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Evaluation of runoff sources in a forested basin in a wet monsoonal environment: a combined hydrological and hydrochemical approach

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ABSTRACT A semiquantitative description of stormflow producing mechanisms is given for a forested basin in central Java, Indonesia. Storm runoff events, consisting of a mixture of channel precipitation, Horton overland flow, saturation overland flow and subsurface flow were studied in terms of contributing areas. Occurrence and importance of the various flow types are tentatively evaluated on a lumped basis per storm by combining field observations and the concept of "minimum contributing area". Description of subsurface stormflow behaviour during storms became possible to some extent by detailed water quality sampling. Subsurface flow contributes to total quickflow throughout storms via the mechanism of displacement flow, becoming dominant during the later stages of the storm hydrograph. It is concluded that the variable source area concept is applicable to this tropical basin.

Estimations des diverses composantes de l'écoulement dans un bassin forestier en climat de mousson humide: une approche combinée hydrologique et hydrochimique
RESUME On donne une description semi-quantitative des mécanismes générateurs de crue dans un bassin forestier du centre de Java, Indonésie. Les débits totaux de crue, consistant en précipitations sur le cours de la rivière, ruissellement superficiel de Horton, ruissellement superficiel par saturation des sols et écoulement hypodermique ont été étudiés en caractérisant l'aire d'origine de chaque terme. On a tenté d'évaluer la nature et l'importance des différentes composantes de l'écoulement en combinant les observations sur le terrain et la notion théorique de "surface contribuante minimale". Une description de l'écoulement hypodermique pendant les crues a été rendue possible, tout au moins en partie par l'analyse de la qualité des eaux. L'écoulement hypodermique contribue au ruissellement rapide total ("quickflow") tout au long des crues par une mécanisme de piston, qui devient dominant lors des stades tardif des crues. En conclusion il apparait que la notion de "l'aire contribuante variable" s'applique à ce bassin tropical.

INTRODUCTION

In spite of an increasing research interest in tropical forests during the last decade, processes of storm runoff generation have received relatively little attention. Yet, knowledge of such processes in forested tropical basins may be helpful in predicting hydrological consequences of changes in land use.

Although some work has been conducted on overall basin response to rainstorms (Dagg & Pratt, 1962; Low, 1971; Gilmour, 1975), studies relating timing and magnitude of the storm hydrograph to source areas are very rare indeed for the tropics. Of the various types of flow that may contribute to storm runoff, overland flow is probably best studied, usually in relation to sediment production (e.g. Kellmann, 1969; Leigh, 1978a; Lundgren, 1980; Wiersum, 1983). Rates of subsurface flow ("throughflow") under tropical forest have been measured in such environments as the superwet rainforests of Queensland (Bonell & Gilmour, 1978) and Dominica (Walsh, 1980), the humid lowlands of Malacca (Leigh, 1978b) and the more seasonal forests of Amazonas (Nortcliff & Thornes, 1981) and Ivory Coast (Roose, 1982). Of all these studies only Bonell & Gilmour (1978) related the behaviour of their stream during storms to hillslope processes in a quantitative manner.

The present paper presents some data on storm runoff for a small forested Indonesian drainage basin, as collected within the framework of a larger investigation of biogeochemical cycling patterns in tropical forest plantations (Bruijnzeel, 1983). Over 40 runoff events, consisting of a mixture of channel precipitation, Horton overland flow, saturation overland flow and subsurface flow (notably local pipeflow and throughflow) have been studied during the rainy seasons of 1975/1976 and 1976/1977 in terms of contributing areas.

To supplement the hydrological observations a limited number of runoff waves and soil moisture, overland flow and pipeflow were sampled for water quality determinations. In this way a separation between chemically more concentrated "baseflow" and dilute stormflow was computed along the lines indicated by Pinder & Jones (1969).

