Géo-Eco-Trop, 1978, 2, 229-242

THE IMPACT OF URBANISATION ON FLUVIAL GEOMORPHOLOGY IN THE HUMID TROPICS

by

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RESUME

La croissance rapide des villes intertropicales a posé de nombreux problèmes tant sur le plan de l'hydrologie que sur celui de la sédimentation parce que les idées et les principes valables pour la zone tempérée avaient été importés sans aucune adaptation au milieu tropical. L'exploitation forestière ou la construction selon des techniques modernes peut faire disparaître rapidement toute végétation, exposant les sols avec altération profonde aux effets du splash et du ruissellement. De même, le tracé de nouvelles routes entraîne la formation de versants en déblais qui est aussitôt la proie de l'érosion. L'augmentation du débit et de la charge qui s'ensuit modifie le comportement des rivières.

Dans le bassin du Sungai Kelang (Selangor, Malaisie), la croissance rapide de la capitale fédérale, Kuala Lumpur, et de sa ville-satellite, Petaling Jaya, ainsi que de la capitale de l'état, Shah Alam, a conduit à des modifications spectaculaires. L'exploitation des gisements alluvionnaires d'étain et la création de plantations de café puis de caoutchouc, enfin celle des zones maraîchères ont entraîné l'augmentation du réseau de drainage. Dans les villes, les eaux de pluie s'infiltrent moins et parviennent plus rapidement à la rivière que dans la forêt voisine. Des sols nus et des jardins, sont arrachés argile et limon qui viennent s'ajouter aux débris solides qui polluent le Kelang. A l'endroit où celui-ci quitte Kuala Lumpur, la concentration en sédiments solides est comprise entre 496 et 11.600 mg/l alors que ces valeurs sont seulement de 5 à 358 mg/l pour les régions forestières en amont.

La Malaisie est un pays où les pluies extrêmement copieuses et les inondations catastrophiques sont des phénomènes naturels courants. De hautes teneurs en sédiments peuvent déjà provenir de secteurs entièrement forestiers. Il faut donc faire le départ, dans ce domaine, entre les effets naturels et ceux dus à l'urbanisation.

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C.H. LEIGH et K.S. LOW (1972) ont montré que les bassins déjà occupés par l'homme avaient des débits de pointe beaucoup plus élevés que ceux couverts de forêt. Toutefois, les secteurs forestiers étant plus disséqués et de pentes moyennes plus fortes, l'interprétation de ce parallèle s'avère difficile.

Un nouvel ensemble de comparaisons peut être réalisé entre des rivières situées entièrement dans la zone urbaine et d'autres passant seulement à travers celle-ci.

Pour évaluer ces processus, les hauteurs de Bungsar à Kuala Lumpur ont été étudiées. Presque toute la crête qui est maintenant dénudée pour l'implantation de nouvelles constructions, constitue une source importante de sédiments. Les eaux du flanc N.-E. sont collectées par le Sungai Puteh, un petit fleuve canalisé qui passe sous la route à grand trafic de Kuala Lumpur à Petaling Jaya. Le limon des aires dénudées est venu obstruer le lit du cours d'eau, ce qui provoque à chaque orage la submersion de la grand-route.

Dans le flanc S.-W. de la même colline, le Sungai Anak Ayer Batu prend sa source puis traverse les localités de Lalang et Belukar. Au maximum d'une crue, après une pluie de 100 mm/h, la rivière peut charrier jusqu'à plus de 80.000 mg/l de sédiments en suspension alors que les concentrations ne dépassent pas, en temps ordinaire, 100 mg/l, voire 10 mg/l dans un affluent tout proche, dans une plantation de caoutchouc. Si l'on considère que l'écoulement par unité de surface est le même en volume et en répartition dans le Sungai Anak Ayer Batu que dans la branche principale du Sungai Kelang, la quantité annuelle de sédiments transportés par le premier doit être de l'ordre de 800 m^3 au km^2, soit 30 fois la charge des rivières qui proviennent des massifs boisés.

Des changements dans l'écoulement et dans la charge en suspension ont produit de profondes modifications dans le comportement de l'Anak Ayer Batu. Son lit mineur profond, étroit et dessinant des méandres, est devenu large, presque rectiligne avec un fond encombré de graviers et sable grossier mal classé. Cet étalement de sédiments ne va pas sans une érosion importante des berges nécessitant une intervention des travaux publics. Une modification semblable a été enregistrée dans d'autres cours d'eau de la région de Kuala Lumpur.

