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NOTES ON SOME HYDROLOGICAL EFFECTS OF LAND USE CHANGES IN PENINSULAR MALAYSIA

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NOTES ON

SOME HYDROLOGICAL EFFECTS OF LAND USE CHANGES IN PENINSULAR MALAYSIA

KEMENTERIAN PERTANIAN DAN PEMBANGUNAN LUAR BANDAR
MALAYSIA

ACKNOWLEDGEMENTS

The rapid development of Malaysia is causing changes in the natural hydrological regimen which could have very serious consequences if not foreseen and allowed for in the design of development. One of the tasks of the Drainage and Irrigation Division, under its hydrological programme, is the assessment of the water resources of Malaysia, and the study of the effects of land use change on the water resources forms an integral part of this work. The study of the hydrological effects of land use changes is complex and usually takes very many years to produce results.

Little information is available for Malaysian conditions as yet and for this reason some basic principles are presented and some experimental evidence from overseas tabulated and commented upon. It is intended as a first step to make designers aware of the variety and magnitude of changes.

The work reported here has been carried out under the programme of the Hydrology Branch of the Drainage and Irrigation Division in association with the Engineering Export Association of New Zealand (ENEX).

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MINISTRY OF AGRICULTURE AND RURAL DEVELOPMENT
MALAYSIA

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NOTES ON SOME HYDROLOGICAL EFFECTS OF LAND USE CHANGES IN PENINSULAR MALAYSIA

BY

CORNELIS TOEBES* AND GOH KIAM SENG†

1. SUMMARY

A schematic diagram is presented of the hydrological cycle in terms of storage reservoirs, and the general philosophy and principles given of what changes are possible to these storage reservoirs subsequent to major land use changes.

For important land use changes, deforestation, afforestation, forest operations, and urbanization, experimental data are given and interpreted for use under Malaysian conditions.

It is shown that water yield increases upon deforestation and decreases upon afforestation. Peak flows and flood volumes increase (for the smaller catchments) upon deforestation and urbanization. The information on the effect of land use changes on low flows and water-tables is conflicting although it appears that if conditions are such that infiltration rates remain high upon deforestation, then low flows may increase and water-tables rise. The reverse is also true and for instance water-tables tend to fall upon urbanization.

A brief summary is given of present and proposed studies by the Drainage and Irrigation Division in Malaysia of the hydrological effects of land use changes.

2. INTRODUCTION

Peninsular Malaysia consists basically of a system of steep, forested, central mountain ranges with limited, developed, flat coastal plains. Historically, relatively moderate land use changes that affect the hydrology of the country have occured.

The mountain ranges have always had a sparse population and although "shifting cultivation" was practised, population pressures were low until relatively recently and the people lived in an ecological balance. In some areas where population pressures built up, and the micro climatic and soil conditions were not conducive to regeneration of the forest, repeated burning and cultivation prevented the regeneration of the natural vegetation and areas were invaded by Lalang (*Imperata Cylindrica*), which appeared as a climax vegetation. In other areas shifting cultivation has resulted in a change in forest condition with in general a regeneration of fewer species.

Rapid development of the rubber industry between the two World Wars caused destruction of the foothills vegetation on an extensive scale to establish rubber plantation, and tin mining on the alluvial flats underwent considerable expansion during this period.

Major changes however are of more recent origin. The Federal Land Development Authority (FELDA) and other organisations have been developing vast tracts of land for oil palm, rubber and other crops; forest logging has become a major industry and the population drift to the cities has caused urbanization on an extensive scale in some areas.

These activities together with the associated development of communications and industry may cause considerable changes in the hydrological system.

Nature develops relatively stable systems with few extremes and human interference, by and large, intensifies the extremes.

The human action upon nature is designed to raise the living standard of the population and this implies more agricultural, forestry, mining and industrial development.

Such development runs counter to the stable hydrological system. Since an increase in the living standard is essential, man's "adjustment" of nature is inevitable, but attempts should be made to design development in such a way that changes to the "natural" hydrological system are minimized.

Such design requires information on what are the likely hydrological effects of changes and which method of development causes the least changes. Many studies have been made in many parts of the world on these problems but unfortunately few have been carried out in tropical areas and virtually none in Malaysia, and at this stage design has to rely upon interpretative and deducive facts.

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This paper, after outlining the hydrological cycle and the general principles and philosophy of hydrological changes, gives some information on facts recorded overseas and in Malaysia and make some inferences on applications to Malaysian conditions. The paper is restricted to water quantity effects and does not report on changes in erosion, sedimentation or water quality. A section on present and future proposed work in this field in Malaysia is given at the end of the report.

3. THE HYDROLOGICAL CYCLE

Fig. 1 shows a schematic diagram of the hydrological cycle in terms of storages, inflows and outflows. Reference to possible modifications to the various storages is given in para. 4 and a standard terminology (Toebes and Ouryvaey, 1970) is given below for some terms:

Evapotranspiration—The sum of water lost from a given land area during a specified time by evaporation from water surfaces, soil and snow, and by transpiration from vegetation and in building of plant tissues. Evapotranspiration normally includes interception loss.

Throughfall—The rainfall which directly reaches the litter through spaces in the forest canopy or as drip from leaves, twigs and stems.

Stem flow—The rainfall which, having been caught on the canopy, reaches the litter or mineral soil by running down the stems.

Depression storage—The volume or depth of precipitation stored in natural depressions on the land surface. Water in depression storage ultimately infiltrates, evaporates, or is drained artificially.

Detention storage—The volume or depth of precipitation on the ground surface or in channels during or shortly after rainfall or snowmelt which is available for surface flow and/or infiltration during or shortly after rainfall ends. Detention storage includes surface detention and channel detention. Detention storage does not include depression storage.

Infiltration—The movement of a fluid into a substance through pores or small openings; in hydrology it is the movement of water into the soil.

Capillary water (*Capillary moisture*)—The water held by surface tension in the capillary spaces and as a continuous film around the particles, free to move under the influence of capillary forces.

Percolation—The movement, under hydrodynamic pressure, of water through the interstices of a rock or soil, except the movement through large openings such as caves.

Surface flow (*surface runoff*)—The flow of water over the land surface. Surface flow includes overland flow and channel flow and is normally water derived from rainfall excess.

Interflow (*Prompt subsurface flow*)—The flow of water from ephemeral zones of saturation. It moves through the upper strata of a formation at a rate much in excess of normal baseflow seepage.

Baseflow—The flow of ground water from beneath a permanent water-table.

Runoff—Normally the flow of water derived from precipitation considered as a volume or as depth of water.

4. GENERAL PRINCIPLES AND PHILOSOPHY OF CHANGE

The philosophy given here is based on basic principles and generalised evidence of which parts of the hydrological system can be changed and how these affect other parts. The various storages with their in and outflows will be considered in turn and attempts will be made to briefly state the changes which could occur and how they could affect other aspects.

Basically, man interferes with storages either by modifying the reservoir (as for instance by changing the vegetation and increasing or decreasing the interception storage) or by removing or adding water to a reservoir (such as for instance by pumping from groundwater storage or recharging an aquifer), but every action on a storage will modify inflows and outflows with many unforeseen consequences and for this reason research is complicated and research results are often conflicting.

4.1 Atmospheric Storage

Weather modifications are possible to a limited extent and have been carried out with varying degrees of success in some places. Modifications to precipitation, by cloud seeding, will affect a hydrological system in all aspects since precipitation is a major input to the system.

Ice-crystals may be caused to form in super-cooled clouds by seeding them with dry ice, silver iodide or other nucleants. Ice crystals play an important part in the precipitation process and the idea of cloud seeding is for instance to induce precipitation to relieve droughts, or to divert typhoons.

Local droughts result from a presistent sinking motion of air, either in anti-cyclones or in the lee of mountains, and are caused by large scale features in the flow pattern around the hemisphere.

