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Journal of Hydrology 235 (2000) 63–71

Journal of Hydrology

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# Runoff processes in headwater catchments—an experimental study in Western Ghats, South India

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Received 30 August 1999; revised 27 April 2000; accepted 1 May 2000

**Abstract**

Field observations and experiments were conducted to study runoff in a headwater region in the mountains near the west coast of Karnataka, a south Indian state. Three catchments were studied. Pipeflow was observed in all three cases, and there was no subsurface lateral flow through the soil matrix. Pipeflow was a significant contributor to quickflow in two catchments. In the third, grassed catchment, a new mechanism of runoff, called pipe overland flow in this paper, was discovered, which contributed to quickflow. The contributing area for pipeflow increases with the magnitude as well as duration of rainfall, but a dual behaviour with respect to average rainfall intensity shows up in one of the catchments. 

*Keywords*: Runoff; Pipeflow; Pipe overland flow; Quickflow

## 1. Introduction

Over the past few years, a number of studies have shown (Hewlett and Nutter, 1970; Dunne, 1978; Schwarz, 1985; Jones, 1987, 1997; Tsukumoto and Ohta, 1988) that runoff on hillslopes is generated by one or more of several mechanisms other than Hortonian. These mechanisms could be subsurface matrix flow, source area overland flow or subsurface pipeflow, depending on the soil formation. Previous investigations have covered regions of rainfall ranging from low to relatively high. The present paper concerns itself with the Western Ghats (mountains) region of the State of Karnataka in India (Fig. 1), where the annual rainfall is very heavy, being of the order of 7000 mm at some places and water surplus is very high (annual ET demand around 1600 mm), and is intended to fill a vacant spot in the existing literature.

Field observations in the Western Ghats have shown (Putty and Prasad, 1994a) that in the upper reaches of streams, a significant contribution to runoff is by subsurface pipeflow (the outlets of these pipes are called *Jala* in Kannada, the local language, meaning water point). Pipes have been found in several continents and climatic conditions. Jones (1971) describes a watershed in the Peak District in England where pipeflow is one of the major hydrological processes. Bannerjee (1972) studied the morphology of pipe structure in West Bengal in India. Atkinson (1978) has observed pipe networks in many areas of upland Britain, especially where the soils are podzolic. Masannat (1980) investigated the impact of piping on agricultural land in Arizona. Bonell et al. (1984) report a pipe network in a Luxembourg watershed

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0022-1694/00/$ - see front matter 
PII: S0022-1694(00)00262-6


Fig. 1. Location map indicating Talakaveri, the region of study.

under a mixed oak and beach forest cover. Tanaka et al. (1986) and Tsukumoto and Ohta (1988) studied pipeflow in forested slopes in Japan. Schwarz (1985) observed pipeflow in a forested catchment in Germany under artificial rainfall experiments. Zhu (1997) has reported pipeflow in a semiarid catchment in the Loess Plateau of China, where overland flow entered pipes at their inlets. Pipes occur in sizes ranging from a few centimetres to more than 20 m. Bryan and Jones (1997) present the pipe size distribution under different land classes, the largest pipes occurring in semiarid regions. Pipes are commonly but largely erroneously thought to result from the activity of burrowing animals or decay of plant roots, but can also form by subsurface erosion, starting with seepage erosion at the outlet and working backward, or erosion of existing macropores and desiccation cracks (Bryan and Jones, 1997), apart from solution. The different processes may also interact in a complex manner.

Study of pipeflow hydrology is hampered by difficulties in measurement and tracing pipe networks. Detailed studies are available in very few catchments. In the Maesnant catchment in Wales (Jones, 1987), pipeflow is a major contributor to baseflow as well as quickflow (amounting to 46% of the total flow). Some pipes can be perennial and others ephemeral. Zhu (1997) found that, compared to the ratio of around 40% between the pipe catchment and his experimental area, pipe contribution to streamflow is often around 50%, and can go up to 80%. Sklash et al. (1996) studied residence times and flow paths of pipe and streamflow in the Nant Gerig and Gwy catchments in Wales using natural deuterium and electrical conductivity of water. They concluded that low flow as well as storm runoff in the pipe and stream consisted overwhelmingly of ‘old’ water, stored in the soil before the rainfall event, although the flow responds quickly to rainfall. They suggested that the old water comes from both near-stream groundwater and upslope groundwater delivered by ephemeral pipes.

