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Contributions to quick runoff in a Headwater catchment - the role of natural pipes and soil macro-pores

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CONTRIBUTIONS TO QUICK RUNOFF IN A HEADWATER CATCHMENT - THE ROLE OF NATURAL PIPES AND SOIL MACRO-PORES

Abstract

Analysis of hydrographs from a 4.3 ha headwater catchment indicate that storm runoff is generated from dynamic source areas. The volume and timing of contributions from different parts of the catchment show, when compared with the extent of surface saturation, that pipeflow generated from areas not saturated at the soil surface is a significant component of quick runoff. A simple model of pipeflow generation and contribution is presented. An approach to modelling the occurrence of surface and sub-surface saturated source areas in all parts of a catchment is considered.

Keywords

Contributing area, Dynamic source area, Hydrograph analysis, Pipeflow, Quick runoff.

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1. Introduction

Measurements of the physical characteristics of vegetated soils have shown that rainstorm intensities in humid temperate climates are rarely sufficient to generate overland flow according to Horton's (1933) classical infiltration excess model of storm runoff generation. It is now widely accepted that distinct zones within a drainage basin produce most of its storm or quick runoff following a burst of rainfall. In this paper quick runoff or, quickflow is defined as that proportion of total runoff which is transmitted to the stream channel at approximately the same speed as overland flow on vegetated slopes.

The areas from which quick runoff is principally generated have been termed partial or contributing areas. The factors which determine the location and extent of these areas in small drainage basins have been identified, in broad terms, by a number of field studies (eg. Dickinson and Whiteley, 1970; Dunne and Black, 1970; Hewlett and Nutter, 1970; Weyman, 1971). These studies have shown that contributing areas are located close to, or around, stream courses, in valley floors or on hillsides where slope orthogonals converge. In upland (headwater) areas an important, topographically distinguishable, form of contributing area is the stream head hollow. The hydrological functioning of hollows was outlined in general terms by Hack and Goodlet as early as 1960 (Hack and Goodlett, 1960), before the development of the contributing area concept (Hewlett, 1961, TVA 1963; Betson, 1964). More recently Anderson and Burt (1978) have reported in detail on the contributions to stream flow and changing soil moisture potentials around a hillslope hollow in the Quantock hills of South West England. These, and other field studies (eg. Dunne, Moore and Taylor, 1974; Bello et al., 1978; Day, 1979), have shown that the extent of the runoff contributing area, storm runoff coefficient and flowing stream length in the headwater area can be correlated with measures of catchment 'wetness' such as prestorm baseflow rate and antecedent moisture indices. Runoff generating areas around headwaters are therefore most accurately referred to as variable or dynamic source areas.

2. Runoff from stream head dynamic source areas

Observations of stream head source areas, notably those of Dunne and Black (1970) and Weyman (1971) have identified two principle mechanisms of runoff generation. The first mechanism has been termed the 'saturation excess' model of overland flow. Overland flow occurs, according to this model when rainfall rates exceed the combined drainage and storage capacity of the soil cover (fig. 1). The second principle mechanism of generating surface flow in dynamic source areas can be called the 'return flow' mechanism after the name originally applied to it by Dunne and Black (1970). They define return flow as

> "Infiltrated water which returns to the land surface having flowed for a short distance in the upper soil horizon."

As with the saturation excess model surface runoff again occurs following the exceedence of the soil covers subsurface drainage and storage capacity, except in this case lateral inflow from upslope rather than infiltration is the cause.

The two mechanisms of surface runoff generation in dynamic source areas identified here are clearly not mutually exclusive, as Pilgrim et al. (1978) have emphasised. The relative contributions of the two processes to the storm hydrograph has, however, been subject to debate. Dunne and Black's study in New Hampshire led them to conclude that subsurface flow rates were too low for the return flow mechanism to be a major component of the storm (quickflow) hydrograph. Results presented by Anderson and Burt (1978) show that whilst the major component of the total discharge from an example hillslope hollow following a storm is a throughflow (return flow) 'pulse', this pulse reaches the stream 30-36 hours after the onset of rainfall and therefore cannot be thought of as quick runoff.