DESCRIPTION OF STUDY AREA

The 19-ha Kali Mondo basin is situated in the hilly northern rim of the South Serayu range, *c.* 5 km south of Banjarnegara, south-central Java, at 7°26'S lat. and 109°45'E long. Basin elevation ranges from 508 to 714 m a.m.s.l.

The site receives on average (1926-1977) 4770 mm of rain per year, distributed over 176 raindays. A dry season occurs between July and September, when on average two months experience rainfall totals of less than 60 mm. Precipitation usually falls in the late afternoon with most showers not lasting more than 2 h. Mean annual Penman evaporation amounts to 1345 mm.

The steeply dissected basin is underlain by Quaternary volcanic ashes of an andesitic nature. Slopes are usually convex and soils developed in the ashes are humic Andosols (FAO/UNESCO, 1974) with locally slight signs of pseudo-gley at a depth of 200-250 cm. The Kali Mondo has incised itself into the underlying Lower Tertiary rocks which consist of andesitic breccia deposits and - in the lower reaches of the basin - shales. Flood-plain size is very limited, with an abrupt and often canyon-like transition to the hillslopes. Ash cover thickness is generally over 6 m on the divides, but may become as thin as 1 m on some steep slopes near the stream (Fig.1).

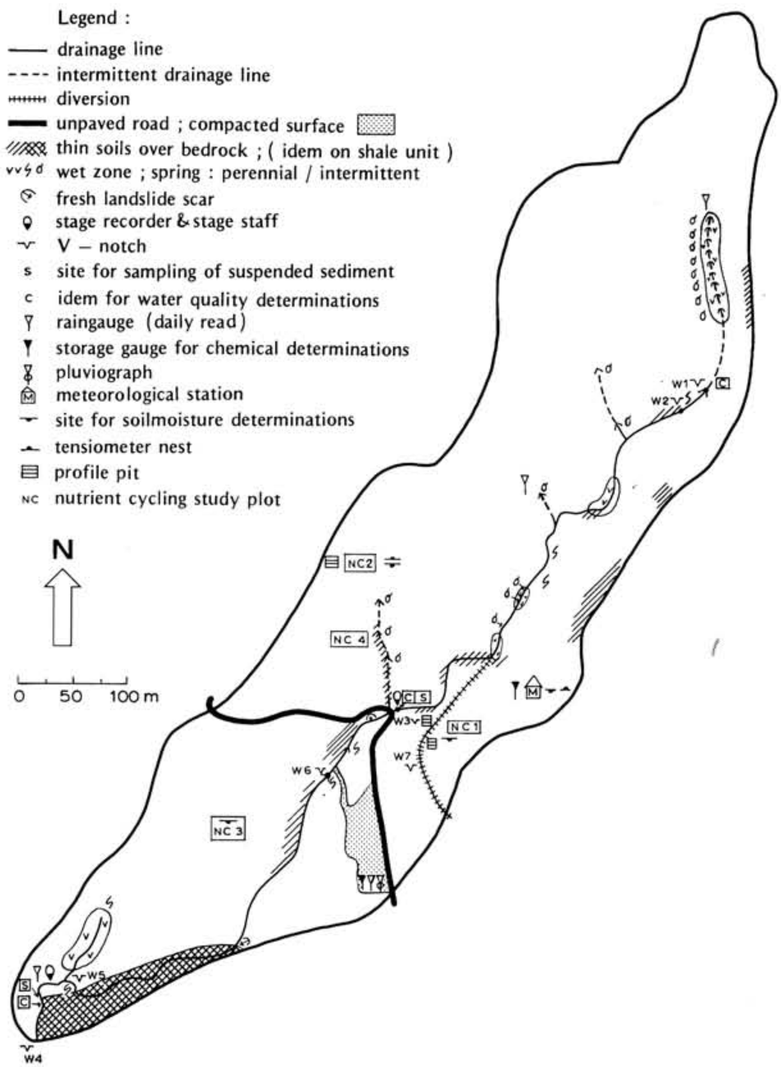

FIG.1 Kali Mondo drainage basin: instrumentation and hydrological features.