Typically, in the Western Ghats area, the valley bottoms are covered with dense evergreen forests and mountain tops with grass. Soil is very deep, of the order of 12 m or more on the forested slopes. The pipe outlets are near the valley bottoms, and the high density of forest vegetation makes it difficult to explore the pipes even to the extent of a few metres from the outlet. As such, pipe connectivity and extent of the network could not be studied. Experiments were limited to measuring infiltration rates, runoff, subsurface matrix flow and groundwater levels. Separation of old and new waters in streamflow was not attempted.

Models developed to take into account varying source area and pipeflow, when applied to large streams in the Western Ghats (Putty and Prasad, 1992, 1994b; Putty, 1994), suggest that pipe contribution to even quickflow during storm periods is significant. The present work deals with the experimental study and analysis of the role of pipeflow in small first order streams. Three such streams were chosen for the study in an area where annual normal rainfall is around 6750 mm. The first is the headwater (in fact, the ‘source’) of Kaveri, which further develops into a major river of southern India. A set of pipes formed a little below the surface opens out into this source, draining 0.8 ha of the Brahmagiri hill. A small masonry tank has been built at the spot (called *Talakaveri*) forming a pond the outflow from which starts the Kaveri river (Fig. 2a). The second stream is Kannike, which drains 2.8 ha of the grassed eastern slope of the same hill into another pond after a journey of about 160 m. The third stream (which has no name, and is called here the ‘forest stream’) also has a length of about 160 m, draining 8 ha of thickly forested catchment.