Sous les tropiques humides, l'urbanisation devrait être assortie d'un survey géomorphologique des versants et du réseau de drainage naturel.

The humid tropics support the most productive forest communities of the world, but much of the productivity is devoted to self-regeneration, most of the nutrients falling to the forest floor being re-used by the growing plants of the forest. H. BUDYKO (1958) equates this high productivity of the tropical rain forest with the high radiation balance. However, in natural conditions vegetation consumes only about 2.5 per cent (T. KIRA, H. OGAWA and K. YODA, 1962) of the available energy and only a small proportion of the available water resources. There is thus much heat energy available for other types of work, and it might be thought that, as Budyko suggests, it would be expressed in large quantities of denudation in humid tropical areas. Yet suspended sediment concentrations at high discharges in tropical rain forest streams are seldom high, the amount of debris in streams being governed by the rate of supply of material which in turn is regulated by the vegetation cover. As soon as the vegetation is removed, concentrations of suspended sediment increase (I. DOUGLAS, 1969a), stream bank erosion, rapid changes in bed form, meander abandonment and first order channel extension occur (I. DOUGLAS, 1974), such changes being the response of a river to an altered hydrologic regime (S.A. SCHUMM, 1971).

The impact of agricultural development is well-illustrated by the Barron River above Picnic Crossing on the Atherton Tableland in North Queensland, a formely rain-forest covered, basalt catchment affected by tropical cyclones. In the cleared areas of this catchment, the cohesion of the clay soil, particulary when the clays are wetted and expanded, tends to inhibit gully erosion. Surface wash of material, particularly between row crops where ploughing runs perpendicular, or at a high angle, to the contours, is important. Nevertheless, some major gullies have developed along lines where the main routes of surface runoff converge.

The steep gullies widen through undercutting by turbulent storm runoff, gully heads usually being much broader than the gully itself and having steep faces. The already considerable suspended sediment concentration of surface runoff from arable land is increased by erosion of gully sides and headwalls, producing major inputs of sediment from gullies to the Barron River. Much evidence of recent channel adjustment is found just upstream of Picnic Crossing, demonstrating how the hydrologic and sediment production changes caused by agriculture have lead to changes in hydraulic geometry, bank erosion and deposition of bed material (I. DOUGLAS, 1969b).

These changes in fluvial geomorphology as a result of agriculture are documented for most tropical countries (see, for Malaysia, M.J. BERRY, 1956 ; J.R.P. SOPER, 1938 ; I. DOUGLAS, 1970 ; C.H. LEIGH and K.S. LOW, 1972 ; C.H. LEIGH, 1973 ; R.P.C. MORGAN, 1974). Similar, but more pronounced, changes arise from the replacement of agricultural land by built up residential, industrial and commercial areas. While the nature of these changes in temperate zone, western cities are reasonably well documented (S.W. JENS and M.B. MCPHERSON, 1964 ; J.C. SCHAAKE, 1972 ; M.G. WOLMAN, 1973 ; J.A. SCHMID, 1974 ; D.R. COATES, 1974) data for tropical cities are not readily available, but are likely to show more severe sedimentation problems (J.E. BISHOP, 1973).

Humid tropical rivers often drain areas of deeply-weathered rocks which are in a delicate equilibrium with the plant cover (I. DOUGLAS, 1969a), their channels having tree roots exposed at the water's edge. Flood channels in hill country may be merely boulder-strewn valley floor depressions between the stems of forest trees, while in the lowlands only the better-drained levees may demarcate the river channel proper from occasionally inundated freshwater swamp forest. This intimate interdependence of vegetation, soil moisture and drainage leads to a large proportion of flow in forest streams being groundwater base flow discharge. Although high intensity, short duration thunderstorms produce rapid fluctuations in river level, much of the water input to tropical catchments is returned as delayed return flow through the regolith or as base flow (I. DOUGLAS, 1971). Any alteration to the plant cover or infiltration capacity of the ground surface will affect stream behaviour. To illustrate the type of effects produced by urbanisation in the humid tropics, the impact of Kuala Lumpur's growth on the Sungai Kelang is studied.