In contrast, Whipkey (1967) and Pilgrim et al. (1978) have shown that rapid subsurface flow can be an important component of the quick flow hydrograph. Subsurface flow velocities recorded by Whipkey (1967) exceed 0.001 ms^{-1} and fall within the range of overland flow velocities recorded for slopes of similar gradient (see fig. 7). The most rapid form of subsurface drainage is through natural soil pipes. Maximum observed pipeflow velocities approach those of channelled flow

(Gilman and Newson, 1980) and are much greater than overland flow velocities. In piped catchments contributions to the storm hydrograph are known to be both rapid and volumetrically important. If rapid subsurface flow (pipeflow) occurs widely over the slope draining to a stream channel greater volumes of quick runoff will be recorded than would be expected for the size of near channel saturated source area (which would generate saturation excess overland flow). In addition, the expansion of the near channel saturated area during a storm will be due more to the flow efflux from pipes, than the continued infiltration of storm rainfall. In an extensively piped catchment then, the dynamic source area for quick runoff will not be exactly equivalent to the near channel saturated area.

In the rest of this paper the size and importance of pipeflow source areas in a very small stream head catchment is assessed by means of simple hydrograph analysis. The functioning of such areas is also considered together with the general problem of defining dynamic source areas in small catchments.

3. Experimental catchment - location and description

Work was carried out in the 4.3 hectare catchment of the Slithero Clough, near Ripponden, Yorks. The catchment covers the South facing side of Joiner Stones Hill (grid ref.: SE 009102), rising from 301 m OD to 360 m at highest point in the catchment. The bedrock geology is massive Namurian Millstone grit of the Kinderscout series (Wray, et al., 1930). The slope itself is convex-linear in profile with a small lithologically produced scarp just below its wide, flat, summit surface. Above the scarp the catchment is truncated below the slope divide by a water supply catchwater (built in the Nineteenth century) which follows the 360 m contour (fig. 2).

On the hillside the Slithero Clough has formed a valley 4 m deep by 7 m wide at its outflow. Stream flow is perennial to 60 m upslope of this point. The perennial flow limit occurs at the junction of two major lines of drainage, beyond which the topographic expression of the surface drainage becomes relatively indistinct. Drainage from the

Easterly part of the catchment reaches the perennial stream through a network of natural pipes, the largest pipe being 0.3 m in diameter. The pipeflow source area is the flatter part of the slope above the scarp. This area has a typical 'wet moorland' Erica sp. vegetation community (Moss, 1931), developed over a peat cover which reaches a depth of 2 m in places. On the mid-slope, below the scarp, a mixed grass vegetation community dominated by Molinia sp. is found on a thin (13-30 cm) sandy ranker type of soil. The Westerly part of the catchment contains only a few small pipes. The main drainage feature in this part of the catchment is a wet boggy area just below the scarp. This bog drains to the perennial channel through a wide Juncus flush (the term flush is used here as defined by Ingram, 1967).

The occurrence of soil surface saturation, for a variety of discharge rates, has been mapped by field survey (see below). For average discharge rates saturation is found in four locations. These are (in order of size), the Juncus sp. flush and bog area draining from the West, the 'valley' floor of the perennial stream head, small scale linear depressions in the slope summit peat cover and isolated patches at the efflux's of pipes on the Easterly mid-slope.

4. Field measurements

A daily water budget account was kept for the experimental catchment over a 64 week period. Rainfall was recorded by an autographic gauge in the catchment and supplemented with data from nearby daily and weekly checked manual gauges operated by the Yorkshire Water Authority. Streamflow was recorded using a $\frac{1}{2}$ 90^0 thin plate metal weir and OTT horizontal drum stage recorder. The time accuracy of rainfall and runoff records was approximately ±30 minutes per week. Evapotranspiration totals were estimated from Meteorological Office M.O.R.E.C.S. map data. The daily catchment water balance calculated from these measurements was set at an arbitrary zero at the beginning of the study period.