## 2. Measurements

Infiltration rates were measured at 50 sites with

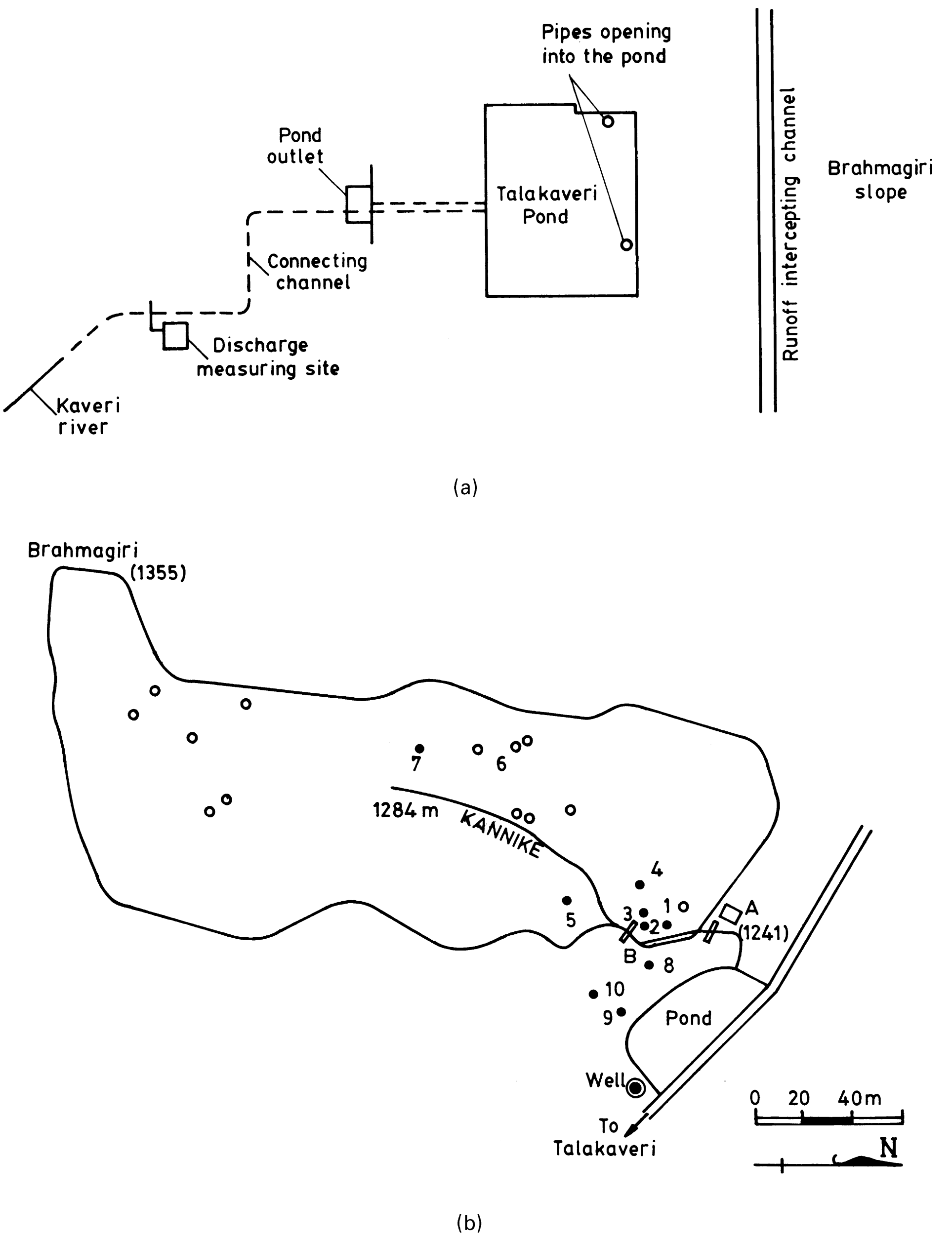


Fig. 2. (a) Layout of the Talakaveri pond. (b) Map of Kannike catchment with locations of weirs and piezometers. A, lower weir; B, upper weir; ●, piezometer; ○, infiltration measurement site.

various land use types using a double ring infiltrometer. The measurements were made during or immediately after rainfall to allow the effect of raindrop impact. Subsurface matrix flows were sought to be measured by inserting trays in trenches (after Dunne, 1978) and in a number of large vertical faces (up to 2.6 m high and 8 m long) of soil exposed at road cuttings near valley bottoms (after Woods and Rowe, 1996). These experiments were done under rainfall events as well as by supplying water from

Table 1
Measured values of infiltration rates

| Land use type | Sample size | Initial infiltration rate range (mm/h) | Infiltration capacity range (mm/h) |
|---|---|---|---|
| Grassed/scrubby | 16 | 30–1080 | 18–276 |
| Afforested (exotic species) | 14 | 60–1200 | 6–318 |
| Forest/cardamom | 12 | 156–1920 | 61–780 |
| Cultivated area | 8 | 33–330 | 12–137 |

trenches dug upslope. The outflow from the Talakaveri pond was measured with a weir and stage recorder. Since the Kannike catchment could be divided into two distinct parts, one with steep converging slopes and the other with gentle plane slopes, flow in the river was measured at two stations. For convenience of measurement, an artificial channel was built and the river diverted into it. Two weirs were installed in the channel, one at the head and the other just above the pond. The upper weir was used to measure the runoff from the steep converging slopes of the catchment and the lower one, the total flow including from the gentler plane slopes, which characterise the catchment between the two weirs. Flow over the lower weir was continuously recorded. At the upper weir, however, discharge could be measured only during a few storms. In this catchment, 10 piezometers were installed all along the course of the stream (Fig. 2b) to measure the groundwater level and thereby the growth