HYDROLOGIC CONSEQUENCES OF URBANISATION

Some of the many changes which occur as forest land is converted to urban uses are summarised in Table I in which the specific consequences of increasingly intensive urban land use in Kuala Lumpur are compared with the type of effects found in the temperate environment of the United States. Some of the hydrologic problems in Kuala Lumpur arise from the attitudes of city administrators to the tropical environment. In the colonial period, ideas and relationships valid for the cities of the temperate zone were often transferred to the tropics without sufficient allowance for the stresses imposed on structures by the environment. Protection against the sun seems to have obsessed the planners far more than the need to cope with the high intensity of rainfalls of the humid tropics. Despite the excellent stormwater drainage systems of colonial suburbs such as the Tanglin area of Singapore or Kenny Hills in Kuala Lumpur, there is abundant evidence that the depth, area, duration, frequency analyses applied in stormwater design are more suitable for those colonial garden suburbs than the densely built up, high rise commercial and residential areas of the modern inner city whose culverts often cannot cope with storm runoff from a largely paved or roofed area.

The human consequences of the hydrologic instability of the tropical city are exacerbated by the squatter problem. Often the unoccupied land on to which squatters move is either steep and relatively unstable sloping ground or low-lying flood prone alluvial terrain along major rivers. Squatters suffer severe losses during floods, yet are the section of the community least able to protect or insure against loss. Ironically, the use of the bulldozer on government housing projects to assist squatters may in itself perpetuate the problem by causing more loss of silt to the stream channels, aggradation of the bed and loss of channel capacity.

The rapid growth of the Malaysian federal capital, Kuala Lumpur, its satellite city, Petaling Jaya and the new Selangor state capital, Shah Alam, in the Sungai Kelang catchment has greatly increased the silt load of the river and changed the channels of many of its tributaries. So rapid has been the residential and industrial growth over the last two decades that channel changes are creating major problems in some areas. All three of the stages of urbanisation listed in Table I are to be found in the Kelang catchment today.

TABLE 1

HYDROLOGIC EFFECTS DURING A SEQUENCE OF CHANGES IN LAND AND WATER USE ASSOCIATED WITH URBANISATION IN KUALA LUMPUR

Change in land or water use	Possible hydrologic effect	Hydrologic effect in Kuala Lumpur
Transition from preurban to early-urban stage :		
Removal of trees or vegetation. Construction of scattered city-type houses and limited water and sewage facilities.	Decrease in transpiration and increase in peak storm runoff. Increased sedimentation of streams.	Development of gullying, as in rubber plantations. Siltation on valley floors. Increased surface wash and soil loss.
Drilling of wells.	Some lowering of water table.	Aggravated by decreased infiltration.
Disposal of domestic and sanitary wastes.	Source of some additional soil water and contimination of nearby wells and spring.	Organic enrichment of streams through direct defecation seepage from earth closets, inflow of water from gardens, rubber factories, animal yards and sawmills.
Transition from early-urban to middle-urban stage :		
Bull-dozing of land for mass housing, top soil removal.	Accelerated land erosion, stream sedimentation and aggradation. Elimination of smallest streams.	Rapid removal of weathered material. Development of dense gully networks on bare sites (e.g. Damansara Heights). Increased peak storm discharges and sediment concentrations. Channel metamorphosis from narrow deep meandering to wide, straight, shallow broadening (e.g. Sungai Anak Ayer Batu).
Mass construction of houses, paving of streets, building of culverts.	Decreased infiltration, increased flood flows, lowered ground water levels. Occasional flooding at culverts. Occasional overtopping or undermining of artificial channel banks on small streams. Rise in water table.	Creation of integrated storm water discharge system conveying thunderstorm runoff rapidly to major streams. Surges of sediment from roadside banks, debris piles and gardens. Occasional local flooding due to decreased channel or insufficient culvert capacity (e.g. Jalan Bungsar prior to 1970).
Discontinued use and abandonment of shallow wells. Diversion of nearby streams for public water supply.	Decrease in runoff between points of diversion and disposal.	Reduction of base flow and thus urban waste dilution capacity in Sungai Kelang, and, to lesser extent, Sungai Gombak.
Untreated or inadequately treated sewage discharged into streams.	Pollution. Death of fish and other aquatic life. Decrease in water quality.	Loss of river ecosystem diversity with establishment of typical narrow-based pollution fauna. Elimination of use of rivers for washing or bathing in urban area.