SCHEMATIC DIAGRAM OF THE HYDROLOGICAL CYCLE IN TERMS OF STORAGES, INFLOWS AND OUTFLOWS

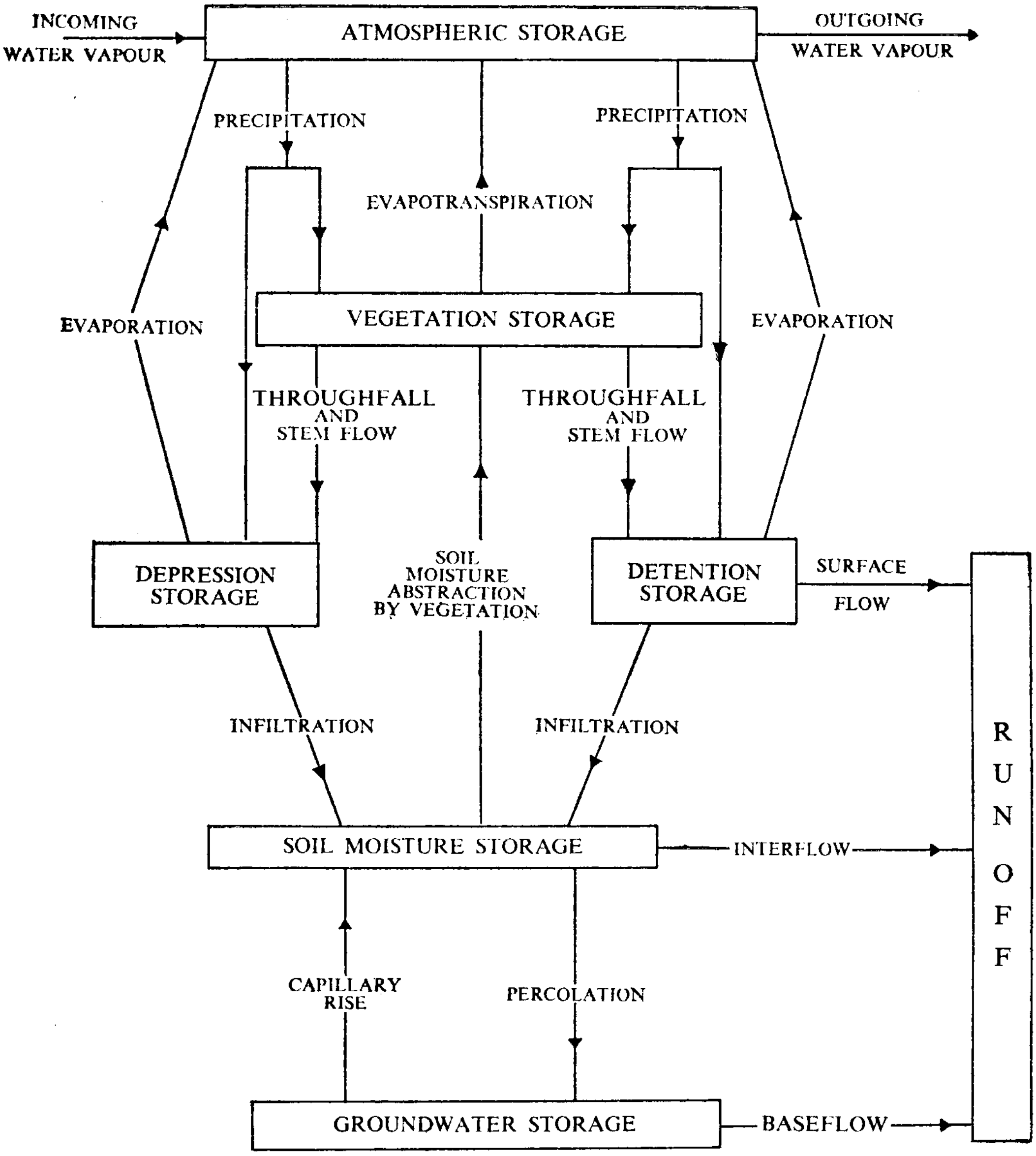

FIG. 1

It is now generally recognised that droughts cannot be terminated by any form of cloud seeding. Seeding may be successful however in orographic high rainfall areas and could contribute to filling reservoirs.

Diverting typhoons could reduce flood peaks, but may also decrease the necessary recharge of aquifers causing lower stream flows in dry periods and lower water-tables/pressures.

Precipitation levels may also change because of an increase in carbon dioxide (CO_2) levels (and to a lesser extent turbidity) in the atmosphere caused by our accelerating industrialisation and use of the internal combustion engine. Forests, which could balance excessive CO_2 levels, are being rapidly converted and this is therefore an added problem. The effects would be a rise in temperature with increased evapotranspiration which could affect water yields and may increase drought severity. Precipitation levels could increase as well, perhaps balancing the rise in evapotranspiration but rainfall events which are now considered extreme could well occur more frequently, giving rise to a greater flood potential.

Urbanization is a process that may cause significant local changes in the climate. Major metropolitan areas are warmer than the surrounding areas and the upward release of heat provides vertical motions of air over the city. In addition, many high rise buildings may serve as a barrier to low level wind providing an equivalent "orographic" effect with additional lift. The vertical airflow coupled with the emission of various small particles from combustion processes in cities, which act as condensation nuclei, causes an increase in rainfall over urban areas. In addition, industrialised areas may release considerable quantities of water vapour which could also contribute to increased rainfall.

4.2 Vegetation Storage

Changes in vegetation storage are possibly the most easily modified storage changes by man.

Some changes are sudden and have large hydrogical effects such as the removal of a forest or the conversion of a natural area to urban use.

Where a change in vegetation occurs, such as the conversion from a forest to a rubber plantation, the actual volumes of interception loss may not be greatly different in both stands, but there could be a considerable change in the regulating effects of the different vegetations.

Basically, the greater the interception loss the less water will arive at the soil surface and be available for stream flow, soil moisture and groundwater recharge. This implies that the greater the interception loss, the lesser the water yield will be. Water yield will be least, theoretically, in dense multi-storied forests which have the greatest interception loss potential.

It is reported in the literature that interception storage is relatively small. Zinke (1967), summarising American experiments, stated that "the storage indicated that one would not be greatly in error to estimate about 1.3 mm storage capacities for most grasses, shrubs and trees". However, because rainfalls (at least in temperature zones) are often light, the annual interception loss for coniferous forest has been reported as being as high as 50 percent of the annual rainfall and 25% to 35% seem to be commonly accepted values for vegetated surfaces.

Interception increases with rainfall volume and duration and since these are somewhat inter-related it is difficult to evaluate precisely the relative value of each.

The main reason (for the increase with rainfall volume and duration) appears that even during rain there is evaporation from the enormous wet surface of the foliage. Wet leaves are generally cooler than the air surrounding the leaves and thus additional energy is available, which in effect increases the potential evapotranspiration as compared with dry foliage conditions.

The above statements generally refer to single vegetation stands and information on multi-storied forests, even in temperate zones, is not available. One could argue that the interception storage is much greater in multi-storied forests such as tropical rain forests, than for instance in a stand of rubber trees, although it must be realised that the leaves of the lower stories will receive rain later than the upper story leaves, thus giving a lower evaporating opportunity for the wetted lower stories during rain. This implies that the total interception storage could not be related simply to leaf area (and condition).

However, a multi-storied vegetation clearly has a regulating effect on rainfall in that it delays and distributes the rainfall more than a single-tiered tree stand.

Throughfall and stem flow are those parts of the rainfall which are not lost by evaporation through interception loss, and in dense forests and/or trees with rough surfaces or complex branching systems, the different arrival times distribute the energy of input at the soil surface and the net effect is a greater infiltration opportunity, increased storage, and lower flood potential.

Vegetation can be harmful in changing the energy pattern of the rainfall, in that raindrops arriving at the soil surface may have more energy than those arriving at the vegetation surface, since raindrops coalesce on the leaf surfaces, and the greater drops may cause a greater energy impact at the ground surface than if the rain had not been intercepted by the vegetation. This could lead to a greater compaction of the soil surface and erosion.

Little is known about this since such effects are often obscurred by "inter tree" vegetation species being able to obstruct and retain the overland flow and sediment generated from around the tree trunks.

Transpiration rates are also affected by vegetation changes and could in some instances be the most important changes because of the large volumes involved.

Little is known about transpiration rates in tropical countries but it may be estimated that daily transpiration rates in dense forests may be in the order of 4 mm per day and perhaps 850 mm per annum. Single tree stands and agricultural crops may have daily transpiration rates in excess of those in multi-storied forests during the growing period because of the greater ventilation and greater penetration of radiation, but values are considerably less during dormant periods.

Evaporation (interception loss plus transpiration) for agricultural crops may be related to potential evaporation by the relation $E_t = K_c E_o$ when E_t is the evaporation, K_c a function of the resistance of the plant and E_o the potential (or open water) evaporation. Blake (personal communication) considers that for instance sorghum would have a K_c value of 0.8 for the growing period of sorghum and 0.3 during the dormant period. Using a daily value of E_o of 5 mm we obtain a daily evaporation of $0.8 \times 5 = 4$ mm for the growing period of sorghum and $0.3 \times 5 = 1.5$ mm for the dormant period. The latter value is somewhat higher than that used for evaporation from bare ground in temperate climates.