The extent and frequency of soil surface saturation and overland flow within the catchment was mapped. A network of 31 quantitative runoff traps (for design see McCaig, 1980) and 51 qualitative crest stage saturation tubes of the type described by Kirkby et al. (1978) recorded the occurrence of surface flow. At a further 25 sites simple tubes were inserted into the soil to qualitatively record the occurrence of saturated throughflow.

The timings of rises in soil water rest level, the occurrence of overland flow and stream water conductivity were also recorded, using a simple automatic monitoring system installed across the floor, sides and adjacent slope of the perennial stream head depression.

5. Quick flow hydrographs

Hydrographs from the Slithero Clough catchment generally rise rapidly and continuously to a single peak. Recession, following a single burst of rainfall, begins almost immediately after the rain stops falling. This feature immediately suggests that runoff generated by the saturation excess mechanism is an important component of the storm hydrograph. The falling limbs of hydrographs are not continuous curves, however, recession curves from a range of peak flow rates show a number of flat sections followed by more rapid recession (fig. 3).

The shape of the storm or quickflow hydrograph has, since Horton's work (Horton, 1935) been used as a guide to the mechanisms of runoff generation in small catchments. Some of the most widely used size/shape indices are: quickflow volume (runoff coefficient) and the times taken for the stream to (i) rise, (ii) peak [redacted] and (iii) deliver half the quickflow volume. The first of these characteristic times identifies the most rapidly responding runoff element. Time to peak will indicate the most important flood wave generating element and the time to centre of mass of the quickflow hydrograph the mean response time of the quickflow generating processes within the catchment. All three of these measures are determined to some extent by the size and shape of the drainage basin and, for any catchment will vary with the extent of the source area (ie. antecedent conditions) as well as storm rainfall characteristics.

The rapidity of response to rainfall from dynamic source areas will be determined by how quickly the combined drainage/storage capacity of the wettest part of the catchment is exceeded. Intuitively, it follows that a characteristic minimum time to rise will be associated with the exceedance of a critical level of catchment <u>wetness</u> when these areas first become saturated. Below this threshold level time to rise will be determined by rainfall intensity and subsurface flow rates. Above the threshold, areas of saturation will generate storm runoff immediately and the delay between rainfall and runoff will be a constant determined by the transmission time of surface flow across the saturated areas to the flow gauging station.

This conceptual model is not validated by the present field observations. Three measures of catchment wetness have been considered: baseflow rate, an antecedent precipitation index (NERC, 1975, p. 390) and catchment water storage level (calculated from the daily water balance, relative to an arbitrary zero at the beginning of the study year). No consistent or threshold relationship is found between these measures and time to rise (fig. 4). In seeking an explanation for the lack of pattern, reinfiltration of overland flow and channel/pipe bank seepage are thought to be important.

Evidence that bank seepage from the perennial channel occurs is provided by data from the automatic monitoring system. Records show that there is a progressive outward movement of saturated conditions across the flat floor of the stream head depression. The effect of significant bank seepage on the relationship between time to rise and catchment wetness will be to delay rises in stream stage until the rate of runoff increase exceeds the rate of transmission decrease. Hence, time to rise delays may occur even under very wet conditions if rainfall intensities are low. In this small catchment then, hydrograph time to rise reflects the effect of processes other than those responsible for runoff generation.

Dunne (1978) has suggested that differences in the lags between rainfall and runoff peaks can be related to the principle mechanisms of storm runoff generation. Times to peak in the Slithero Clough catchment range between 2-22 hours; a composite of Dunne's graphs (fig. 5) indicates that the catchment could be described as a member of either the variable source area or the subsurface stormflow dominated groups. The median time to peak for the study year (7.5 hours) plots closer to this second group.

Time to peak, like time to rise can, however, be shown to be dependent upon factors other than simply the processes of runoff generation. Plotting time to peak and rainfall duration for a series of storms reveals a very clear relationship (fig. 6); the longer it rains the longer the period of stage rise. The timing of peak flow in catchments where quickflow is generated by the saturation excess mechanism will also be sensitive to rainfall intensity since high intensities over small areas may generate greater volumes of overland flow than lesser ones over large saturated areas.

