamp forest have been developed or converted to other land uses. By the end of 1996, the total area has been reduced to about 0.3 million ha, mostly in the States of Johore, Pahang and Selangor (Hashim, 1997). The North Selangor Peat Swamp Forest (NSPSF) is located on a flat coastal plain in the northwest of the State of Selangor. Covering a total area of about 76,800 ha, it consists of the Raja Musa and Sungai Karang Forest Reserves. The forest reserves together with the upper Sungai Bernam Catchment form important sources of water for irrigation and domestic supply. Despite the additional flow through diversion from the Bernam River, the irrigation scheme is still facing water shortage. Logging activities in the forest reserves have been identified as one of the factors that contribute to water shortage in the irrigation scheme.

Quantifying runoff is crucial for a better understanding of the hydrological cycle in peat swamps and assessing the logging impacts on water resources. This paper presents runoff estimates from the NSPSF based on the hydrogen ion concentration and volume ratio of peat swamp and non-peat swamp water.

STUDY SITE

Prior to the gazettement as a forest reserve, the forest was originally a state land. Logging activities had been taking place over the past 50 years on a rotational basis. The logging operations resulted in extensive construction of canals for extracting logs. A preliminary estimate suggests that the total canal length for the whole forest reserve exceeded 500 km. Site inspections showed that some of the canal ends, joining the main river had not been adequately dammed or blocked, leading to a continuous water outflow from the forest.

Land uses

The major land uses adjoining the forest reserve are the Tanjung Karang Irrigation Scheme to the southwest, oil palm plantations to the north and northwest, and the Rhinoceros Rehabilitation Centre to the east (Figure 1). The Tanjung Karang Irrigation Scheme covers an area of about 20,000 ha, extending in a northwest-southwest direction over a length of 40 km along the coast with an average width of 5 km. The scheme is one of the eight granary areas designated for achieving up to 60% of paddy production for domestic needs.

Way back in 1936, water for the irrigation scheme was first provided for a single wet-season paddy crop by a weir on the Tengi River via a 38 km canal along the southwest border of the existing forest reserve. In 1957, a 15 km feeder canal was excavated through the peat swamp forest to divert water from the Bernam River to Tengi River, and from there to the Main Irrigation Canal (Figure 1). This was to augment the water production to cope with water requirement for double cropping. The additional flow from the Bernam River was estimated at between 20 and 25 m^3s^{-1} during normal conditions but to drop to 15–20 m^3s^{-1} during the critical low flow periods of June-September and December-April (DID, 1996). Despite the diversion, the problem of water shortage for the irrigation scheme still exists, more or less every alternate year.

Climate

Similar to many parts of Peninsular Malaysia, the study site generally receives heavy rainfall, and haas high humidity and temperature. The mean annual rainfall varies from 1,750 mm y^{-1} along the coastal belt to 2,750 mm y^{-1} in the inland. The rainfall pattern shows two distinct peaks, during April-May and November-December, which coincide with the onsets of the southwest and northeast monsoons, respectively. Dry months generally fall in February-March and June-August. The mean annual temperature is 28 °C and the relative humidity is 77%. Average evaporation, recorded at Kuala Kubu station, about 60 km to the southwest is 1907 mm y-1.

METHOD

Due to very flat landscape, it is extremely difficult to measure runoff using the conventional approach by means of flow gauging. As noted by the DID (1996), such exercises would require flow gauging data and continuous water level records at all canal outlets inside the forest and those flowing into the irrigation scheme, over an extended period of a few years. Back-flow or reverse-flow which seems significant at several outlets will further complicate the measurement.