The greatest changes clearly occur when forests are felled. As a direct result of the change in daily evaporation from about 4 mm to say 2 mm, water yields will increase until regeneration or planting provides a vegetation cover similar to the original forest.

4.3 **Depression Storage**

The irregular features of the land surface which are filled with water during rainfall and which does not run off but infiltrates or evaporates, are easily modified by human action.

Land tillage, roading and housing construction, swamp drainage, the construction of terraces, fish ponds, etc. tend to change the natural depressions.

Depression storage by and large has a beneficial effect since part of the storage infiltrates and will be available as soil moisture and groundwater. The greater the depression storage, the lesser the overland flow, and in theory, the lower the flood potential.

Also depressions, if sufficiently large, such as swamps in upland catchments, tend to regulate the water yield and provide a more stable supply of flow in stream channels.

In Taranaki, New Zealand, a large number of swamps were drained in the upland catchments over the past 50 years providing a reason for the popular belief that water-tables have dropped and that low flows in streams are less.

Natural depression storage (excluding swamps) is normally small and ranges perhaps from 1 mm to 50 mm with perhaps 10 mm being a typical value. It is generally much less on slopes (where it is most needed) and Boughton (1970) estimates that the construction of absorption banks and terraces could increase the depression storage by about 50 mm on moderately sloping ground to 75 mm on fairly flat ground.

Reservoirs and artificial flood plains are generally most beneficial in reducing hydrograph peaks but each individual case should be considered in relation to its size and to the time of concentration of other tributaries.

4.4 **Detention Storage**

4.4.1 SURFACE DETENTION

The amount of water detained on the land surface that provides the head for overland flow is directly associated with the roughness and condition of the land surface. Overland flow is, in general, more pronounced in arid conditions, but because of high intensity rainfalls in the tropics is of significance and can be decreased by suitably modifying the land surface storage.

Izzard (1944) studied the relation between the surface detention and overland flow. The problem can be considered as one of spatially varied unsteady flow under rainfall in which the rate and depth of flow increase down the length of flow path. The equation is

$$De = Klq_c^{1/3} \quad \text{where}$$

De is the detention volume under equilibrium conditions in cu. ft.;

K a coefficient;

l the length of flow in ft.;

q_c the discharge per unit width of equilibrium $= \frac{Il}{43{,}200}$ in cu. sec./ft.,

The value of K depends on the effective rainfall intensity I in inches/hr., the slope of the surface S. and a roughness factor c, that is:

$$K = \frac{0.0007\ I + c}{S^{1/3}}$$

Values of c have been evaluated as follows:

Very smooth asphalt	0.0070
Tar and sand	0.0075
Concrete pavement	0.0120
Tar and gravel	0.0170
Closely clipped sod	0.0460
Dense blue grass turf	0.0600

The work by Izzard allows the hydrograph of flow over a variety of surfaces under steady rainfall conditions to be calculated and although Izzard indicated that his findings would only apply to laminar flow, later applications indicated that the method was satisfactory to turbulent flow as well.

Overland flow is most significant in its contribution to flood volume, but in relation to the magnitude of the flood peak is of greater importance on small areas than on larger catchments since channel storage and the hydraulic characteristics of channels are more important factors in controlling flood peaks than the depth of overland flow.

It is obvious that by changing surface conditions, for instance by urbanization, or for that matter by any form of road construction, overland flow increases, since the infiltration opportunity is reduced and as a consequence the flood potential is increased, and less water may be available for soil moisture and groundwater recharge.

4.4.2 CHANNEL DETENTION

This includes channel storage in rivers and small waterways, storage in detention dams for irrigation, flood control, etc. and swamps with natural outlets.

As for surface detention a fixed relation exists between channel detention and discharge, generally of the type:

$Q = k\ D_c{}^{m}$ where

Q is the discharge

k a coefficient.

D_c the channel detention and

m an exponent.

Channel detention is of great importance in flood control. On medium to large catchments, especially under heavy rainfall conditions, channel storage configuration largely determines the size of the flood peak and modification of channel storage by siltation, clearing debris or blockages, building reservoirs or flood banks and straightening rivers can significantly contribute to flood peak changes. Such changes can be calculated by using standard routing procedures.

The effect of storage modifications upstream (e.g. by detention dams on small tributaries) should not be confused with storage modifications downstream (e.g. by one large dam, flood banks or similar). These have a different purpose and for instance small detention dams in upstream catchments will reduce flooding in the upper catchment more than in the downstream direction since the storage capacity of a channel increases in a downstream direction (albeit less than the increase in drainage area). One storage reservoir on a large catchment downstream would have more effect in controlling dowstream flooding; whichever is chosen depends on the purpose for which flood peak modification is sought.

The discharge relationship in channels is normally calculated by the Manning equation:

$$V = \frac{R^{2/3} S^{1/2}}{N}$$ (metric units) where

V is the mean velocity

R the hydraulic radius

S the slope and

N the roughness coefficient.

Values for the roughness coefficient in natural channels vary from 0.015 to 0.15 with typical values of 0.03 to 0.05 in channels with vegetated banks in an average maintenance condition. Channels choked with debris may develop extreme values of as high as 0.15 and this indicates the value of channel maintenance in flood control.

4.5 **Soil Moisture and Groundwater Storage**

Soil moisture storage is often referred to as the water in the zone of aeration as opposed to the zone of saturation where water is classified as groundwater.

Water in the zone of aeration is strictly speaking called suspended water with soil moisture being the water storage in the soil where plant roots occur and intermediate water being the water storage below this and above the water-table. Simply speaking the difference between soil moisture and groundwater is that soil moisture is under tension and groundwater under pressure. Soil moisture tensions are often expressed in atmospheres and a limit of tension at 15 atmospheres is called wilting point when no water is available to plant roots.

Since water moves in the soil by capillary and gravitational action, an approximate constant of soil moisture when water movement is entirely capillary is the field capacity. The tension of field capacity is about 1/3 atmospheres and its practical use is that water available for plants lies between field capacity and wilting point. Soil moisture in the root zone is subject to withdrawal by plants and to vertical and lateral movements in the soil. When soils are deep and fine textured and plant roots extensive, such as for instance is found in tropical lowland forests, the soil moisture storage between field capacity and wilting point can be extremely large and values such as 300 to 500 mm or greater are not uncommon and storage in deep tropical soils with deep rooted crops may be up to 750 mm.

The soil moisture storage between saturation and field capacity is frequently of the same order, but since this water drains away after rainfall in the order of 48 hours, it is of significance only as a factor in controlling the so called initial loss, i.e. that quantity of water of the infiltration that occurs before the infiltration reaches an approximate constant rate (*see* Fig. 2).

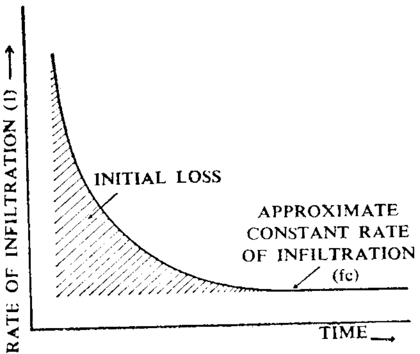

FIG. 2

The soil moisture storage can be changed principally by two methods—firstly by a lesser or greater utilisation of the soil moisture by the vegetation, therefore by a vegetation change, and secondly by drainage.

Because of the large storage capacity of soils, modifications to storage have a major effect on water yields. For instance a shallow rooted crop such as maize would only utillise say the top 600 mm of the soil moisture storage, while rain forest may have rooting depths up to perhaps 5,000 mm.

For this reason, deep rooted vegetation sands can create greater soil moisture deficiencies where there is sufficient water demand. The net effect is a lesser surface runoff since there exists a greater infiltration opportunity and/or a lesser recharge of groundwater. The latter aspect is very complex and depends on depths of water-tables, rainfall volumes, etc.

Drainage will decrease the soil moisture storage and groundwater storage and its effect depends on the pre-drainage and post-drainage conditions. The greatest changes could occur if a non-fluctuating soil moisture level is achieved. In such cases the vegetation will develop an optimum rooting condition with maximized transpiration (strictly speaking optimum rooting conditions would develop if soil moisture tensions do not fluctuate and the actual tension in such cases is of far lesser importance). For this reason drainage will cause a reduction in water yields because of greater evapotranspiration and because of lower water-tables. Flooding will be less, most likely, since a greater storage is created. To what extent such changes do occur may be calculated by measuring soil moisture storage in the pre-and post-drainage conditions.