Similar problems are also encountered when attempting to interpret lags between hyeto and hydrograph ($_{\text{quickflow}}$) centres as being characteristic of hydrologic processes. Field data shows a lack of pattern, time to centre of mass once again being independent of measures of catchment wetness. The distribution of times is positively skewed and has a greater variance than time to rise. The skew suggests once again a dependence in the timing of this hydrograph feature on rainfall characteristics.

Despite these problems, hydrographs from the Slithero Clough catchment do indicate that some sort of variable source area mechanism is responsible for quickflow generation. The relationship of times to peak with increasing storm duration, shows that the area within the catchment contributing to runoff increases during the course of a storm. The form of the quickflow hydrograph contains two elements that further confirm the hypothesis that storm runoff is generated from a dynamic source area. First, the continuous rise of hydrographs to a single peak indicates that the most rapidly responding runoff generating element in the catchment is also a component of the peak flow generating area. Second, the rapid decrease in streamflow rate following the cessation of rainfall implies an equally rapid conversion of rainfall to runoff (overland flow generation by the infiltration or saturation excess mechanisms).

Thus far, the conclusions that it seems fair to draw from examination of quickflow hydrographs appear to support Dunne and Black's (1970) model of a dynamic source area, this being a near channel saturated zone expanding during a storm. The most noticable feature of the catchment in the field however, is the occurrence of natural pipes and, associated with them, isolated patches of saturation. The rest of this paper examines the importance of these features of catchment hydrology in determining the size and shape of the quickflow hydrograph.

6. Proportion of quick runoff generated from pipe source areas

Consider again the delay between rainfall cessation and recession commencement. This delay represents the mean time for runoff generated by the last block of rainfall to reach the stream gauging station. Hydrograph records show that the length of this delay is independent of peak discharge and has a mean of 2 hours. Measurements of the saturated area and flowing drainage line length (a drainage line being defined as a line of flow with some depth, but not contained within banks cut by itself) around the perennial stream head show that the mean overland flow distance to a drainage line is only of the order of 2 m. Measured and published velocities of overland and various forms of drainage line flow are given in fig. 7. Taking a velocity of 0.1 - 0.3 m^{-1} for flows in flushes/drainage lines and 0.2-0.5 ms^{-1} for flow in channels, to account for the 2 hour delay over these distances overland flow velocities would be of the order of 0.0002-0.0005 ms^{-1}. This figure is lower than the ranges given in fig. 7, and indicates that quick runoff for peak flow rates between 0.13-1.7 $mmhr^{-1}$, is not generated solely from the near channel saturated area in the lower part of the catchment.

The relative proportion of quick runoff delivered to the gauging station from natural pipes was calculated from stream conductivities, utilising the differences in dissolved solids concentrations found between flow from pipes (mean 100 mgl^{-1}) and the near channel saturated area (mean 56 mgl^{-1}). Dissolved solids concentrations in both areas were independent of discharge, a feature noted for pipeflow in the Mendips by Finlayson (1977).

Proportions of flow were calculated from the equation:

$$\frac{Q_s}{Q} = \frac{C_p - \bar{C}}{C_p - C_s}$$

where Q = total discharge

Q_s = discharge generated from saturated area

C_p = dissolved solids concentration of pipe flow

C_s = dissolved solids concentration of saturated area flow

$\bar{C}$ = dissolved solids concentration of total flow.

The relationship between flow proportions and catchment runoff rate is shown in fig. 8. Comparison of this figure with the mapped extent of surface saturated areas in the catchment for various discharge rates (fig. 9) shows that the extent of saturation in pipe source areas increases with discharge but not at the same rate as the proportion of quickflow generated from it. A conclusion that can be drawn from this comparison, is that the extent of saturation in the upslope areas does not correspond to the extent of the pipeflow source area.

The size of this extra non-saturated quickflow source area can be calculated in a general manner. Steady conditions of continuous rainfall in a catchment will establish the equilibrium between rainfall and runoff:

$$i_* = iA_c$$

where i_* = instantaneous runoff rate

i = instantaneous rainfall rate

A_c = contributing area.