Infiltration rates of these forest soils are very high, but are virtually zero on compacted surfaces such as trails and the yard of the forestry station (Fig.1).

Basin vegetation consists of *Agathis dammara* plantations ranging in age between 11 and 35 years and exhibiting different degrees of stocking. In the more open stands vigorous shrub thicket is found on the better sites, whereas poorer sites have been invaded by alang-alang grasses *(Imperata cylindrica)*. Further details of drainage basin characteristics are given by Bruijnzeel (1983).

PROCEDURES

The hydrological instrumentation of the basin is shown in Fig.1. The raingauges were inspected daily and the arithmetical mean of all readings was used for the areal precipitation estimate. Most of the data presented in this paper have been collected during the rainy season of 1975/1976. During this time streamflow was monitored at the basin outlet V notch weir by a water level recorder equipped with a daily chart for detailed reading. At the start of the 1976/1977 wet season a second weir and recorder (W3 in Fig.1) were installed just upstream of the compacted area. Both this and the existing recorder were equipped with weekly charts since November 1976. Small discharges (up to 20 $l\ s^{-1}$) were determined at these and other sites (see Fig.1) by volumetric gauging, higher flows were usually measured by the salt dilution or the area-velocity methods.

Rates of surface water entry were determined with a small double-ring infiltrometer (Hills, 1970) at more than 40 sites (three to five measurements per site) randomly distributed over the basin. Subsoil permeabilities were measured in the same way in a soil pit of mid-slope position (NC 1 in Fig.1).

Size of channel area and associated saturated zones, occurrence and size of areas having surface compaction or thin soils over bed-rock as well as locations and discharge of springs and pipes were mapped during a hydrological reconnaissance survey (Fig.1).

Nine runoff waves were sampled throughout their duration to obtain information on variations in stream water quality during storms: four at the lower weir and five at the upper weir (W3, see Fig.1). Riparian and hillslope soil moisture was extracted by means of vacuum tube lysimeters (Wood, 1973). Major springs and baseflow were sampled on a weekly basis.

RESULTS AND DISCUSSION

A hydrological approach to runoff sources

In the present context "quickflow" or "stormflow" is defined as the amount of water leaving the drainage basin during and "immediately after" a rainstorm minus the basal flow. The latter statement requires some explanation. For most storms the bulk of the quickflow is made up of some kind of overland flow and subsurface flow ("translatory flow") from the immediate surroundings of the stream. The time required for this water to travel from the headwater area to the lowest gauging point exhibits a strong inverse relationship with prevailing discharge level. Application of travel times obtained with this formula (30-120 min) to storm hydrographs revealed the co-incidence of the end of overland flow and the second of two knick-points on the recession limb. The line between this point and the start of hydrograph rise has been taken as the separation of quickflow and baseflow. In this way a consistent set of data was obtained. Although subsurface flow will continue to contribute to the recession limb of the storm hydrograph beyond the selected knickpoint, this is seen as a continuous process which may last for days. As such it has been included in the baseflow component from which it is hard to distinguish hydrologically.

During the rainy season the Mondo basin reacts to rainfall almost immediately. Hydrographs are typically single peaked, unless reflecting more complex patterns in rainfall intensity. Major storms produce an increase in baseflow but no secondary peak. Quickflow volumes (Q_q) of 42 storms recorded during the 1975/1976 season related to storm rainfall (P) according to the equation:

$$Q_q = 0.009\ P^{1.415} \qquad (r^2 = 0.90) \qquad (1)$$

with Q_q and P expressed in millimetres. Distinguishing between "relatively wet" and "relatively dry" antecedent conditions did not raise the coefficient of determination.

