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The role of subsurface water exfiltration in soil erosion processes

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ABSTRACT The study describes overland flow phenomena in relation to erosion processes in a small forested drainage basin located in the western suburbs of Tokyo, Japan. The field evidence showed that the major portion of overland flow was produced by water flowing out onto the soil surface through decayed stumps and soil pipes. Outflow points were concentrated in small restricted areas on the valley floor where the hydraulic gradients of the subsurface water evidenced upward flow toward the ground surface. These phenomena were largely controlled by dynamic conditions of the flow system within the subsurface zone. The concept that erosion processes are largely controlled by overland flow due to subsurface water exfiltration is defined as the Subsurface Water Exfiltration Erosion Model (SWEEM). Using this model it would be possible to explain the development of the stepped profile observed in the study basin.

INTRODUCTION

The Horton (1945) infiltration model of runoff and erosion involves the generation of surface runoff when rainfall intensity exceeds the infiltration capacity of the soil and this overland flow is responsible for soil erosion. This form of runoff is known to occur on unvegetated hillslopes which have low infiltration capacities and little soil development (Dunne *et al.*, 1975).

According to Kirkby & Chorley (1967), the Horton model is one end member of a suite of erosion models. The other end member is the GOEM (Groundwater Outcrop Erosion Model) concept developed by De Vries (1976) in the Netherlands. In the GOEM model, infiltration capacity is not exceeded and no overland flow occurs. This concept could, however, only be applicable to areas of relatively flat land with high soil permeability and moderate precipitation rates such as in the Netherlands.

Most of the recent studies of storm runoff in forested drainage basins in humid regions have stressed that Horton overland flow does not occur and that subsurface storm flow is the main source of storm runoff (Whipkey, 1965, 1969; Hewlett & Hibbert, 1967; Weyman, 1970; Pilgrim *et al.*, 1978; Mosley, 1979). Dunne & Black (1970a, 1970b) and Freeze (1974) emphasized the importance of the variable source area which generates saturation overland flow as the main source of storm runoff. On the other hand, some field investigations have shown that subsurface water may move rapidly through soil pipes (Jones, 1971) or through biologically created non-capillary channels

(Whipkey, 1965, 1969).

These recent studies of the behaviour of water during storm events in forested basins have proposed new concepts for possible flow and erosion models. If the occurrence of overland flow on the hillslope is restricted, the areal extent of terrain subjected to surface erosion by running water may be much smaller than Horton supposed.

The purpose of the present study is to analyse basin response during a typical storm event and to provide additional information on the relative importance of runoff generating mechanisms.

THE STUDY AREA

The study was conducted in a small forested drainage basin with an area of approximately 2.2 ha in the headwaters of the Tama River system located in the western suburbs of Tokyo, Japan (Fig.1). The

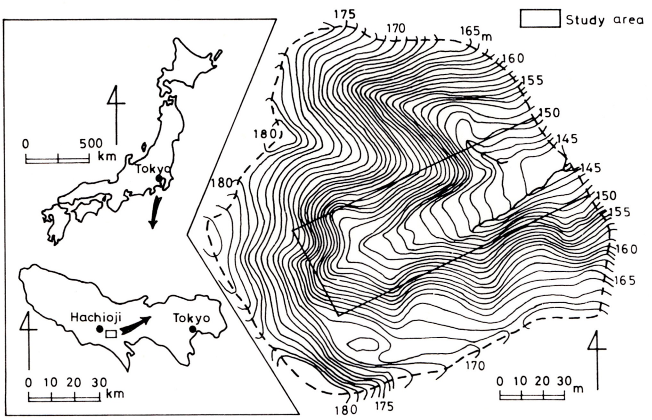

FIG.1 Location of the study area.

basin is located in the Tama Hills which are underlain by the Pliocene Miura group and Pleistocene Narita group (Juen & Harada, 1961). The former is composed of sand, mud and gravel and the latter of gravel and volcanic ash soil, the so-called Kanto Loam. The topography is typical of a dissected diluvial hill having a valley floor slope of about 12% and steep hillside slopes of about 50%. Grain size analyses of soil samples from the valley floor are shown in Fig.2. The upper 2 m of the soil are broadly classified as clay loam and silty clay. The vegetation consists of dense deciduous trees approximately 15 m in height and sparse bamboos 1-2 m high with a dense ground cover of ferns and small shrubs.