Considering the above constraints, runoff from the peat swamp was estimated from the hydrogen ion concentration (JICA, 1987). It is possible to use this method due to the contrasting pH of water in the peat swamp and that diverted from the Bernam River. The technique assumes that waters from these two different sources have mixed completely once they reach the Main Irrigation Canal at the Tengi River Headwork. In FRIM's laboratory, each sample of peat swamp water was added in stages into a known volume of water from the Feeder Canal. Changes in pH were recorded and compared with the pH of mixed water in the Main Irrigation Canal. A relationship between hydrogen ion concentration $[H^+]$ against the volume ratio was then established. $[H^+]$ can be determined from pH values in the following manner:

$$
\begin{aligned}
pH &= -\log[H^+] \\
&= \log 1/[H^+] \\
[H^+] &= 1/10^{pH}
\end{aligned}
$$

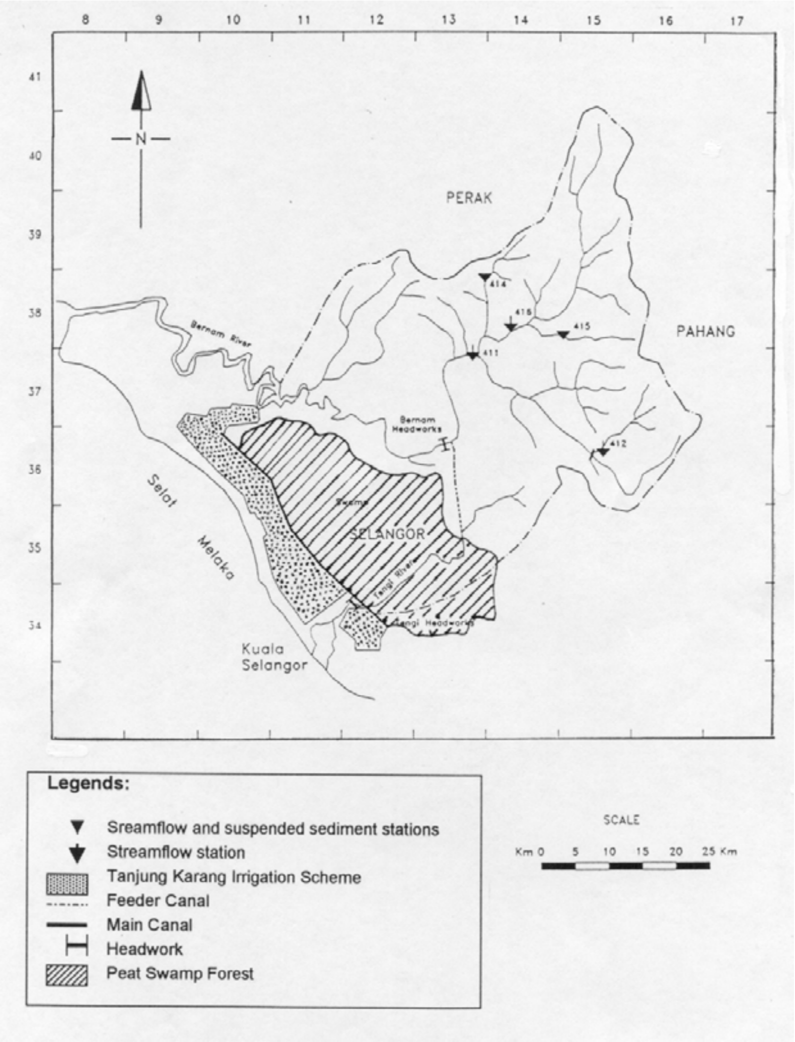

Figure 1: The North Selangor Peat Swamp Forest

RESULTS AND DISCUSSION

Runoff from Peat Swamp

Based on a biweekly sampling, water in the extraction canal (peat swamp) was the most acidic with mean pH at four sites between 3.70 and 3.84 whereas the feeder canal was the least acidic with a mean pH of 6.02. An intermediate mean pH of 5.88 was recorded in the Main Irrigation Canal. This was much closer to the pH in the feeder canal, suggesting that water chemistry in the Main Irrigation Canal was very much influenced by water from the upper Bernam Catchment and not from the peat swamp forest itself.