Quickflow normally makes up 5-7% of monthly runoff in the wet season, a figure comparable to the 8-9% reported by Dagg & Pratt (1962) for a Kenyan basin of similar geology. It is distinctly lower, however, than found for forested basins in Dominica (Walsh, 1980; up to 20%) or Queensland (Bonell & Gilmour, 1978; 47% on an annual basis). (The presently applied quickflow-separating technique leads to slightly lower estimates than a more traditional approach (cf. Hewlett & Hibbert, 1967). In the latter case one would arrive at a figure of 10% at most. Implications of differences resulting from the two techniques are currently being evaluated.) Clearly the Javan and Kenyan basins have smaller contributing areas than the other basins quoted, reflecting their specific geological and climatological settings.

Dickinson & Whiteley (1972) defined the concept of "minimum contributing area" (MCA) as the minimum area, which, contributing 100% of the effective rainfall, would yield the measured direct

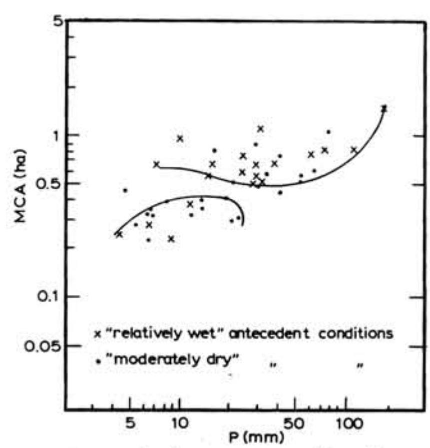

FIG.2 Minimum contributing areas vs. precipitation for the Kali Mondo basin (wet season values).

runoff. Values of MCA have been evaluated for the storms referred to above, with MCA expressed in hectares (Fig.2). Gross rainfall instead of effective rainfall had to be used since no canopy saturation value for the drainage basin vegetation was available. This resulted in slightly lower estimates for the MCA's corresponding with low rainfalls. Minimum values of MCA in Fig.2 amount to 0.22 ha, whilst MCA's of more than 0.90 ha (5% of basin area) are only rarely attained.

Field observations revealed that stormflows in the Mondo basin consisted of a mixture of channel precipitation (CP), saturation overland flow (SOF) from wet riparian zones, Horton overland flow (HOF) from the compacted area as well as subsurface flow (SSF) emerging from pipes and cracks in the stream banks. The relative importance of these flow types will now be discussed in terms of "sub-MCA's".

Permanently wet zones are found along the principal drainage lines (Fig.1), making up *c.* 0.09 ha. Channel area itself varies between 0.145 and 0.155 ha. Together this implies a basic contributing area of 0.24 ha or 1.3% of total basin area. This agrees well with the minimum value of 0.22 ha in Fig.2, the difference being caused by the use of gross rather than effective rainfall in the computation of MCA. This basic area produces CP, SOF and SSF, probably via a "push-through" mechanism ("translatory flow" of Hewlett & Hibbert, 1967).

Horton overland flow-producing trails and yards occupy *c.* 0.165 ha or 0.9% of total basin area. This type of overland flow has never been observed on the forest floor. Even rainfall intensities of 200 mm h^{-1} (as recorded on 25 November 1975) were not sufficient to produce HOF on noncompacted surfaces.

So far the various flow categories could be linked to a certain areal extension by field mapping. Such an approach is not directly possible for the subsurface component (SSF). Although perhaps a corollary of the limited size of the sample population, Fig.2 suggests a low frequency of MCA-values between 0.4 and 0.5 ha. Since the headwater area of the basin produces runoff only above a certain level of wetness (Bruijnzeel, 1983), it may be argued that an MCA of 0.5 ha represents a threshold value for a significant contribution of SSF. Taking the maximum value of MCA observed during the 18 months of investigation (viz. 1.45 ha - 7.7% of basin area - for a rainstorm of 169 mm fallen in 3 h) as a first approximation of the maximum annual flood, an additional contributing area of 1.05 ha (1.45 minus 0.4) has to be accounted for. This contributing zone will not be evenly distributed along the stream, but will rather consist of isolated saturated patches. Areal extent of these will be governed by spatial and vertical distribution of permeabilities (Bonell & Gilmour, 1978) and local topography (Anderson & Burt, 1978).