A special feature of the drainage basin is the wide extent of the valley floor in comparison with the total basin area (Fig.1). This is a common feature of the dissected diluvial hills located in the Kanto district of Japan. The valley floor longitudinal profile is shown in Fig.3. The slope profile of the valley floor is composed of five integral parts, i.e. upper convex slope, straight slope, cliff face, debris slope and lower concave slope, respectively. These

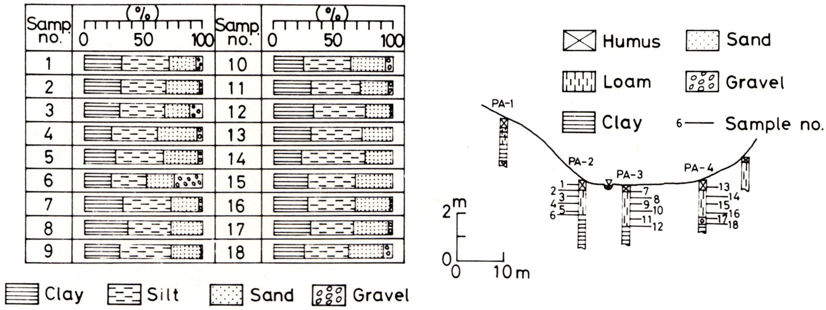

FIG.2 Grain size analyses.

topographical features may be attributed to the results of erosional processes acting on the drainage basin. These step features in the slope profile have been recognized in the semiarid Great Plains of the USA by Hadley & Rolfe (1955) and named seepage steps.

THE EXPERIMENTAL DESIGN

Within the drainage basin, the valley floor was instrumented for intensive study (Fig.4). To analyse the dynamic response of the basin during a storm event, tensiometer and piezometer nests were utilized. Pressure heads of soil water were measured at 10 sites using 54 tensiometers. The location of these sites is shown in Fig.4. Pressure heads of groundwater were measured by piezometer nests which were arranged in nests of one to three piezometers at

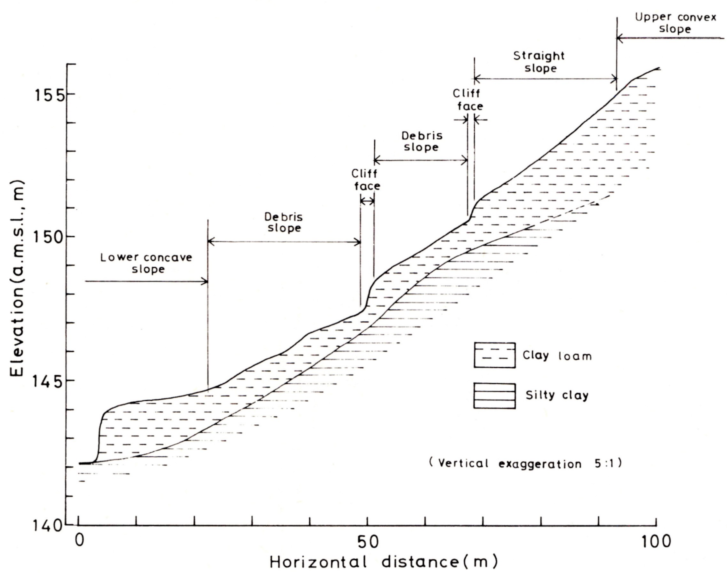

FIG.3 Longitudinal profile and geological section of the valley floor.

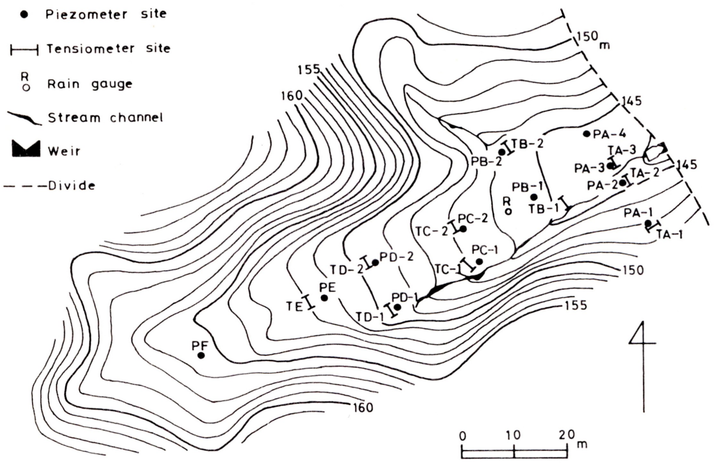

FIG.4 Map of the valley floor studied.

the 12 different sites shown in Fig.4. The piezometers consisted of 7.5 cm diameter PVC pipe with the perforated lower end covered with a fine mesh screen. A schematic diagram showing the installation of a tensiometer and piezometer nest is shown in Fig.5.