Our laboratory experiment showed that $[H^+]$ was strongly correlated against the volume mixing ratio. The relationship was best fitted in the following form:

$$[H^+] \quad = \quad ae^{kx}$$

where [H^+] is the hydrogen ion concentration in meq/l and x is the volume ratio. The coefficients a and k represent intercept and slope respectively. With coefficients of determination (r^2) ranging from 0.93 to 0.99 (Table 1, Figures 2) this technique should be able to provide a reasonably good estimate for runoff. Solving the above equation, the volume ratio, after complete mixing in the Main Irrigation Canal can be determined as:

$$x = 1/k.\ln[H^+]/a$$

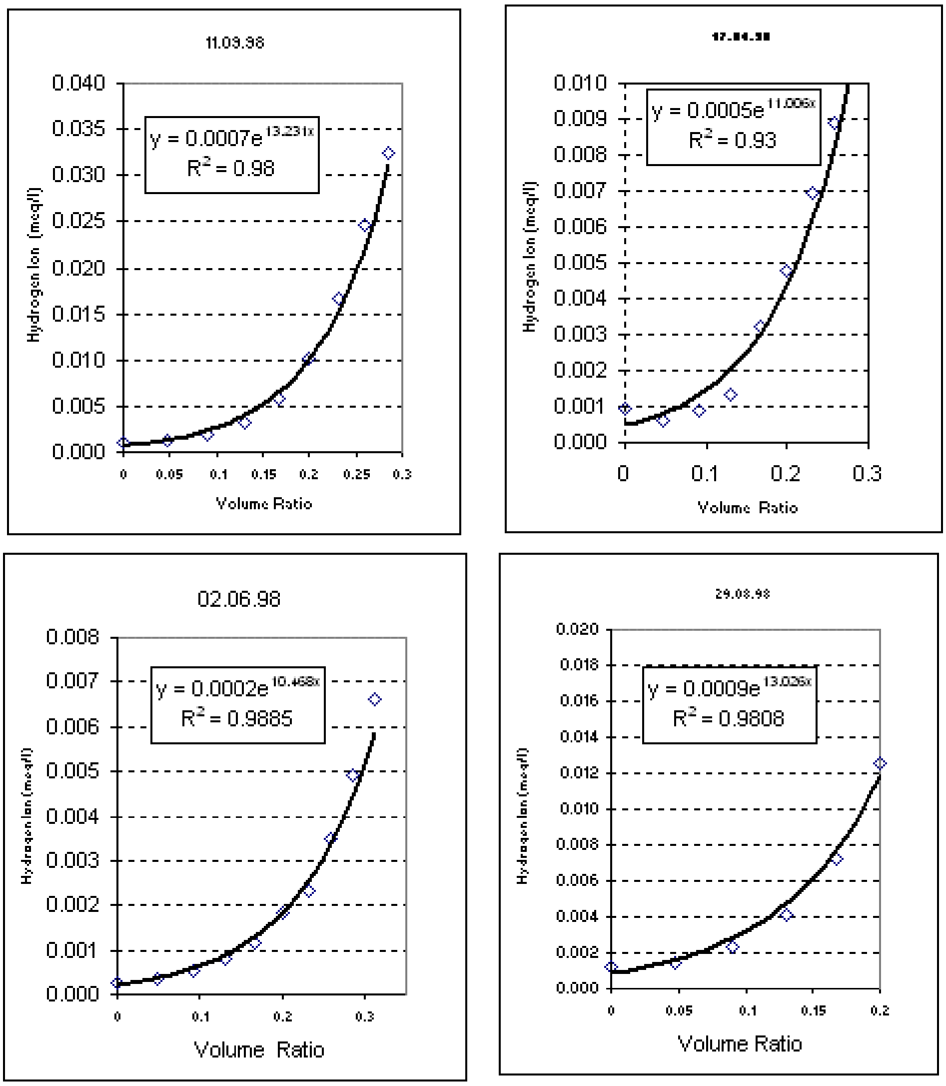

Figure 2: Relationship between hydrogen ion concentration against volume ratio of peat swamp and non-peat swamp water

The analysis suggests that runoff from the peat swamp constituted between 7 and 20% (average, 10.9%) of the total water in the Main Irrigation Canal (Table 1). The remaining 89% was provided for by the upper Bernam Catchment. The lower percentages on 11/5, 17/4, 25/9, 13/10 and 27/10 were obtained during low flow conditions whereas the higher values on 2/6, 29/8 and 11/9 represented high flow conditions. This may imply that instead of the peat swamp forest holding back excess water, it allows the runoff to gush out rather quickly during storms. On the other hand, the outflow during dry periods was remarkably small. The much larger runoff during storms may also indicate that the capacity of the peat swamp forest in retaining water might have deteriorated. Again, this could be the consequence of canal excavation in the forest.