Areas of special interest, therefore, are those with bedrock relatively close to the surface (cf. Fig.1), major concavities (discharging their water through pipes in the present case) and the lowermost parts of hillslopes. Channel lengths associated with "shallow rock areas" are such that a sub-MCA of 0.25 ha at most can be assigned. Similarly the "headwater pipe area" contributes a maximum MCA of 0.22 ha (Bruijnzeel, 1983).

Since the stream is mostly incised in a canyon-like manner there is little opportunity for widespread extension of saturated lenses in the valley bottom. This area, termed "occasionally wet area" (OW) contributes *c.* 0.06 ha. With respect to the rest of the riparian zone does the limited information on "riparian permeability" suggest that the average of 760 ± 640 mm h^{-1} (n = 10, surface entry values) is sufficient to account for the remaining 0.5 ha needed to explain the maximum observed value of MCA. Figure 3 summarizes the above information on sub-MCA's.

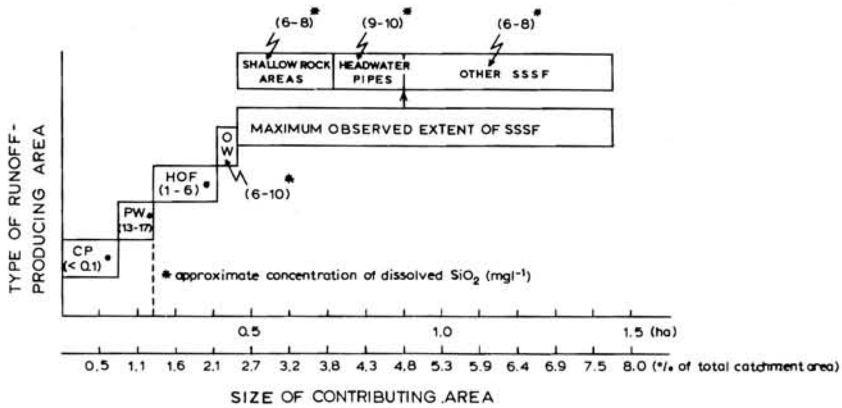

FIG.3 Contributing area and runoff type in the Mondo basin.

A hydrochemical approach to runoff sources

Thus far the various contributions to the storm hydrograph have been considered on a lumped basis. The contrast in chemical composition between baseflow and (bulk) quickflow was used by Pinder & Jones (1969) to separate the two by means of a mass balance equation having as its solution:

$$Q_{bf} = [(C_t - C_q)/(C_{bf} - C_q)]Q_t \tag{2}$$

where Q_t and Q_{bf} are respectively discharge of mixed water ("total runoff") and baseflow (l s^{-1}); and C_t and C_q are respectively concentration of a selected chemical parameter in the mixed water and quickflow (mg l^{-1}).

The question arises to what extent the complex patterns of storm runoff generation prevailing in the Kali Mondo drainage basin can be approximated by this two-component model. Direct data on the discharge patterns of the various runoff components during the storms are not available, but their approximate chemical concentrations are known. Especially silica concentrations differ per flow type and therefore are a good marker (Fig.3). As a compromise weighted mean silica concentrations were assigned to the bulk quickflows of those runoff events that were sampled in detail, based on the approximate relative importance of each flow type according to the MCA-approach.

Figure 4 shows the variation of streamwater silica concentration with time and discharge and the resulting runoff separation for a double-peaked storm of 89 mm falling in 2 h. Other examples are