Transition from middle-urban to late-urban stage :

Urbanisation of area completed by addition of more houses and streets, and of public, commercial and industrial buildings.	Reduced infiltration and lowered water table. Streets and gutters act as storm drains creating higher flood peaks and lower base flow of local streams.	Encroachment on flood plain leading to canalization of Sungai Kelang (double trapezoidal cross-section from Jalan Pekililing to downstream of Brickfields). Change from houses with gardens to apartment blocks with paved car parks. Increased storm runoff. Increased risk of major flooding from exceptional storms of the 1926 and 1971 type.
Larger quantities of untreated waste discharged into local streams. Abandonment of remaining shallow wells because of pollution.	Increased pollution and consequent biological impacts. Further degradation of water quality. Rise in water table.	As urban area grows, squatter settlements expand with consequent sewage disposal problems. Use of detergents washed down household gutters to storm drains increases complexity of river pollution.
Provision of water supplies from outside catchment area.	Increase in local streamflows if supply is from outside basin.	Main effects of diversion of watercourses arise from hydraulic tin mining and irregular releases of mining waste waters to streams.
Channels of streams restricted at least in part to artificial channels and tunnels.	Increased flood damage (Higher stage for a given flow). Changes in channel geometry and sediment load. Aggradation.	Streams diverted into roadside drains of insufficient capacity. Increase in drainage density upstream creates stormwater runoff peaks in excess of drain capacity causing nuisance flooding or roads and buildings in many parts of Kuala Lumpur. Drains and culverts of insufficient gradient lose capacity through siltation.
Construction of sanitary drainage system and treatment plant for sewage.	Removal of additional water from area, further reducing infiltration and recharge of aquifer.	Sewers in Kuala Lumpur only take part of wastes from kitchen sinks and bathwater, the bulk of which enters the storm water system. Sanitary wastes are treated upstream of Petaling, treated water affecting lower reaches between Petaling and Puchong.
Improvement of storm drainage system. Drilling of deeper, larger-capacity industrial wells.	Alleviation of flooding of buildings and streets. Lowered water pressure of artesian aquifer ; perhaps some local overdrafts (withdrawal from storage) and land subsidence.	Nuisance flood alleviation in drained areas but more rapid arrival of storm peaks in main stream. Abundant surface water supplies reduce need for wells in Kuala Lumpur.
Increased use of water for air-conditioning.	Overloading of sewers and other drainage facilities. Possibility some recharge to water table, due to leakage of disposal lines.	Exhaust water vapour and liquids raise temperatures of atmosphere and streams.

* Types of change and possible hydrologic effects in temperate U.S.A. are based on a table by J. SAVINI and J.C. KAMMERER (1961) as modified by S.W. JENS and M.B. McPHERSON (1964).
Impacts in Kuala Lumpur are based on the writer's fieldwork and on J.E. BISHOP (1973).

Transition from preurban to early-urban stage

New suburban growth involves the clearing of former rubber and oil palm plantation land and the reclamation of former tin mining areas. A small tributary of the Sungai Anak Ayer Batu draining a rubber plantation is representative of the conditions immediately before clearance for suburban development. Careful weeding and maintenance of the plantation has ceased. Minor gullies have developed between the trees, changing original first-order streams to second or even third-order channels. Gully bank and head erosion increases sediment yields, but in the heaviest storms overland, linear, concentrated flow begins well upslope of gully heads. The bed of the channel, adjacent to a minor road linking Kuala Lumpur to the northern suburbs of Petaling Jaya, is cut into the clays of the weathered sediments of the Kenny Hill formation. Storm runoff, carries considerable quantities of suspended sediment, rising to over, 5,000 mg l^{-1} , well above the peak concentrations of about 1,000 mg l^{-1} found in the Sungai Gombak forested head waters at 13th milestone. Flood peaks are occasionally sufficient to overtop the channel banks and flow across the road.