Precipitation was measured by a tipping bucket recording raingauge located in the middle part of the valley floor, and discharge from the basin was continuously recorded at a 90° sharp-crested V-notch weir (Fig.4). Contributing areas of overland flow to the storm hydrograph were mapped by field observations during storm events.

WATERSHED RESPONSE DURING A TYPICAL STORM EVENT

Intensive field observations were carried out from August to October 1980. During this period, one of the major storm events occurred from 9-12 September and provided a total rainfall of 195.0 mm. Fig.6 shows the hydrograph for this heavy storm. The

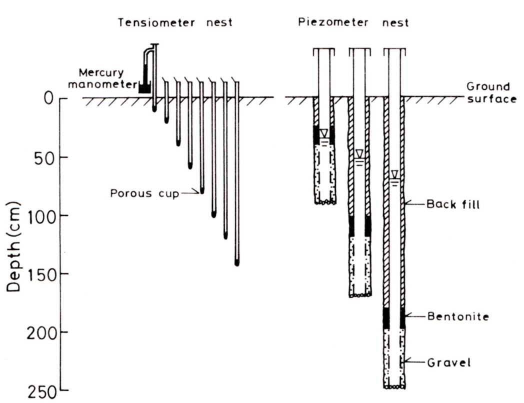

FIG.5 Schematic diagram showing the installation of a tensiometer and a piezometer nest.

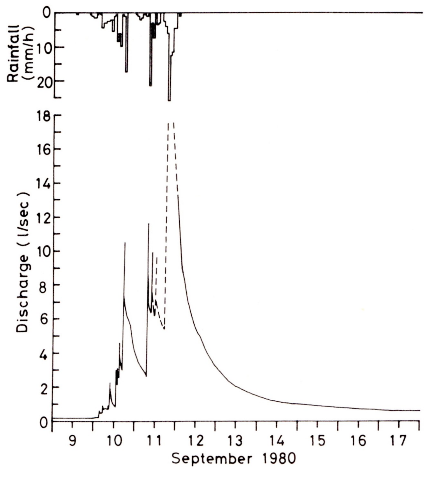

FIG.6 Discharge hydrograph for the storm event, 9-12 September 1980.

rainfall record evidenced three separate peaks and corresponding hydrograph peaks were observed. Discharge began within minutes of the onset of rainfall and the peak discharge occurred within 10 min of the rainfall peak.

In this drainage basin, overland flow occurs on the valley floor when the total amount of precipitation exceeds 50 mm. No significant overland flow is produced on the steep hillside slopes during storm events.

Fig.7 shows the overland flow contributing area of the storm hydrograph at the time of maximum discharge (0200 h, 12 September). It is obvious that overland flow does not occur over the whole area of the valley floor but occurs from restricted areas. Observations made during the storm indicated that the majority of the overland

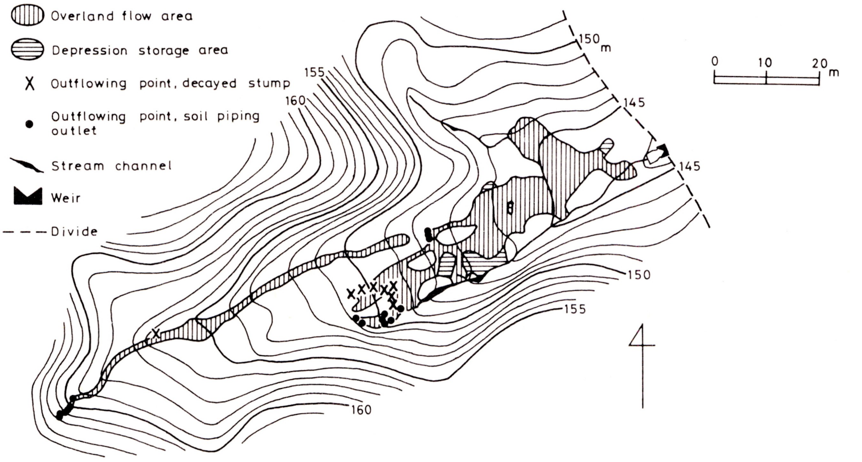

FIG.7 Areas contributing stormflow and the distribution of outflow points at 0200 h, 12 September 1980.

flow comprised return flow appearing at the soil surface through decayed stumps and soil pipe outlets. An important fact related to the overland flow phenomenon is that these outlets were concentrated in three zones of the valley floor, i.e. about 147.5, 150 and 160 m a.m.s.l., respectively (Fig.7). This fact seems to suggest the existence of a mechanism which induces the outflow of water from the subsurface zone.