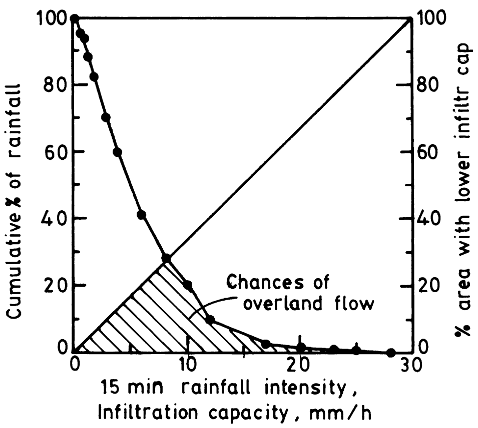


Fig. 3. Comparison of rainfall intensities with infiltration capacities in the heavy rainfall zone of Western Ghats.

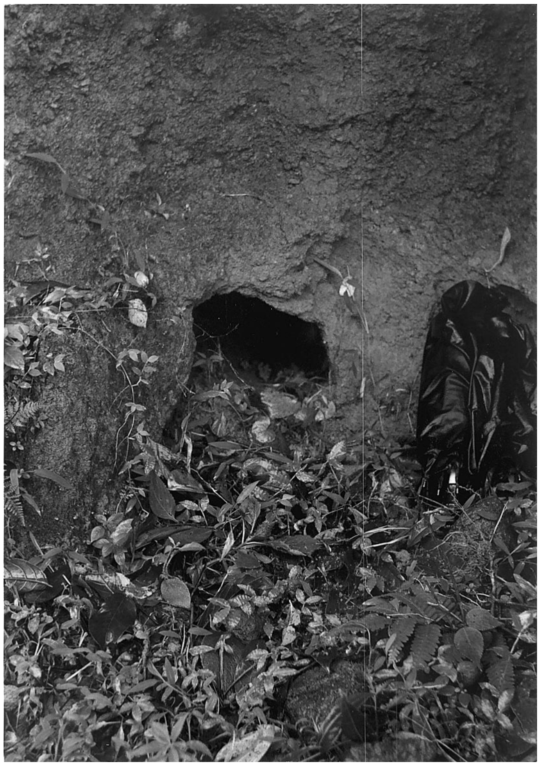

Fig. 4. Pipe outlet.

of the surface saturated zone. These piezometers were read daily to record the maximum level of the water table during the preceding 24 h. Flow in the forest stream was monitored continuously. No direct measurement of pipeflow was made in the grassed and forested catchments.

## 3. Results and analysis

The measured infiltration rates are shown summarised in Table 1 in terms of the initial rate (which, of course, depends on the moisture content for a particular soil) and the infiltration capacity (at saturation). The maximum 15-min rainfall in the area is about 15 mm and the infiltration capacity exceeds this rate in most places. Infiltration excess overland flow of the Hortonian type can, therefore, occur only in very small parts of the catchment such as cultivated areas and animal paths. An estimate of the probability of overland flow can be made from Fig. 3, where the

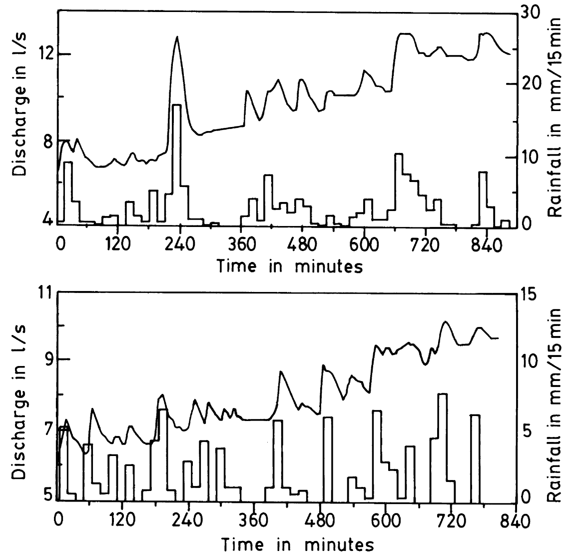


Fig. 5. Outflow hydrograph at Talakaveri (Rainfall in bar diagram).

cumulative area with infiltration capacity lower than a given value is assumed to vary linearly. The rainfall at Agumbe (amounting to around 7500 mm annually) is used in this diagram. Agumbe is also in the Western Ghats, has the typical Western Ghat rainfall pattern and is characterised by grassed slopes. Even with a conservative estimate of the maximum infiltration capacity at 120 mm/h, the probability of overland flow is quite small. It is, therefore, to be concluded that most of the runoff is generated by non-Hortonian processes.