Transition from early-urban to middle-urban stage

The effects of mass bulldozing of land for housing are clearly demonstrated by the Bungsar Heights development between Kuala Lumpur and Petaling Jaya. Here a large section of a ridge of the Kenny Hill Formation has been completely cleared for future housing development, creating a steep bare surface in soft, deeply weathered sediments over which gully development and sediment removal has proceeded rapidly causing grave problems for land occupiers further downstream. On the north-east flank of the ridge, water drains to the Sungai Puteh, a small stream flowing in a culvert under Jalan Bungsar, a major traffic route linking Kuala Lumpur and Petaling Jaya. Silt from the cleared area has choked the bed of the Sungai Puteh, threatening the homes of squatters and railway workers, and partially blocking an old culvert under Jalan Bungsar to such an extent that flooding of the road after every major thunderstorm led to the construction of a much larger culvert in 1970. Prior to its construction, heavy traffic had to be diverted by alternative, congested routes with many hours being lost by the delays caused by flooding.

On the southwest flank of the Bungsar ridge rises the Sungai Anak Ayer Batu, which flows through Lalang and Belukar to the University of Malaya campus. At peak discharge following rainfall with an intensity of 100 mm $hour^{-1}$ for at least 45 minutes, the stream carried 81,230 mg l^{-1} , the highest concentration measured anywhere on the Kelang catchment. If it is assumed that runoff per unit area from the Sungai Anak Ayer Batu is similar in volume and distribution to that in Kelang itself, the suspended sediment load of the Anak Ayer Batu would be of the order of 800 m^3 km^{-2} yr^{-1} , compared with 25 m^3 km^{-2} yr^{-1} on the Gombak at the 13th milestone weir, 463 m^3 km^{-2} yr^{-1} on the Gombak on the northern edge of the city at Jalan Pekililing, and 336 m^3 km^{-2} yr^{-1} on the Kelang just above the tidal limit at Puchong weir.

The changed runoff regime and increased silt load have led to the erosion of the banks of the Sungai Anak Ayer Batu and its metamorphosis (SCHUMM, 1971) from a relatively deep, winding channel to a straighter, shallower, wider and steeper channel able to cope with a more episodic regime. At high flows the whole channel is occupied by rapidly flowing sediment-laden water, while at low flows the Talweg winds between bed forms on coarse sand or braids through rapidly deposited coarse debris. These channel adjustments have threatened playing fields at the Mosque at the University of Malaya, requiring expensive protective measures such as the installation of gabions. Storm runoff often cuts campus roads and causes havoc in settlements further downstream.

Streams like the Anak Ayer Batu carry large pulses of sediment into the main stem of the Kelang. Sudden loss of channel capacity due to the dumping of such large volumes of sediment in the main stream can cause local flooding at discharges less than those normally associated with overbank flow (I. DOUGLAS, 1975).

Transition from middle-urban to late-urban stage

The growth of Kuala Lumpur from a small trading post for Chinese tin-miners in the 1850s to a modern federal capital with multi-lane highways and multi-storey office buildings has caused an escalation of land values, with increased intensity of land use for commercial premises in the core of the city around the confluence of the Sungai Kelang and Sungai Gombak, and the use of increasingly steeper land for housing. Twice in the last fifty years the central business district has suffered major flooding from exceptional storms which produced prolonged downpours right across the Malay peninsula. Although the storms were natural events which caused flooding in all major rivers, human activity in the Kelang catchment concentrated their effects, especially in Kuala Lumpur, where, prior to 1926, buildings extended right to the top of the banks of the river channel proper.

After the serious losses of the 1926 flood the section of the Kelang through the city centre was straightened and given a double trapezoidal cross section to accommodate flood flows. The effect of these works was to extend the storm water drainage system to the downstream limits of the city. Runoff from short duration, but intense, thunderstorms causes rises to within the higher, wider part of the cross-section where the greater width can contain the increased discharge. However, further urban growth since the canalisation of the 1930s, especially the Malay working class and squatter settlements downstream of Brickfields at Kampong Pandan, Kampong Haji Abdullah Hukum and Kampong Pandan Dalam, has again produced intensive flood plain occupance with a large population at risk. Flood waves pass through the canalized section at high velocity but enter a more restricted, tortuous channel downstream of Brickfields where pulses of sediment discharge from tributaries cause occasional restrictions. Heavy thunderstorms in late 1969 produced flooding in these Malay Kampongs on several occasions.