Table 1: Contributions of peat swamp runoff to the total water in the Main Irrigation Canal

Date	PH			Equation	Ratio^{+}	%$^{++}$
	a	b	c			
11.03.98	3.80	6.63	6.36	$H = 0.0002e^{8.586X}$; $r^2 = 0.988$	0.09	7.9
17.04.98	3.89	6.28	5.94	$H = 0.0005e^{11.006X}$; $r^2 = 0.929$	0.08	7.0
02.06.98	3.83	6.54	5.89	$H = 0.0002e^{10.468X}$; $r^2 = 0.988$	0.18	15.0
29.08.98	3.63	5.93	5.36	$H = 0.0009e^{13.026X}$; $r^2 = 0.981$	0.12	10.8
11.09.98	3.64	5.90	4.75	$H = 0.0007e^{13.231X}$; $r^2 = 0.984$	0.24	19.6
25.09.98	3.59	6.12	5.67	$H = 0.0006e^{12.947X}$; $r^2 = 0.993$	0.10	8.9
13.10.98	3.53	6.24	5.80	$H = 0.0006e^{16.916X}$; $r^2 = 0.986$	0.06	5.4
27.10.98	3.60	6.16	5.81	$H = 0.0005e^{13.084X}$; $r^2 = 0.988$	0.09	8.0
15.11.98	3.59	6.65	5.41	$H = 0.0002e^{16.182X}$; $r^2 = 0.998$	0.18	15.5

Notes: a – water from peat swamp; b – water from the feeder canal; c- water in the main canal. + - volume ratio of a to b: ++ percentage of volume (a) to the total (a+b).

Water Balance

The actual runoff and ground water recharge can be further estimated using water balance equation for the peat swamp ecosystem as follows:

$$P + Q_b = Q_t + q + Et + Gr + \Delta G + \Delta S$$

where P and Q_b are inputs into the ecosystem as rainfall and the diverted flow from the Bernam River respectively. Q_t is the diverted flow that reaches the Main Irrigation Canal whereas q is the runoff from the peat swamp comprising both outflow from the extraction canals and lateral seepage. Et denotes evapotranspiration loss and Gr, the recharge to ground water. ΔG and ΔS represent changes in the soil moisture and groundwater storages respectively. These variables are expressed in unit depth (mm).

At the NSPSF, overflow along the feeder canal is not common, at least during the study period. As such, it is possible to assume that there is no significant loss of water as it travels from the diversion point at the Bernam River Headwork (BRH) to the Main Irrigation Canal. Q_t would therefore be equal to Q_b. Over an extended monitoring period of one year or so, changes in soil moisture and ground water storage are expected to be small, therefore ΔG and ΔS could be ignored. The model could then be reduced to:

$$P = q + ET + G$$

In Malaysia, *Et* for tropical rain forest catchments has been estimated at several sites (e.g. Low & Goh, 1972; DID, 1986; Abdul Rahim, 1990; Malmer, 1992; Zulkifli et al., 1998). The values range from 1,253 to 1,540 mm y^{-1} with an average of 1,508 mm y^{-1}. Based on results from selected studies in Southeast Asia for lowland and hill forest sites, Bruijnzeel (1990) suggested an average *Et* of 1,459 mm y^{-1}. Due to a higher soil moisture, trees in peat swamp forest are expected to transpire more water compared to hill forests. However, this would have been offset by a relatively low stand density at the present site. In this analysis, a guesstimate of 1,500 mm y^{-1} was used.