The trays inserted in the soil in trenches and road cuttings did not collect any runoff. The subsurface matrix flow would therefore be largely in the vertical direction. At many places, particularly in the valley regions, pipes varying in size from a few centimetres to more than a metre were observed (Fig. 4). Large pipes are usually observed in semiarid regions (Bryan and Jones, 1997), but in the humid western Ghats, many dug wells are known to derive their water from large pipes

The pipes appear to form a good network, draining very deep soil mantles (about 3 m thick on grassed slopes and more than 12 m on forested slopes). The vertical matrix or macropore flow collects in the pipes and flows through them into the streams. During the monsoon season, water can be seen flowing out of these pipes near valley bottoms and at road cuttings.

The Talakaveri pond (Fig. 2a) receives flow from a set of pipes draining a catchment of 0.8 ha, apart from direct rainfall on its surface and surrounding paved areas totalling about 300 $m^2$. A few hydrographs of outflow from the pond in the year 1993 are shown in Fig. 5 along with the corresponding rainfall hyetographs. Typically, the discharge shows a steady rising trend with multiple peaks. The peaks are due to rainfall on the pond surface and the steady rise can be attributed to pipeflow, since no overland flow enters the pond, and soil matrix throughflow is not observed in the area. Rainfall in the region occurs in long duration spells with short breaks in between. As the water collects and builds up storage in the pipes, outflow increases in step with the storage. While a part of the pipe outflow is from the storage built up during previous rainfall events, some part would presumably be from current rainfall also. An empirical method of separation between the two is used here, by considering the part of the flow above the (linearly) extrapolated

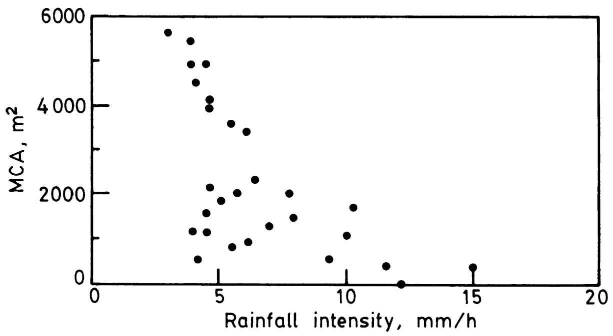


Fig. 6. Minimum contributing area as a function of rainfall intensity in Talakaveri catchment.

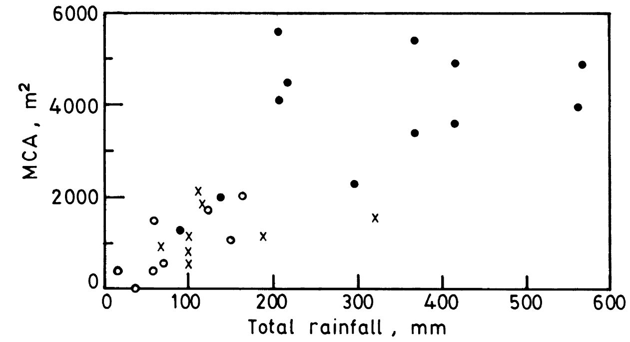


Fig. 7. Dependence of contributing area on total rainfall in Talakaveri. ○, rainfall duration 3–21 h; ×, 18–50 h; ●, 40–143 h.