5. EXPERIMENTAL EVIDENCE OF THE HYDROLOGICAL EFFECTS OF LAND USE CHANGES

Since the number of land use changes that can be carried out are very large, and experimental results for many changes are limited, only evidence of major land use changes of immediate relevance to Malaysian conditions is presented.

These changes are the hydrological effects of deforestation, afforestation and forest operations and of urbanization.

5.1 Effects of afforestation, deforestation and forest operations

5.1.1 EFFECTS ON WATER YIELD

Many studies have been carried out in various parts of the world and these have proven conclusively that manipulation of forest cover affects water yield for reasons as given in paras 4.2 and 4.5.

Table 1 shows the results of a large number of experiments on the effects of deforestation on water yield and Table 2 the effects of afforestation on water yield.

First year reponses to clear felling varied from 34 mm to over 460 mm of increased streamflow. It appears that the greatest yield increases are associated with high rainfall. It is not to be construed from this that a direct relation exists between rainfall volume and yield increase since the rainfall distribution throughout the year will have a considerable effect also.

Little evidence is available from tropical areas but what is available shows a similar pattern. Engineering consultants studying the Johore Tenggara area of Peninsular Malaysia (Hunting Technical Services, Ltd., 1971), reported that the average runoff increases by 10% when forest is converted into oil palm/rubber. They drew their conclusion from a comparison of observations and measurements on a number of different catchments under existing catchment cover conditions. In terms of water yield the change is in the order of 120 mm.

In clear felling deciduous forests, the major changes occur during the annual growing season and little or no changes have been recorded for the dormant season. This is not necessarily an indication that because tropical forests have no dormant period, that changes will be greater in the tropics since the growing period of the deciduous trees is one of major energy demand while this demand may be more evenly spread throughout the year in the tropics.

It is to be noted that in terms of percentages, the Kenya experiments showed the greatest change (80%). It cannot be said for certain that water yield changes in the tropics are greater than in temperate climates since for the experiment reported from Hawaii (20° latitude) a very moderate change is shown (21%), although the very deep soils that occur in Malaysia tend to suggest that water yield changes could be very great (*see* para 3.5).

Partial cutting or selective logging has a lesser effect, the increase being approximately proportional to the percentage of forest volume removed, as is shown in Table 1.

Afforestation experiments (Table 2) show a reduction in water yield, confirming the deforestation experiments. Typically, little changes are noted for the first 4 years until the tree crowns form a reasonably close canopy and the reduction persists until 10 or 15 years when a biomass equilibrium has been reached.

Replanting logged areas with crops will in due course also minimize, or even nullify, increases in water yield. The Johore Tenggara results cited above is one example and the studies in Kenya (Pereira, 1965 and Blackie, 1970) show that the replanting of tea bushes and pine plantations on catchments previously cleared of tall rain forest and montane bamboo forest respectively, caused the water yield to return to its original level upon maturation of the tea and pine.

UNESCO (1969) has reported that from experiments in the USA it was found that continuous selective forest logging does not appreciably change the water yield.

5.1.2 EFFECTS ON LOW FLOW

Since forests have an important regulating effect on streamflow (para 4.2), it would imply that catchments under forest will have greater "low flows" than in catchments which are cleared or have a less dense vegetation.

The available experimental evidence is meagre and conflicting. Reinhart et al (1963), Pierce et al (1970), Sopper and Lynch (1970), all report a reduction in the number of days that flow was less than a given value, consequent upon clear felling. Johnson and Meginnis (1960) indicated that removal of the forest caused the low flow discharge to deplete more slowly in the absence of rain.

On the other hand, Waugh (1970, 1971), Grant (1971), and Scarf (1972) observed that the geology of a basin is the dominant parameter controlling low flow and Waugh, although not observing a definite relationship between the percentage of catchment under forest and the respective minimum flow, noted that some catchments with a high percentage of forest cover did have a slightly greater minimum flow.

Engineering Consultants working in the Johore Tenggara area of Peninsular Malaysia (Hunting Technical Services Ltd, 1971), reported that by comparing observations and measurements on a number of different catchments under existing catchment cover conditions, clearing of jungle results in a decrease of run of river yields. Also, observations revealed that some of the smaller streams in the Jengka Triangle, Pahang dried up after the area had been cleared for agricultural development (Chong, 1973).

The conflicting evidence seems associated with the size and condition of the study catchment. The first group of researchers all studied small experimental catchments (< 4 km^2) in the USA while the second group obtained their results from considerably larger representative basins (4 — 250 km^2) in New Zealand, or similar sized catchments in Malaysia.

The problem is also related to the actual level of groundwater. Some evidence is available to show that, when forests are cleared, water-tables tend to rise. This does not necessarily need to cause an increase in stream flow since this depends on the height of the water-table and also on the relative contribution of so called bank storage to low flows in streams. If the latter is significant, then clearly, the removal of riparian vegetation would cause an increase in low flow.

It can also be reasoned that in certain cases upon clear felling water-tables should drop, because of lower infiltration opportunity; consequently low flows would most likely be less than in forested conditions in this case.

Perhaps the only fact that is likely to be consistent under all conditions is that extreme low flows are similar under any type of land use excluding urbanization but tend to be higher for forested condition.

5.1.3 EFFECTS ON FLOOD FLOW

As outlined in paras 4.3 and 4.4, changes in depression and detention storages clearly affect flood volumes and flood peaks. As stated in para 4.4.2, land use changes that modify surface detention will have an effect on peak flow on relatively small catchments only while the flood peak modification on larger catchments tends to be a function of channel detention.

This is borne out by experimental evidence. Small catchment experiments by Reinhart et al (1963), Reinhart (1964), Pereira (1965), Nakano (1967), Hewlett and Helvey (1970) and Blackie (1970), all indicate an increase in peak flow consequent upon forest removal. As a corollary it has been found from small catchment studies by T.V.A. (1962), Pereira (1965), Ellertson (1968), Ayer (1968) and Blackie (1970) that afforestation (or in the case of Pereira and Blackie, the planting of tea bushes) reduced peak flow.

Flood volumes and the frequency of the flood event are affected also. Little experimental evidence is available but Scarf (1970) reports that the conversion from a scrub area (Ulex europeus) to a cultivated area, caused considerable increases in the number of flood events of a magnitude less than the main annual flood. This was also confirmed by Toebes et al (1968), who found a decrease in the number of flood events in changing from an open to a dense pasture.

Scarf's findings also indicate that the larger flood events are affected to a much lesser extent and this confirms the common observation that so called "old man floods" are of the same magnitude irrespective of land use.

Although reduction in peak flows and flood volumes have been quoted in the literature, these are most variable and very much associated with the particular catchment under consideration and the size of the flood peak. For instance Ayer noted a reduction in flood peaks in winter by about 40%, but observed no reduction in winter floods. Scarf showed that for small flood events increase up to 900% could occur, and Hewlett and Helvey reported an average increase of 7% only.

Recent studies by Dunne and Black (1970) indicate that flood water in a catchment may be generated by an expanding and contracting source area which may occupy no more than 30% of the catchment. This is likely to be true for most catchments except the smallest ones and for this reason any experimental evidence can only confirm that flood peaks change and actual values may mean little.

Logging operations, as distinct from deforestation, may cause significant changes in flood peaks, flood volumes and flood frequencies since tractor logging and logging roads compact the soil with a decrease in infiltration opportunity (*see* para 4.4.1) and cause in general additional ephemeral flood channels and therefore reduce the collective time of concentration in a catchment, but experimental evidence on the effect of logging operations only are virtually absent from the literature.

5.1.4 EFFECTS ON SOIL MOISTURE

Although no special studies appear to have been concluded on the effects of forest operations on soil moisture, many agricultural experiments refer to findings that confirm the statements expressed in para 4.5.

Typically, Toebes et al (1968) refer to a reduction in the fluctuation of the soil moisture content of the soil consequent upon a change from an open to a dense pasture. It is relevant to consider that from a hydrological point of view, the change from an open pasture to a dense pasture lies somewhere between bare ground and a forested area.

5.2 **Effects of urbanization**

Urbanization is a phased process which normally starts with the erection of some dwelling houses and perhaps the use of some wells tapping the groundwater. A subsequent phase would include activities such as excavation of culverts and diversion of waste water to water courses. A final phase includes the establishment of sewage and water supply systems, the conveyance of urban runoff separate from sewage and centres with dense complexes of buildings.