In January 1971 the extreme prolonged rains of 1926 were repeated. Again the central business district was inundated, the basements of many banks and insurance buildings containing valuable documents suffering particularly. Although the total rainfall over the catchment area was probably less than in 1926, the depth of flooding was greater, probably as a result of the greater impermeable surface and larger agricultural and urban area.

Loss of channel capacity is probably important in the local flooding caused by small area, short duration, high intensity thunderstorms, but slow effects in major floods tend to clear the channel of obstructions. However, bank erosion is a major problem in all natural channels in the urban area, with much haphazard protection of industrial properties.

Further complications have arisen from the building of houses on steep, hilly land which requires steep access roads. During storms such roads become cascades of water, often carrying silt from minor landslips. Roadside drains on former first-order valley floors are often too small to carry this runoff, which can spread right across roads and through houses to reach river channels. As in many cities throughout the period since the industrial revolution, the city as a physical system requiring adequate sewerage and drainage channels has not been perceived by planners and developers. Culverts adequate when urban development only occupied a quarter of a tributary catchment are quite inadequate when the whole catchment has been cleared and developed.

TABLE 2

SUSPENDED SEDIMENT AND DISSOLVED SOLIDS CONCENTRATIONS IN THE SUNGAI KELANG CATCHMENT

Stream and location	Range of Suspended Sediment concentration $mg\ l^{-1}$	Range of total dissolved solids concentration ppm
Rubber plantation of Sungai Anak Ayer Batu at Jalan Damansara	4- 5,146	13-98
Sungai Gombak at 13 th milestone weir	7- 1,080	10-140
Sungai Anak Ayer Batu at Jalan Damansara	55-81,230	29-110
Sungai Gombak at Jalan Pekililing	109- 4,237	17-113
Sungai Kelang at Puchong	56- 8,622	37-145
Sungai Kelang at Jalan Pekililing (above Gomback confluence)	33- 1,823	13-103

OVERALL EFFECT OF URBANISATION ON THE SUNGAI KELANG

Comparison of the ranges of suspended sediment and total dissolved solids concentrated in Table 2 shows that silt is the dominant pollutant of the Kelang. Only once in 67 samples taken at Puchong was the suspended sediment concentration less than 100 mg l^{-1} and in 38 samples it exceeded 1000 mg l^{-1}. The total suspended sediment load carried past Puchong exceeds that estimated for the Irrawaddy at Prome, Burma and the Mekong at Vientiane (Table 3), but is of the order of that carried by the Chindwin and less than that carried by small streams draining badly eroded marls in Indonesia.

Although at any given discharge per unit area, the load carried past Puchong exceeds that carried at the same discharge past stations higher upstream on the Kelang and its major tributaries, the total load per unit area at Puchong is considerably less than that carried by the Gombak at Jalan Pekililing. At Puchong the effects of all the consequences of urbanisation, agriculture, forestry and tin mining are felt. The flows at Puchong are the expression of the combined effects of flood waves and sediment pulses from a number of tributaries. As most thunderstorms only produce rain over a portion of the catchment, the surge of sediment from one tributary is diluted by the base flow from another. On the headwaters of the

Kelang the Kelang Gates Dam holds back the public water supply and releases clear compensation water to the Kelang. At the confluence of the Kelang and Gombak in Kuala Lumpur, the silt laden Gombak water is diluted by the relatively clear Kelang water (Table 2). The Gombak usually carries high concentrations of suspended sediment (over 200 mg l^{-1}) from tin-mining wastes, so the contrast between the total load carried by the Gombak and the Kelang at Puchong may be explained by the persistence of high sediment concentrations at all times in streams from tin mining areas, while streams draining the urban area only carry high sediment concentrations during peak stormwater discharges.