recession limb of the previous hydrograph as quickflow and the rest as delayed flow. The quickflow volume divided by depth of rainfall can be considered as the minimum runoff contributing area (MCA), of which the pond surface also forms a part. The MCA seems to be well correlated with the average rainfall intensity (Fig. 6). The rainfall intensities in Fig. 6 have been calculated for several rainfall events of durations varying from 1.2 to 143 h. For average intensities less than 7.5 mm/h, two distinct branches of the relationship can be seen. For long durations in the range 44–143 h (upper branch), MCA decreases with increasing rainfall intensity, while for shorter durations from 11 to 71 h (lower branch), it increases. For intensities greater than 7.5 mm/h, characterised by still shorter durations of 1.2–15 h, a decreasing trend in continuation of the upper branch can be discerned. According to the variable source area theory (Bonell, 1993), both rainfall intensity and duration would determine the extent of source area. This is true of pipeflow contributing area also. When MCA is plotted against total rainfall, however, the differences induced by duration are no longer evident (Fig. 7), possibly masked by other factors affecting the formation and growth of the contributing areas. The contributing area extends beyond the pond area and the surrounding paved surfaces (ca. 300 $m^2$) only for total rainfall events greater than 50 mm (Fig. 7), and duration greater than about 5 h, but rainfall intensity can be in a wide range (Fig. 6). The ratio of MCA to the catchment area (0.8 ha) indicates the fraction of rainfall which appears as quickflow. For durations of the order of a day, contribution of what is here inferred as pipeflow to streamflow ranges from 15 to 25%, and for durations of four to five days, more than 60% of the rainfall is drained by pipes (Fig. 8). Watershed modelling studies also indicate similar results (Putty, 1994; Putty et al., 1996).

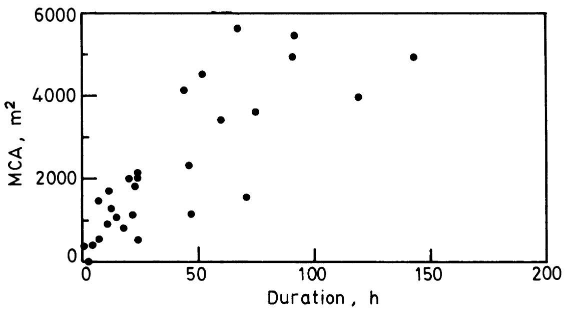


Fig. 8. Relation between contributing area and rainfall duration in Talakaveri.

## 4. Runoff in the Kannike and forested catchments

Pipeflow has been observed to contribute to flow in both these streams. In the Kannike catchment, it was observed that overland flow also occurred on the slopes adjacent to the stream channel during rainfall. Using piezometer water levels, the zone of surface saturation adjacent to the stream channel was mapped and planimetered, and its area was much less than that required produce the observed surface runoff. Measured infiltration capacities in this zone range from 24 to 100 mm/h, which are higher than the maximum rainfall intensities recorded during the rainfall events studied. The overland flow observed could not, therefore, have been Hortonian. Surface runoff

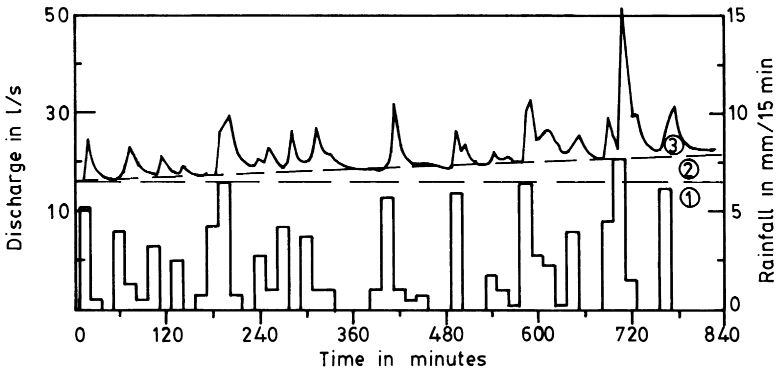


Fig. 9. Hydrographs of river Kannike at the lower weir (Rainfall in bar diagram). 1, baseflow; 2, pipeflow; 3, pipe overland flow.