Antoine (1967) gives the following percentages of impervious surface as related to the lot size of residential areas.

Lot size of residential area	*Impervious surface area*
ft²	%
6,000	80
6,000-15,000	40
15,000	25

In city centres the impervious surface area frequently approaches 100% unless parks are a significant feature of the centre.

The effects of urbanization are complex and few experimental data are avialable to support any postulates or general observations. No results appear to have been reported on the effects of urbanization on water yield or low flow and only data on the effects on precipitation, flood flows and groundwater are given here.

5.2.1 EFFECTS ON PRECIPITATION

Landsberg (1956) considers that there is a very substantial change in the composition of the atmosphere around cities and states that an increase in precipitation is a characteristic feature of cities. He says that there was an increase of 10% or more in the number of days per year having thunderstorms in Nuremberg, Germany.

Munn (1969), and Hogstrom (1972) report similar changes and in France observers note more precipitation on weekdays than on the weekends, apparently because of differences in air pollution emissions.

5.2.2 EFFECT ON FLOOD FLOWS

One indicator of a change in flood volume consequent upon urbanization is the storm runoff/rainfall ratio. Low (1971) quotes value of 41% to 51% for small, upland, forested catchments in Malaysia and Low and Goh (1972) quote 60%-65% for a partially urbanized catchment in Kuala Lumpur, Malaysia. Chia and Chang (1971), calculated ratios of 64%, 67% and 74% in 3 small urbanized catchments in Singapore for a heavy storm in December 1969.

Not only are flood volumes affected, but the flood peak increases and the lag time (the time from when half the storm rainfall has fallen to the time half the runoff passed the measuring station) is considerably shortened.

Moore and Morgan (1969) quote changes in peak flow and lag time from a number of experiments and give results in terms of the unit hydrograph (*see* Table 3).

Table 3

CHANGES IN PEAK DISCHARGE AND LAG TIME DEFINED IN TERMS OF THE UNIT HYDROGRAPH, CONSEQUENT UPON URBANIZATION

Catchment	*Catchment area mls^2*	*Peak discharge change in %*	*Lag time* changes*	*Record*
Sharon Creek, California ...	0.38	+ 40	– 40%	—
Waller Creek, Texas	—	+ 27	shortened	15 yrs
Brays Bayon, Texas	—	+ 350	– 3 hrs	22 yrs
Brays Bayon, Texas	—	+ 100 to + 400	—	27 yrs

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* The time required for 9/10th of the storm runoff to leave the catchment.

Several other investigators report increases in peak flow and Leopold (1968) using information from a range of experiments developed relations which can be directly used by urban planners.

Fig. 3 shows the effect of urbanization on the mean annual flood (return period 2.33 years) for a 1 square mile catchment. It gives the ratio of peak discharge after urbanization to before urbanization as related to the percentage of impervious area and the percentage of area served by storm sewerage.

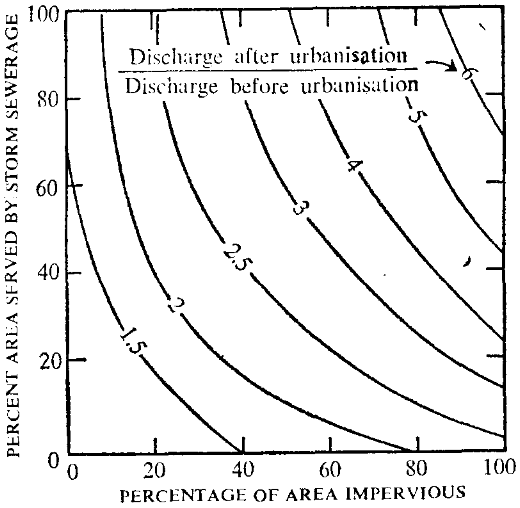

Fig. 3

Leopold also refers to the fact that channels tend to overflow during the "annual flood" and that the "bankfull stage" has a frequency of occurrence of about 1.5 to 2 years, a value somewhat less than the statistical return period of the annual flood (2.33 years).

Clearly, with urbanization, the channel will exceed its capacity not only once in 1.5 to 2 years on the average, but more frequently and Leopold derivel flood frequency curves for a square mile basin in various states of urbanization (Fig. 4).

The above results are likely to be directly applicable to Malaysia since the urban pattern is not greatly different from that developed in the USA.

5.2.3 Effect on water-tables

The complex situation that occurs with groundwater when forestlands are cleared, with sometimes increased and sometimes lowered water-tables does not appear to arise when urbanization takes place. All publications on this subject refer to a lowering of the water-tables, although it must be stressed that a lowering of water-tables causes frequently subsidence and a collapse of structures, and is therefore of more interest for reporting than if a rise were to occur. However, urbanization clearly causes a lower infiltration opportunity and this can only result in a lesser recharge to groundwater.

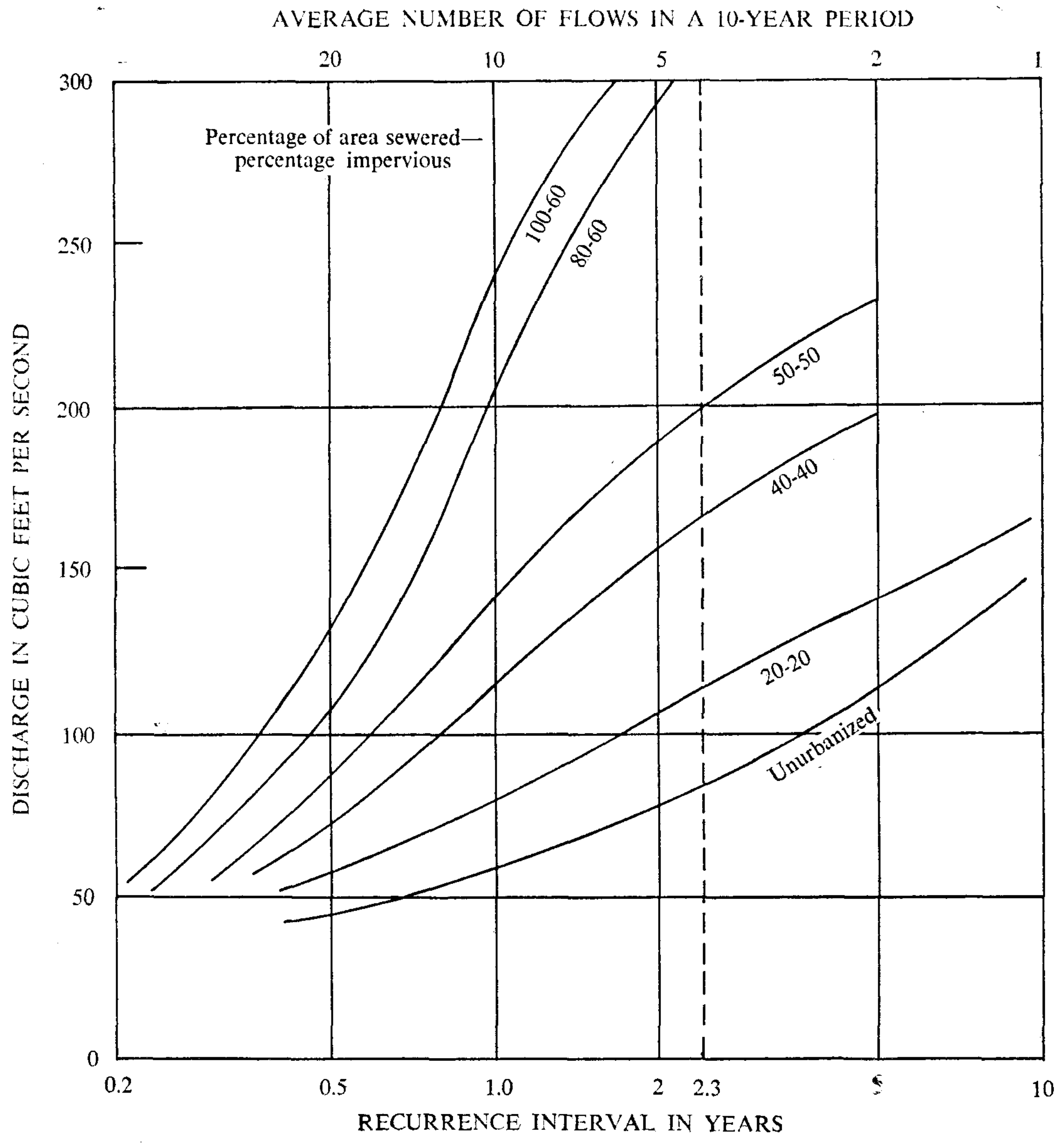

FIG. 4

Not many details are available as to actual water-tables before or after urbanization and more details are given as to actual levels of subsidence. For instance Marsal (1960) reports a subsidence of 5 to 7 m in central Mexico City, causing the inclination of Guadalupe Cathedral, and Lindth (1972) reports subsidences of 0.5 to 1.0 m in Swedish cities. Leakage from reticulation systems can obscure falling water-tables and for instance Howe (1971) reports that the mean loss from reticulation systems for 91 cities in the USA was 12% of the total production.