Soil water pressure heads, piezometric and water table elevations measured during the storm showed that the water table was close to the ground surface in the zones where water issued from the soil surface. Fig.8 shows the distribution of equipotentials and the corresponding flow directions of subsurface water in the vertical cross section of the valley floor at 0130 h, 12 September, based on the data obtained from tensiometer and piezometer measurements. Flow directions drawn on Fig.8 have been corrected for the exaggerated vertical scale by the method of van Everdingen (1963). The flow pattern in Fig.8 shows the influence of heavy rainfall on the subsurface water flow system.

From Fig.8 it is obvious that the hydraulic head gradients evidence upward flow both above and below the water table at two levels; about 145.5-147.5 and 149-151 m a.m.s.l., respectively. These levels correspond to the above-mentioned zones where water issued from the soil surface except for the case of the zone at 160 m a.m.s.l. From this evidence, it is concluded that there was upward flow of subsurface water to satisfy outflowing water conditions at the soil surface. This flow process may be classified as exfiltration, according to the definition of Freeze (1974). Therefore, subsurface water exfiltration from relatively small areas seems to be the major contributor to overland flow in the basin.

In the erosional sense, water issuing onto the soil surface may be a more active agent than surface runoff *per se* because the outlet is in a free face and erosion by water issuing at this point

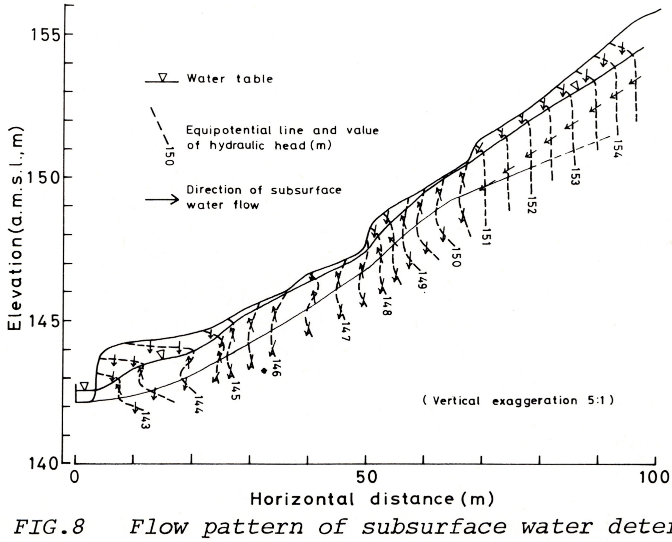

FIG.8 Flow pattern of subsurface water determined by field evidence at 0130 h, 12 September 1980.

initiates passage formation. This consideration would be justified by the fact that the outflow points are concentrated just under the cliff face of the study basin.

The field evidence has emphasized the importance of subsurface water exfiltration in the overland flow phenomena and in soil erosion processes. As a result of the present study, the author proposes the concept of a Subsurface Water Exfiltration Erosion Model (SWEEM).

CONCLUSION

The Horton model of surface runoff and erosion has been widely applied but it is now becoming apparent that this model is only applicable to restricted regions such as unvegetated slopes in arid and semiarid regions.

In the study basin, overland flow occurs in small restricted areas on the valley floor and the major portion of overland flow seems to be produced by subsurface return flow issuing at the soil surface through decayed stumps and soil pipes. These phenomena are largely controlled by the dynamic conditions of the flow system within the subsurface zone during a storm event.

Most active erosion occurs where overland flow is present. Therefore, it can be demonstrated that the dynamic response of subsurface water during a storm event is a most important factor when considering soil erosion processes in humid regions.

The SWEEM model proposed in the present paper is much more appropriate to runoff generating mechanisms in humid vegetated regions such as Japan. Using the SWEEM model, it would be possible to explain the development of the stepped slope profile observed in the study basin.

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