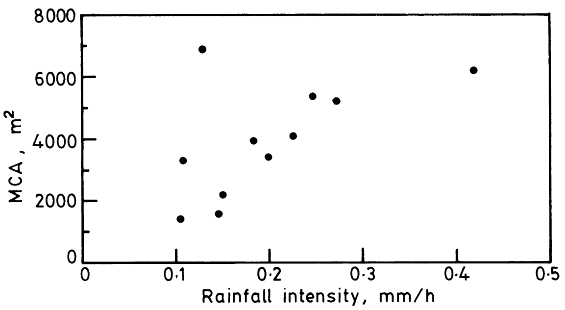


Fig. 10. Variation of contributing area with rainfall intensity in Kannike catchment.

occurred even on the gentle plane slopes where piezometer levels were 80 cm or deeper below the surface. Yet another runoff generating mechanism was therefore suspected. Careful and extensive field observations revealed that wherever such overland flow occurred, pipes had opened out at the surface. The water emerging from the pipes had spread on the slope, saturating the soil from above. Rainfall over such land became overland flow of the saturation-excess type. This, being in contrast to overland flow caused by saturation of the soil by build-up of water table from below (Dunne and Black, 1970), can be called *pipe overland flow*, and forms a new mechanism of runoff generation. The Kannike catchment slopes have been artificially afforested, and in the process, pipes appear to have been damaged, forcing them to open out at the surface. An extensive survey of the headwaters of other streams in the Western Ghats also showed that afforestation activities have damaged pipes, resulting in substantial overland flow. Incidentally, this needs to be taken note of by foresters in carrying out afforestation programs. Pipe overland flow was not observed in the forested catchment on a significant scale since the infiltration capacities are so high that pipe outflow does not create saturation of the soil.

Typical hydrographs of Kannike are shown in Fig. 9.

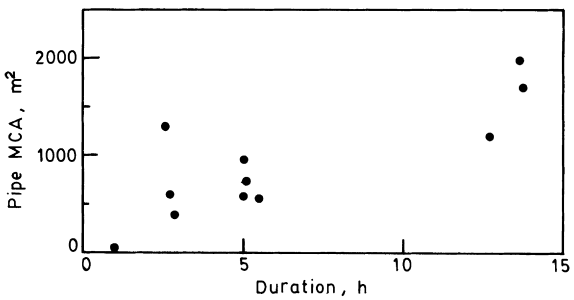


Fig. 11. Pipe contributing area in relation to rainfall duration in Kannike catchment.

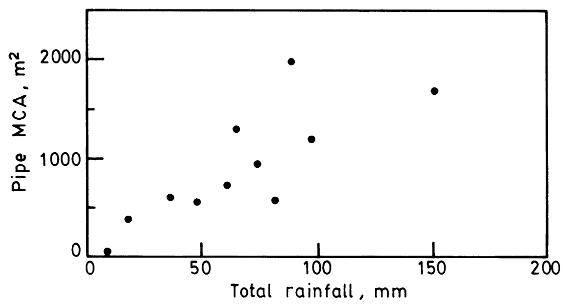


Fig. 12. Pipe contributing area in relation to total rainfall in Kannike catchment.

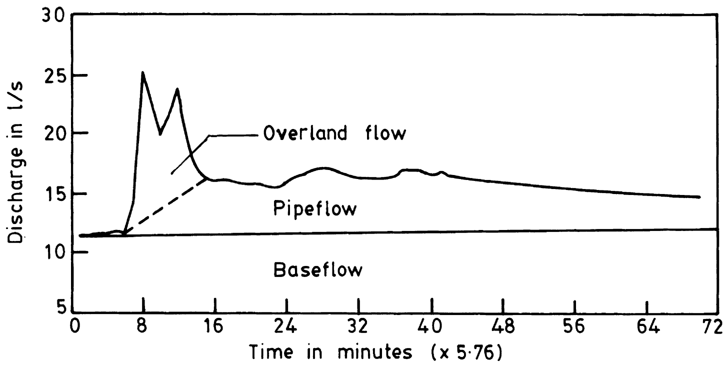


Fig. 13. Hydrographs of forest stream.