In time averaged form, for a storm, the above equation can be rewritten:

$$Q = \bar{A}_c \times \bar{R}$$

Q = quickflow volume

$\bar{A}_c$ = mean contributing area for storm

$\bar{R}$ = storm rainfall.

Assuming that $\overline{A}_c$ is directly proportional over the <u>whole</u> catchment to the peak flow contributing area, the extent of any non-saturated quick flow source area is given by:

$$\overline{A}_c - A_{c_{obs}} \propto NSA$$

NSA = non saturated area

$A_{c_{obs}}$ = observed saturated area for storm.

The value of $A_{c_{obs}}$ is determined from the relationship between flow rates and total saturated areas shown in fig. 9. The results of this calculation for a limited number of storms demonstrate that the extent of non-saturated area increases with discharge rate (fig. 10). The non-saturated source area appears to behave in the same way as other types of dynamic source areas, expanding and contracting with wetter and dyer conditions. Reference back to fig. 8 leads to the inference that the location of the non-saturated source area is almost exclusively in the piped part of the catchment, since here the anomaly between saturated area and proportion of flow is greatest.

Runoff contributions transmitted via natural pipes from upslope non-saturated source areas are, then, detectable elements of the experimental catchments quickflow hydrology, accounting for 2-10% of total amount of quick runoff.

7. A model of pipeflow generation and contribution

The 'leaky bucket' conceptual model of soil hydrology described in Section 1 (fig. 1) can be as equally well applied to pipeflow as overland flow generation. In the former case, however, the 'bucket' overflows before surface saturation occurs (the soil acts as a non-saturated source area) and the 'overflow' route to the stream channel is via macro-pores and natural pipes rather than over the soil surface. The onset of pipeflow will therefore be closely correlated with the exceedence of some critical soil moisture level. This type of pipeflow generating mechanism has previously been outlined by Gillman and Newson (1980) and is clearly demonstrated in the experimental catchment (fig. 11). The apparent threshold value of catchment storage represents the critical level to which saturated conditions must rise in the soil before lateral flow in macro-pores and pipes can occur. Gilman and Newson (1980) suggest that this level in peat soils is related to the depth to which large scale dessication cracking occurs during the dry summer months.

Initial contributions to the quickflow hydrograph from piped source areas will be delayed by three factors:

(i) The infiltration process
(ii) Raising of soil water level to the pipeflow threshold
(iii) Transmission of the flow through the macro-pore-soil crack system to larger size of pipes.

Delays due to transmission through traceable pipes (>6 cm diameter) can be ignored since velocities in pipes of this size are in the range of 0.1-0.3 ms^{-1}, implying a transmission time to the gauging station of <15 minutes.

Some information concerning the length of the delays due to these factors can be extracted from records of the changes in dissolved solids concentrations observed at the catchment outflow during hydrographs. There is an average delay after the stream rise of 2.75 hr before solute concentrations increase. This implies a 2.75 hr delay before the rate of increase in quickflow contribution from the pipe source areas exceeds that of the stream head sources. The combined time for infiltration, recharge of storage and transmission to pipes for areas close to pipes is therefore c. 2.75 hrs. In contrast, the delay between the hydrograph peak and solute peak is an average 12 hrs. This delay shows that the proportion of flow generated from the pipe source area does not decrease until c. 12 hrs after the hydrograph peak. In other words recession in the pipe source area is less rapid before and more rapid after 12 hrs after the peak discharge. This implies that the recession limb of pipe hydrographs are convex, an observation reported by Gillman and Newson (p. 53, 1980). The exact timing of the solute peak appears in some hydrographs to occur at the end of a 'level' section of the streamflow recession limb, suggesting that a very rapid 'shut off' occurs once the level of the soil saturation falls below the pipeflow threshold.

This delay figure gives, therefore, a maximum transmission time for flow generated in the pipe source area to the gauging station which can be included as a quickflow contribution since the mean flow velocity over the transmission distance of 0.009 ms^{-1} is still within the range of overland flow velocities.