6. PRESENT AND PROPOSED STUDIES IN MALAYSIA ON THE HYDROLOGICAL EFFECTS OF LAND USE CHANGES

Rapid agricultural development is taking place in Malaysia and under the current Development Plan, between 25,000 to 50,000 ha. of forest lands are being converted annually to rubber, oil palm and other agricultural crops. Planners and project managers require to know what the hydrological effects are upon conversion of forestlands to tree crop plantations, and whether these effects are detrimental and if so, how they can be minimised.

6.1 Toebes (1972, 1973) suggested the setting up of a network of Representative and Experimental Basins in Peninsular Malaysia to monitor changes in the hydrological environment of catchments undergoing land use changes. Representative Basins established in typical environments are aimed at the understanding of the hydrological processes each of which involves the interaction of a number of hydrological characteristics or variables with the environment. Experimental Basins on the other hand study the influence of a man on the environment.

6.2 In Peninsular Malaysia the establishment of Representative and Experimental Basins has been preceded by the delineation of the Peninsula into a number of hydrological regions (Toebes and Ouryvaev, 1970, Goh, 1975) within each of which similarity in major hydrological characteristics was assumed. The delineation was based on lithology, an important environmental parameter and potential annual runoff (annual precipitation minus annual potential evapotranspiration), an important hydrological characteristic. Altogether 66 Regions were identified.

6.3 The proposed studies in the representative basins comprise the following:

(i) The prediction of low and mean flows within Hydrological Regions. For this reason, data from representative basins will be vital in the future for the assessment of water resources and the formulation of water allocation plans. It is planned also to generalize data in the form of maps showing the occurrence of low and mean flows for given probabilities of occurrence for the entire country.

(ii) The study of hydrological processes such as rainfall, runoff, interception, evapotranspiration and infiltration. Other studies that can be carried out include soil moisture studies, water balance studies and water quality studies.

(iii) The development of mathematical models. Data from representative basins will be used as input into mathematical models for the derivation of model parameters. These models, once developed, may be used to predict mean flows, floods, low flows, etc.

Up to the time of this report, two representative basins have been set up by D.I.D. in Peninsular Malaysia, both of them in Selangor. Additional representative basins are being planned.

6.4 In order to study the hydrological effects of land use changes, two programmes have been proposed by D.I.D. In the first programme, a few sites in an area where different stages of development are taking place simultaneously, will be selected. An approximate determination of the water quantity and water quality changes due to a conversion from forest to tree crop will be made. From the data collected, rough inferences of the effects of land use change will be made. This is a short term programme and will be carried out in the Jengka Triangle area where large-scale conversion from forest to oil palm is being carried out.

6.5 The second programme consists of the establishment of a network of experimental basins of a long-term nature. These basins should ideally be set up in various soil/vegetation complexes where land use changes are about to take place. However, owing to the high cost involved both in the setting up and operation of these basins and the shortage of trained technical staff in the running of the experimental studies, the initial work has been confined to the setting up of an experimental basin study in a typical problem area where development activities such as logging, conversion from forest to oil palm, rubber, cash crops, shifting agriculture, etc. are taking place. In this connection, two small catchments (49.4 ha. and 98.4 ha.) were selected within FELDA's Tekam Research Area in Pahang. These catchments are still under logged forest conditions and are located in a typical environment—yellow brown podzols and related red and yellow latosols on gently to highly sloping land undergoing changes from logged forest to oil palm, rubber and cocoa plantations. The two catchments will be studied under its current land use status for a period of three years after which one of the catchments will be cleared and planted with oil palm. The other catchment will remain undisturbed. Studies will continue until the oil palm plants reach maturity.

6.6 Apart from determining the hydrological effects due to land use change, the objectives of the Sg. Tekam experimental basin programme are also to determine how the soil moisture status can be improved to increase oil palm production and whether oil palm is the most suitable crop under this particular type of hydrological environment; to study different planting patterns and management techniques in relation to soil moisture behaviour and production and to train local personnel in experimental basin studies. The project is being carried out in conjunction with the FELDA Oil Palm Agrometeorology Research Project being implemented under an UNDP/FAO Technical Assistance Programme.

6.7 The Sg. Tekam experimental catchments were instrumented in October 1973 and initial stream flow and rainfall data have been analysed and reported upon (Scarf, 1974). The results of the analysis indicated that the catchments are suitable for experimental basin studies. Additional instrumentation has now been planned for the study.

6.8 Under its hydrological programme, D.I.D. proposes to set up in due course more experimental basin studies for the study of hydrological problems in other soil/vegetation/land use complexes. Experimental basin studies involve great cost and highly skilled technical staff and it will not be possible for any single agency to carry out any such study alone. It is hoped that other interested agencies will participate actively in all these experiments. In this way, more people will become aware of the development problems facing the country and contribute towards a concerted effort in the quest of practical solutions to these problems.

7. CONCLUSIONS

From the evidence given here, as reported in the literature and from the basic principles enunciated, it is postulated that in spite of a lack of data from Malaysia, or for that matter for tropical conditions, that land use changes in Malaysia have at least as great an effect on the hydrology as in temperate zones.

The greatest changes are an indirect cause of a change in the amount of water held as soil moisture storage, through a change in vegetation (by reducing or increasing evaporation) or by compacting soils or by making them impervious, thereby reducing the infiltration opportunity.

From the data given in this paper on the amount of water that can be held in various storages within the hydrological system, Table 4 has been prepared, and this indicates the magnitude of the soil moisture storage in relation to other storages. No reference is made here to groundwater storage, which can be of great magnitude but changes to groundwater storage are consequent upon other storage changes for the land use changes dealt with in this paper and therefore not relevant to the discussion.

Channel storage changes will of course occur also when forest operations are carried out or urbanization occurs. The magnitude of channel storage for Malaysian condition is in the order of 100 mm but it would be impossible to generalize to what extent this will be modified with any land use changes.

TABLE 4

TYPICAL STORAGE CAPACITIES FOR MALAYSIAN CONDITIONS

	Forested	*Bare ground*
Vegetation storage	1.3 mm*	0 mm
Depression storage	10 mm	Normally little change
Surface detention	11 mm†	3 mm‡
Channel detention	100 mm	Normally little change
Soil moisture storage (rooting zone) ...	250 mm	50 mm (soil evaporation zone)

* Based on US data, could be slightly higher for Malaysia.

† Assuming a slope of 0.0001, a rainfall of 50 mm in 2 hours, a densely vegetated surface, and a C value of 0.60 in Izzard's formula.

‡ Assuming a slope of 0.0001, a rainfall of 50 mm in 2 hours, bare soil, and a C value of 0.015 in Izzard's formula.

It is to be noted that soil moisture storage in Malaysia (and in many tropical countries) is very large as compared with temperate zones and this lends support to the thesis that land use changes could have a greater effect on the hydrology in Malaysia than in the temperate zones. However, there are no experimental data available to verify this.

The significance of the vegetation storage, although only of the order of 1.3 mm, is also of great importance. The value of 1.3 mm is the absolute storage at any time and it is reasonable to assume that on an annual basis the interception loss is between 25% to 35% of the rainfall.

No precise data are available on changes in water yield, low flow, flood flow or water-tables from overseas experimental data. For the major land use changes discussed in this paper viz. deforestation, afforestation, forest operations, and urbanization, it can be said for certain that deforestation increases water yield, afforestation decreases water yield and that partial logging or planting changes yields in approximate proportion to the area logged/planted.

It has been shown from available experimental data that clear felling increases the water yield by an amount varying between 34 mm to 460 mm, and the greatest yield increases tend to be associated with high rainfall. From the little evidence available from tropical regions, water yield changes in Malaysia could be of the same order and tending towards the higher values and this confirms what has been said about the interception loss and soil moisture storage being very high in Malaysia causing a very great reduction in evapotranspiration upon clear felling.

Typically, for Peninsular Malaysia, we have 2,500 mm rainfall (P) per annum and therefore say 30% interception, 30% × 2,500 = 750 mm interception loss which is entirely evaporated.