TABLE 3

ESTIMATED ANNUAL DENUDATION RATES
(for the study period 1st june 1969 - 31 st May 1970)

Stream and Location	Catchment area	Rate of denudation ($m^3 km^{-2} yr^{-1}$)	
		suspended	dissolved
Sungai Gomback at 13th milestone	41.3	24	15
Sungai Gomback at Jalan Pekililing	140.0	463	31
Sungai Kelang at Puchong	1196.6	336	24
Comparative estimates (for sources see Douglas, 1968)			
Irrawaddy at Prome	367,000	309	
Mekong at Vientiane	229,000	164	
Chindwin, Burma	114,500	347	

URBAN FLUVIAL GEOMORPHOLOGY AND PLANNING

The Kuala Lumpur case study demonstrates the need for extending soil conservation practice into urban areas. New subdivisions should be designed to minime soil loss, yet cater for efficient storm water runoff. Practices for urban watershed management developed in Maryland and in Australia could be adopted in the humid tropics, but because of the extreme erosion hazard on bare soil, experimental catchment data are needed to calculate tolerable thresholds of channel capacity and sediment loads.

Attention should be paid to the dynamics of sediment movement in urban areas, especially the effects of a sequence of storm events on sediment production (I. DOUGLASS, 1975). The magnitude and frequency of local flood events caused by individual thunderstorms has to be distinguished from exceptional widespread rain events. The latter produce flood flows like the 1971 Kuala Lumpur floods and the 1974 Brisbane floods on which the extra effects of urbanisation are small. Land use adjustment to cope with such rare events is probably not feasible, but insurance against losses from such events could be made more readily available. However, much of the more frequent, more localised flooding arising from urbanisation could be eliminated by increasing and maintaining channel capacities, reducing the supply of sediment to rivers and introducing appropriate detention structures to slow down the rate of storm runoff to major streams.

The geomorphologist can assist in this management of urban drainage networks by identifying erosion hazards, mapping areas of slope instability and monitoring fluvial processes in the urban environment. With the rapid growth of large cities in the humid tropics, the need for this kind of work is urgent.

ACKOWLEDGEMENT

The collection and analysis of data used in this paper had been made possible by assistance and grants from the Universities of Hull, Malaya and New England, the Natural Environment Research Council of the United Kingdom, the twentieth International Geographical Congress Fund, and the United Kingdom Grant-in-aid of Scientific Investigations administered by the Royal Society. The help of many individuals, especially Soh Hoo Hong in the laboratory, is gratefully acknowledged.

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DISCUSSION

J. Flouriot : Les problèmes géomorphologiques liés à l'urbanisation sont, au Zaïre, du même type que ceux signalés en Malaisie par M. Douglas : enlèvement de matériaux et ravinement sur les pentes sur sol peu cohérent (sables), remblaiement très rapide des fonds de vallée et engorgement des réseaux de drainage existants. La destruction de la végétation ne suffit pas pour expliquer le phénomène, il faut aussi que la densité de la population atteigne un certain seuil. A Kinshasa, l'érosion se déclenche sur des pentes de 4 % après défrichement alors que la densité de population atteint 20 à 30 habitants à l'hectare.

I. Dougals : La population humaine déclenche l'érosion par l'évolution des chemins, sentiers et routes et par leur activité dans les jardins urbains. Mais, souvent, sur les roches assez altrérées non homogènes, le défrichement de la végétation déclenche l'érosion et le ravinement. L'importance de la lithologie pour la géomorphologie urbaine doit être souligné.

J.P. de Queiroz Neto : Il faut tenir compte des différences de comportement selon la nature de sous-sol : à Sao Paulu, sur le massif ancien, les problèmes d'érosion ne sont pas aussi importants que l'augmentation du ruissellement qui produit des crues violentes. Sur les roches sédimentaires, l'érosion devient très importante et la masse des sédiments transportés par l'eau provoque des problèmes d'ennoyage des fonds de vallée.

I. Douglas : La grandeur des villes brésiliennes et leurs problèmes de glissement de terrain sur l'escarpement vers le littoral oriental souligne l'importance de l'histoire géologique et des mouvements du sol. Les processus géomorphologiques dans les villes ont toujours des conséquences sociales et économiques sévères.

O. Slaymaker : Was the effect of urbanisation on solute load equally spectacular ?

I. Douglas : As shown by the figures of solute load in Table 3, there is an increase in solute load between the 13 m.s. and Jalan Pekililing stations on the Sungai Gombak. Some of this increase is due to the passage of the river through the Kuala Lumpur limestones, but part to the discharge of organic and inorganic wastes from homes, farms and factories. However the effect of urbanisation on solute load was far less dramatic than on sediment load. The dominant pollutant of the Sungai Kalang system is sediment.