They show sharp peaks in quick response to individual rainfall events, superposed on an otherwise slowly rising flow. The peaks are due to pipe overland flow, and the slowly rising component is assumed to be due to subsurface pipeflow. Both these components as well as the base flow are separated empirically as shown in Fig. 9. The groundwater levels as measured in the piezometers were always below the channel bed, so the subsurface flow is presumably solely through pipes. But the contribution of the presumed pipeflow to quickflow is relatively small and runoff is dominated by pipe overland flow as seen in Fig. 9. The MCA increases with rainfall intensity in the range of measurement (Fig. 10), apparently corresponding to the lower branch of Fig. 6. While the total MCA does not correlate well with rainfall duration (not shown here) pipe MCA increases with duration (Fig. 11) as well as total rainfall (Fig. 12).

Hydrographs for the forest stream are shown in Fig. 13. In this case, overland flow is a significant contributor to runoff only during short duration events and pipeflow is the major mechanism generating runoff over long durations. The total MCA, which is only slightly greater than pipe MCA, increases with rainfall (Fig. 14) as well as duration (Fig. 15), but decreases with increasing rainfall intensity (Fig. 16).

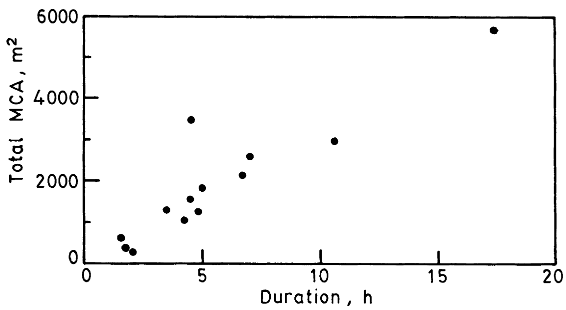


Fig. 15. Relation between forest stream contributing area and rainfall duration.

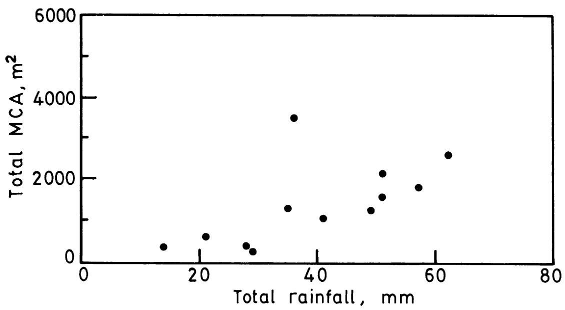


Fig. 14. Forest stream contributing area as a function of total rainfall.

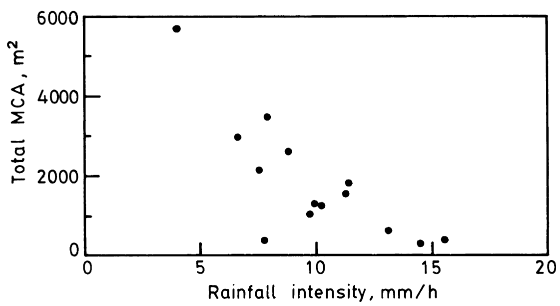


Fig. 16. Relation between forest stream contributing area and rainfall intensity.

## 5. Conclusion

The results of the study concerning runoff processes in the heavy rainfall upland areas of river Kaveri in the Western Ghats of Karnataka can be summarised as follows:

1. Subsurface flow, which forms a major component of streamflow in the region, is essentially through pipes.
2. Pipeflow being relatively slow, contributes significantly (up to 60%) to quickflow in first order streams only during low-intensity long duration rainfall events.
3. The flashy response of the predominantly grassed catchment is due to a combination of Hortonian overland flow, saturated area runoff and pipe overland flow, the last involving surface runoff produced as a result of pipes opening out on the slopes away from the stream channel.

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