In para 4.2, it was stated that the annual transpiration of a typical tropical forest could be in the order of 850 mm per annum and therefore the total annual evapotranspiration (E) is 750 + 850 = 1,600 mm per annum. This value compares with calculations made using well proven formulas. The runoff being the difference between P and E is say 2,500 — 1,600 = 900 mm per annum. Upon clearing an area the interception loss and transpiration loss become zero. However the soil evaporation, which is relatively insignificant under tropical forest, increases sharply to perhaps 500 or 1,000 mm per annum.

Assuming say 1,000 mm, the runoff upon clearing will be 2,500 — 1,000 = 1,500 mm per annum or an annual increase of 600 mm (65%), a value not significantly different from that found in Kenya (*see* para 5.1.1). It must be realized of course that much of this additional water is lost during floods and the beneficial effect of an "added" usable water resources is not necessarily great.

The situation is confusing however and this is portrayed by what happens to low flows upon deforestation. Experimental evidence is conflicting and it appears to depend on the subsequent use of the cleared land.

Most experimental studies refer to "freshly cleared land" when infiltration capacities are still high. Subsequent use of cleared land for agricultural purposes will compact the soil and cannot but produce lower water yields. The ultimate change in infiltration characteristics of course is urbanized land and ample evidence is avaliable that water-tables tend to fall upon urbanization with a consequent decrease in low flows. Because of the lack of well controlled and documented experiments for rural catchments, no specific information can be given on the effect on low flows except to say that "extreme" low flows are at least as low, and likely lower, under cleared land conditions as compared with forested land.

It can also be said for certain that flood volumes and flood peaks increase upon deforestation and upon urbanization, at least in the smaller catchments. There is also ample evidence to show that the smaller flood events occur more frequently with these changes in land use.

Flood peak increases reported in the literature range up to 900% but such phenomenal changes have been recorded on small catchments and depend in the particular land use change also.

Leopold derived a graph for urbanization for a one square mile catchment and assuming a lot size in a typical modern urban development in Malaysia as 1,500 ft^2 with a fully developed storm sewerage system, the peak discharge would increase by 600%.

Similarly, flood frequencies will change, few data are available for deforestation/afforestation experiments, but assuming a similar urban catchment size and condition as used before, the frequency of a 100 cusec flood upon urbanization would increase from a recurrence interval of about 4 years to approximately 0.4 years.

Clearly, information is required in Malaysia to confirm the fact and to assess magnitudes of changes peculiar to Malaysian conditions. Although urbanization is a similar practice throughout the world and the hydrological effects of urbanization in temperate countries are well documented (Leopold, 1968), some studies should also be carried out in Malaysia where urban development is advancing at such a rapid pace, for comparison with overseas results. Further more virtually no data are available for deforestation/afforestation in tropical areas and the conversion of forest to oil palm/rubber although restricted to a few countries in the world, is of particular importance to Malaysia. In view of this, an experimental basin has been set up in FELDA's Sg. Tekam Research Area in Pahang not only to provide the necessary local experimental evidence required but also to recommend the practice with the least damaging effect. This implies a fairly long term study with a possible succession of a range of practices. More experimental basins are expected to be set up in the future. Besides the experimental basin programme, representative basins are being established to study the hydrological processes in natural catchments where little or no physical changes are anticipated. A better understanding of the hydrological processes in natural catchments will assist us in interpreting the results obtained from studies conducted in experimental basins.

8. RECOMMENDATIONS

It is recommended, in view of the tremendous development that is taking place in Malaysia, and the paucity of data that exists on the hydrological effects of development that:

- urgency be given to the establishment of representative basins;
- the programme of the Sg. Tekam experimental basin be carried out as programmed;
- a few simple studies are made on urban catchments to obtain some data that can be compared with overseas;
- studies are made by the D.I.D. or encouraged by the D.I.D., for the determination of soil evaporation and soil moisture storage in principal soil/climate complexes;
- planning is carried out now on the establishment of further experimental basins in Peninsular Malaysia.