The runoff from the peat swamp, *q* as estimated from the hydrogen ion concentration constituted about 11% of the total water arriving in the Main Irrigation Canal ($Q_b + q$). Based on 33 discharge measurements in the feeder canal (DID, 1996), the discharge range from 8.75 to 32.21 m^3s^{-1} with an average of 21 m^3s^{-1}. This average was used for calculating the total flow over a year. With rainfall of 2,300 mm y^{-1} the ground water recharge, *Gr,* can be estimated in the following manner:

Total annual inflow from the BRH, Q_b, is

$$21 m^3/s \times 60 \times 60 \times 24 \times 365 = 662{,}256{,}000\ m^3y^{-1}$$

Adding the 11% contribution from the peat swamp forest, the total water in the Main Irrigation Canal ($Q_b + q$) is

$$1.11 \times 662{,}256{,}000\ m^3 = 735{,}104{,}160\ m^3y^{-1}$$

Runoff from peat swamp, *q,* is

$$735{,}104{,}160\ m^3 - 662{,}256{,}000\ m^3 = 72{,}848{,}160\ m^3y^{-1}$$

Assuming that only two-thirds or 50,000 ha of the forest in the east and south contribute runoff to the Main Irrigation Canal, *q* in unit depth is

$$\frac{72{,}848{,}160\ m^3 \times a}{50{,}000 \times 10{,}000\ m^2} = 145.7\ mm\ y^{-1}$$

a = a conversion to mm unit = 1,000

The ground water recharge, *Gr* would be

$$\begin{aligned} Gr &= 2{,}300 - 146 - 1500 \\ &= 654\ mm\ y^{-1} \end{aligned}$$

The above results suggest that the bulk of water entering the peat swamp is returned back to the atmosphere through evapotranspiration which accounts for about 65% of the rainfall. Ground water recharge constitutes 29% and runoff into the Main Irrigation Canal forms about 6% of the rainfall. It is indeed quite surprising to note that the runoff from the peat swamp is much smaller compared to hill forest catchments. Runoff for primary and matured second growth forests on hilly or undulating catchments range from 56 to 61% of the rainfall in Sabah (Malmer, 1992) and 32 to 47% of the rainfall in Peninsular Malaysia (see Low & Goh, 1972; Abdul Rahim, 1990; Zulkili et al., 1998). However, the low runoff for the peat swamp could be explained in terms of its small hydraulic gradient as the topography is almost flat, thus providing greater opportunities for the excess water to infiltrate and contribute to groundwater recharge.

MANAGEMENT IMPLICATIONS

About 90% of the water requirement for the irrigation scheme is provided for through a diversion from the Bernam River and only 10% from the peat swamp forest. The heavy dependence on the upper Bernam Catchment for water accentuates the need to accord greater emphasis on monitoring and controlling the land-use development in the upper catchment which is partly located in the State of Perak. There is also a need for integrated water resource management and better understanding of upstream and downstream interactions. This is especially crucial since areas in the upper catchment have been earmarked for water extraction and dam construction for the future water resource development for Perak. The environmental impact must be addressed at a macro-scale covering the downstream impacts, in particular, the peat swamp forests.

Peat swamp forests, particularly in areas with low annual rainfall, need occasional flooding or overflow to regulate the water table and maintain their ecological functions. However, with huge flow diversions, the extent and frequency of floods might have been considerably reduced especially in the downstream of Bernam River. The impact of this drainage alteration on the hydrology and ecology of the peat swamp is yet to be assessed, but signs of ecological degradation are already manifested.

Log extraction canals, especially where the lower ends that join rivers have not been adequately dammed or blocked, could facilitate water outflow from the forests. The argument is undrscored by the increase in proportion of peat swamp runoff during or immediately after storms. There is need to determine a suitable width of buffer from the river bank and introducing other remedial measures for reducing water loss.

The water balance analysis shows that groundwater recharge is much larger than the value that appears as runoff. As such a greater emphasis should be accorded in understanding the role of peat swamps in recharging the ground water and their response to human disturbances.

CONCLUSION

The NSPF is an example of a wetland ecosystem with the surrounding area that has been opened and disturbed. The forest itself had been logged quite extensively before being gazetted as a forest reserve. There is a clear competition for water resources. On one hand, water is needed for irrigation and on the other hand, the forest itself needs water to sustain its ecological functions. Unfortunately, the biological aspects of the catchment were not given enough consideration during the development of the irrigation scheme. The ecosystem is now degrading. There is an urgent need for research to improve the management of peat swamp forests.

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