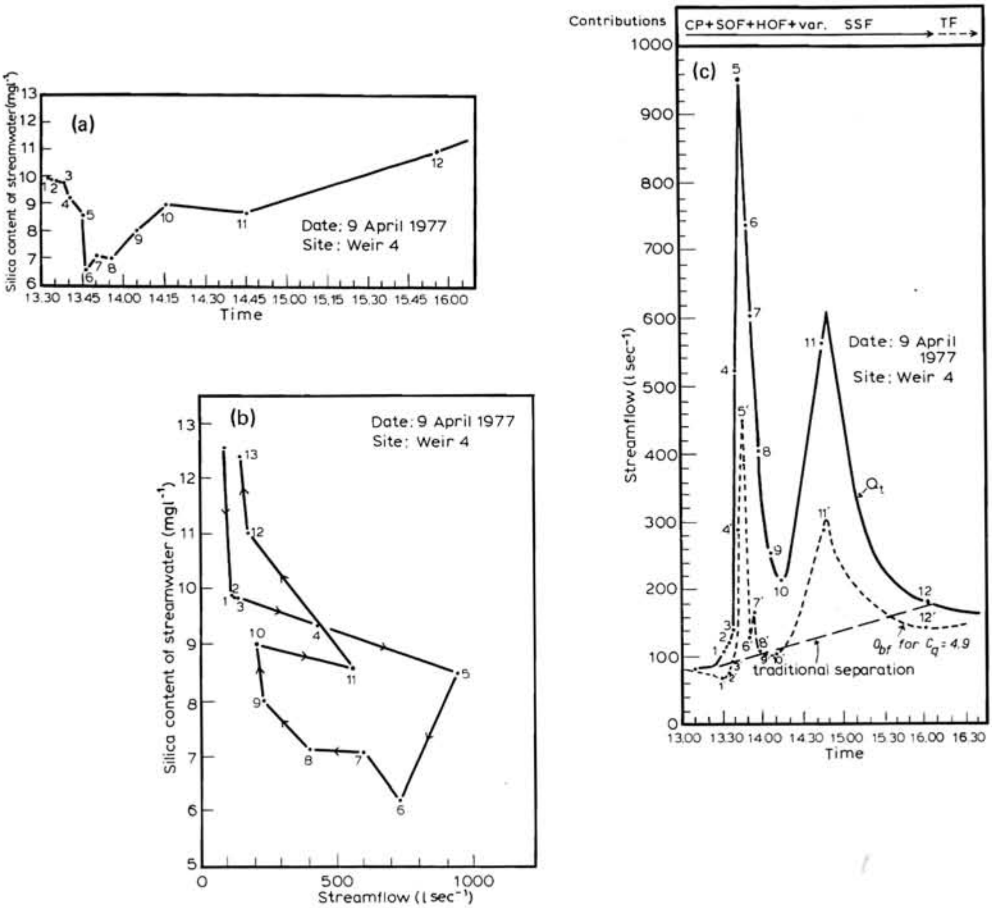

FIG.4 Variation of streamwater silica concentration with time and discharge and a separation of quickflow and baseflow according to equation (2).

given by Bruijnzeel (1983).

The strongest dilution of basal flow is observed for the rising limb of the hydrograph, with a slower return to pre-storm concentrations on the recession limb, giving the typical loop shown in Fig.4(b). Strong dilution is interpreted as contributions by CP and HOF mainly, whereas the apparent "stabilization" of silica levels during much of the recession will represent a dominance of inflows from subsurface sources.

The mixing model of equation (2) indicates a rapid contribution of water having pre-storm silica concentrations ("baseflow") which closely follows fluctuations in total runoff (Fig.4(c)). The data suggest that the mechanism at work is "translatory flow" or "displacement flow" (Hewlett & Hibbert, 1967). This flow type occurs throughout the runoff event but becomes the dominant supplier of runoff during the later stages (cf. Fritz *et al.*, 1976). It remains difficult, however, to translate these findings into a general runoff separation technique.

CONCLUSIONS

In conclusion it can be stated that the investigated basin responds to rainfall in a quite predictable manner. Field mappings indicate that contributions to stormflow by CP, HOF and SOF originate from well-defined and relatively constant areas in the basin. Subsurface contributions are more variable depending on basin wetness before and during storms and the "variable source area" model seems applicable to this tropical basin. Subsurface flow contributes throughout storms via a mechanism of displacement flow and becomes dominant during the recession stage.

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