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TABLE 1

SUMMARY OF EXPERIMENTAL RESULTS: INCREASED WATER YIELD RESULTING FROM DEFORESTATION

State and Country	Catchment	Lat.	El. m	Area ha	Geology	Soil	Precipitation mm	PRETREATMENT CONDITION				POST TREATMENT CONDITION						Reference
								Vegetation Cover	Basal Area $m^2 ha^{-1}$	Volume $m^3 ha^{-1}$	Run-off mm	Vegetation Cover	Increase in Runoff (mm) Year 1	2	3	4	5	
Colorado, U.S.A.	White River	39°N	?	197,000	?	?	265	Conifers, predominately spruce	?	?	?	24% forest destroyed by insect attack	58 average for 5 years					Love (1955)
Colorado, U.S.A.	Wagon Wheel Gap, B.	39°N	3,110	81.1	Quartzite	Clay loam	536 (50% snow)	84% thinly forested aspen and conifer 16% non forested	?	low	157	100% clear felled, slash burnt and regeneration	34	47	25	22	13	Bates and Henry (1928)
Washington, U.S.A.	Mc Cree	48°N	1,350	514	Granodiorite	Ash and pumice	580 (70% snow)	100% pinus ponderosa and Douglas fir	?	> 210*	112	100% forest destroyed by fire	94					Helvey (1972)
	Burns		1,400	565					?	> 210*	155		104					
	Fox		1,490	472					?	> 210*	175		69					
California, U.S.A.	Placer C	39°N	175	5.04	Igneous	Clay loam	635	100% scrub and hardwood predom. oak sp.	?	54	145	100% deforestation by spraying and ring barking	114 average for 3 years					Lewis (1968)
Arizona, U.S.A.	Castle Ck West Fork	33°N	2,400	364	Basalt	Sand loam	640	100% pinus ponderosa Douglas and White fir	31	190	51	17% patch cut of mature trees	19 average for 3 years					Rich (1972)
California, U.S.A.	Monroe Canyon	35°N	820	354	Gneiss	Sand loam	640	Hardwoods: 66% live oak. 10% sycamore	?	low	64	4% clear fell of riparian vegetation	9 maximum					Rowe (1963)
Colorado, U.S.A.	Fool Ck.	38°N	3,200	289	Gneiss	Clay loam skeletal	760 (75% snow)	100% lodgepole pine, spruce	?	?	283	40% patch cut in strips, regeneration	86	53	79	97	53	Goodell (1958), Martinelli (1964), Heede (1972)
Minnesota. U.S.A.	Marcell	48°N	?	34.8	Glacial till	Tillite	770	73% aspen, birch and maple, 27% spruce		210	193	46% patch cut	86					Verry (1972)
Waldai. U.S.S.R.	Tojeshny	53°N (ca)	?	45	?	?	790	98% fir	?	?	215	Compared with arable land and meadow adjacent	144					Sokolovsky (1960)
Pennsylvania U.S.A.	Leading Ridge 2	41°N	350	43	Sandstone/shale	Silt loam	940	100% Appalachian hardwood; oak, maple etc.	?	> 200*	410	20% clearfell, regrowth sprayed annually	60 average for 4 years					Sopper and Lynch (1970) Lynch et al (1972)
Nelson, New Zealand	Moutere 10	41°S	115	4.54	Glacial gravels	Clay loam	1,060	100% grose ca. 3m high	?	low	156	100% cleared and cultivated	91 average for 4 years					Scarf (1970)
New Hampshire, U.S.A.	Hubbard Brook 2	44°N	630	15.6	Glacial till	Sand loam	1,230 (30% snow)	100% hardwoods, beech, birch, maple, spruce	16.5	112	910	100% clearfell, regrowth sprayed annually	286 average for 3 years					Pierce et al (1970)
Hokkaido, Japan	Kamikawa Kitatani	43°N	?	645	Granite	?	1,440 (35% snow)	60% oak sp. 40% spruce and fir	?	270	808	100% clearfell and regrowth after typhoon destruction	268	175	225			Nakano (1967)
New South Wales, Australia	Byron Creek	29°S	?	36.8	?	?	1,520	100% sclerophyll encolyptus forest	?	low	480	Almost completely cleared for pasture	280 average					McArthur and Cheyney (1965)
West Virgina, U.S.A.	Fernow 4	39°N	790†	38.8	Sandstone/shale	Silt Loam	1,480	100% Appalachian hardwoods; oak	24†	132	618	6-11% intensive selection	No significant change					Trimble et al (1963) Reinhart et al (1963)
	Fernow 3		805	34.4			1,500	Naple, beech. black cherry	24†	153	635	16% intensive selection	8	0 non-significant				Lull and Reinhart (1967)
	Fernow 5		780	36.4			1,480		24†	185	760	23% extensive selection	25	8				Worley and Patric (1971)
	Fernow 2		780	15.4			1,500		24†	132	660	42% extensive selection	66	36	8			Patric and Reinhart (1971)
	Fernow 1		755	29.9			1,520		24†	155	585	84% clearfell with regeneration	130	102	76	61	46	
	Fernow 6		790†	22.0			1,440		26.2	185	492	50% clearfell and regrowth sprayed	154 average for 2 years					
												100%% clearfell	260					
	Fernow 7		800	23.7			1,460		26.4	196	772	50% clearfell and regrowth sprayed	150 average for 3 years					
												100% clearfell	258 average for 2 years					
California, U.S.A.	Castle Ck.	36°N	2,400†	1,040†	Granite		1,880 (60% snow)	52% forest; red fir, lodgepole pine	?	100†	?	12% timber removed by selective logging	53					Rice and Wallis (1962)
North Carolina, U.S.A.	Coweeta 6	35°N	790	8.8	Granite	Sand Loam	1,820	100% Appalachian hardwoods, oak ap.	21.8	165†	831	12% clearfell of riparian vegetation	Small increase, non-significant					Dunford and Flectcher (1947)
	Coweeta 19		960	28.2			2,000	Chestnut, maple, hickory, pitch pine	26.0	190†	1,222	22% basal area cut, understory only, regrowth	71	64	55	47	39	Meginnis (1959)
	Coweeta 40		1,035	20.3			1,950		?	?	1,052	27% selective logging, regeneration	Small increase					Hibbert (1967)
	Coweeta 10		975	85.8			1,850		?	?	1,072	30% selective logging over 14 years regeneration	25 average					
	Coweeta 41		1,065	28.7			2,030		?	?	1,285	35% selective logging, regeneration	55 average					
	Coweeta 1		840	16.1			1,730		19.3	145†	788	25% veg. poisoned	46	24	36			Swank and Miner (1968)
												100% clearcut, burned	152	15	55	46	68	
	Coweeta 22		1,035	34.4			2,070		18.4	140†	1,275	50% poisoned in alt. 10m strips, regen. restricted	198	155	130	112	110	
	Coweeta 28		1,200	144			2,270		?	?	1,532	51% clearcut, 26% thinned, regeneration	200					
	Coweeta 3		825	9.2			1,810		?	?	607	100% clearfell for agriculture	127	95	59	113	80	
	Coweeta 17		885	13.5			1,890		18.4	140†	775	100% clearfell, regen. to year 2, then cut annually	408	335	235	167	230	
	Coweeta 37		1,280	43.7			2,240		21.0	160†	1,583	100% clearfell, regeneration	260	90	90	25		Swank and Helvey (1970)
	Coweeta 13		810	16.1			1,850		25.5	190†	792	100% clearfell regeneration	367	276	278	248	200	Kovner (1965) Hoover (1944)
	Coweeta 13		810	16.1			1,850		18.5	140†	860 (ca)	100% clearfell, regeneration	380	200	130	100	85	Swank and Helvey (1970)
Kenya	Kericho Sambret	0°	2,200	688	Phenolite	Clay loam	1,910	Bamboo and mixed decid. hardwoods	?	?	416 (ca)	34% clearfell	103					Pereira (1962, 64)
	Kamakia A		2,440	35.2			2,010		?	?	568 (ca)	100% clearfell	457					Blackie (1970)
Hawaii, U.S.A.	Kaukonahu	20°N	400	12.0	Basalt lava	Sand loam	2,360	65% decid. forest 35% fern...	?	low	480	100% cleared and burned	100 average for 2 years					Anderson et al (1966)
Oregon, U.S.A.	H. J. Andrews 3	44°N	760†	101	Breccia, tuff	Black clay loam	2,400	100% predom. Douglas fir; some hardwoods; maple, dogwood	92	670†	1,370	8% clearfell for roading	Non significant					Rothacher (1965, 1970)
												30% patchout 3 areas	150	162	254	297	226	
	H. J. Andrews 1		760†	96.0			2,400		92	670†	1,340	100% clearfell	462	457				
Yamagata, Japan	Kamabuchi 2	38°N		2.48	Tuff	?	2,620	Cryptomeria sp. and chamaecyparis sp. Some beech and oak	?	30	2,075	100% clear felled, cleared annually by cutting or burning	82 average cutting annually					Nakano (1967)
													155 average burning annually					

* Estimated.
† Approximated.

TABLE 2

SUMMARY OF EXPERIMENTAL RESULTS: DECREASED WATER YIELD RESULTING FROM AFFORESTATION

State and Country	*Catchment*	*Lat.*	*El. m*	*Area ha*	*Geology*	*Soils*	*Precipitation mm*	*PRETREATMENT CONDITION*		*POST TREATMENT CONDITION*	*Decrease in Runoff mm*	*Reference*
								Vegetation Cover	*Runoff mm*	*Vegetation Cover*		
Jonkershoek, South Africa	Bosbank loof	33°S	520	208	?	?	?	Sclerophyll scrub	475	53% afforested with pinus radiata	104 average 16-20 years after afforestation	Banks and Kromhout (1963)
	Biesievle		365	32.0	?	?	?	Sclerophyll scrub	490	98% afforested with pinus radiata	142 average 8-12 years after afforestation	
Ohio, U.S.A.	Coshocton 172	40°N	350	17.6	Sandstone/shales	Sandy Loam	940	Abandoned farmland 30% variable age hardwoods	300	70% afforested with pine sp. 30% variable age hardwoods	135 after 19 years —	Harrold eta (1962) McGuinness and Harrold (1971)
New York, U.S.A.	Sage Brook	43°N	525	181	Sandstone/shales and glacial till	Silt Loam	970 (some snow)	Abandoned farmland 20% mixed deciduous woodlots	535	47% afforested with conifer sp. mainly spruce	130 †after 26 years (major decrease of 106 mm during dormant season)	Schneider and Ayer (1961)
	Cold Spring Brook		565	391		Silt Loam	1,030 (some snow)		616	35% afforested mainly red pine and spruce	200 †after 24 years (major decrease of 172 mm during dormant season)	Ayer (1968)
	Shackham Brook		520	808		Silt Loam	1,030 (some snow)		627	58% afforested mainly larch spruce and pinus sp.	154 †after 24 years (major decrease of 130 mm during dormant season)	—
New York, U.S.A.	Adirondacks Sacandaga R.	43°N	575	1,210	Glacial till	Silt Loam	1,140 (some snow)	Low volume north American deciduous forest	770	Basal area increased from 17 to 28 m² ha-¹ by planting and management of conifer sp. with existing forest	196 after 38 years of which 132 mm occurred during dormant season	Echner (1965)
Tennessee, U.S.A.	White Hollow	36°N	410	694	Kaast limestone	Shallow clay soils	1,180	65% abandoned pasture 35% mixed hardwoods and pine, b.a. 10 m² ha-¹	460	34% reforested mainly pine sp.; b.a. 25 m² ha-¹ after 24 years	No significant change	T.V.A. (1961)
	Pine Tree Branch		160	35.7		Silt Loam	1,230	77% abandoned farmland 23% poor forest	255	75% afforested with pinus sp.	115 after 16 years	T.V.A. (1962), Ellertson (1968)
Natal, South Africa	Cathedral Peak No. 2	33°S	?	190	?	?	1,660†	Sclerophyll scrub and poor pasture	830	74% afforested with pinus patula. Remainder scrub land	YR 3 6 9 12 15 0 60 220 340 360 and 374 mm after 17 years	Nanni (1970)
North Carolina, U.S.A.	Coweeta 1	35°N	840	16.1	Granite	Sand Loam	1,725	100% clearcut burned	790†	100% afforested with white pine	YR 3 6 9 0 65 145	Swank and Miner (1968)
	Coweeta 17						1,895	100% clearcut, regeneration cut annually	990	100% afforested with white pine	YR 3 6 9 11 0 40 120 ?250 (major reduction in dormant season)	

† Approximated.

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Water Resources Publications Previously Published

1. Surface Water Resources Map (Provisional) of Peninsular Malaysia (1974)	$5.00
2. Hydrological Regions of Peninsular Malaysia (1974)	$6.00
3. Sungei Tekam Experimental Basin Annual Report No. 1 for 1973 - 1974 (1975)	$5.00