Approximate calculations of the rates of infiltration, storage recharge and lateral flow transmission can be made using these data. First the quickest response time of <2.75 hrs could be accounted for by the filling of a initial moisture deficit alone rather than an infiltration delay. Rainfall falling at the median storm intensity recorded in the catchment (2 mm hr^{-1}) would account for the 2.75 hr delay if the soil moisture level was only 5.5 mm further below the pipeflow threshold than areas near the perennial stream channel were less than saturated.

An indication of the maximum transmission time of flow through macro-pores is gained from measurement of pipe drainage densities. From this the maximum inter-pipe distance, for traced pipes, was calculated to be 22-85 m. Using the solute data, the rate of transmission to pipes over this distance would be 0.00057 ms^{-1}. This value is far in excess of measured lateral hydraulic conductivities for peaty soils on low gradients, implying that draining water rapidly enters a system of soil macro-pores which progressively develop into larger pipes.

It is reasonable to assume that the relationship between flowing pipe length and pipe source area is similar to that found for saturated source areas and surface drainage lines. That is, the delay between rainfall cessation and recession commencement (the mean transmission time from source area to channel) is a constant independent of discharge. This suggests a conceptual model of the relationship between the distribution of non-saturated source areas and flowing pipes that is exactly the same as for surface saturated source areas. As storm rainfall raises soil moisture levels the area capable of generating pipeflow increases, and originally dry pipes begin to flow, as the source area expands upslope.

Since the maximum, as well as the mean transmission time for flow to traceable pipes will also be a constant independent of discharge it is possible to use the solute delay data to investigate the relationship between pore size and flow velocity.

For a straight segment of slope, discharge will be linearly related to the distance travelled downslope or between pipes:

$$q = v \cdot \frac{\Pi d^2}{4} \propto L$$

where q = slope discharge

d = pore diameter

L = distance.

The empirical Hazen-Williams formula (Albertson and Simons, 1964, p. 7-18) for turbulent flow in rough pipes shows that velocity is a power function of diameter:

$$v \propto d^{0.64}$$

Combining the above equations gives the result:

$$v^4 \approx KL$$

where K is a suitable constant.

Field data can be used to roughly scale this model. Traceable pipes (>6 cm diameter) have a drainage density that defines the approximate inter-pipe distance as 22.85 m. Observations of flow in these (full) pipes gave velocities of 0.05-0.1 ms^{-1}. Figure 12 shows model results using this data. The curves indicate that nearly all the 'transmission time' delay is taken up by flow through pores of <18 mm diameter in the first one metre of flow. Predicted flow velocities in these pores (0.01-0.02 ms^{-1}) are similar to overland flow rates. These results indicate that a considerable proportion of the transmission delay is due to flow in capillary sized pores, a size range for which the model is not applicable. The model is also unsatisfactory since macro-pore size is unlikely to be a simple function of slope discharge. It is probable that tension cracks less than a certain size do not form and that pores may only be enlarged by piped discharges once a threshold velocity, determined by tube diameter and roughness (equivalent to pore size or soil texture at this scale) has been exceeded.

The model and field results together suggest that whilst infiltrating water rapidly enters the soil macro-pore system (giving the short 'initial contribution' delay of ≈3 hrs), at the end of a storm drainage, over a short distance, from capillary to macro-pores occurs and extends the period for which pipe discharges are maintained.

8. Comment

(1) Summary of experimental findings

The work described above has shown that whilst the storm response of the experimental catchment is in some senses typical of a dynamic source area headwater catchment, two different types of source area exist within the catchment. These are:

(i) Saturated stream head source area
(ii) Non-saturated pipeflow source area.

A third, minor type of source area, saturated areas below pipe effluxes were also found by field mapping. The essential differences between the two types are their location, timing of contribution and flow generating mechanism.

Pipe source areas occur on the flatter slope summit of the experimental catchment. Stream head source areas occur in the hollow of the perennial stream draining the catchment. Pipeflow contributions, accounting for 2-10% of the quickflow hydrograph, are somewhat delayed compared to contributions from the stream head source area. The effect of this delay is seen in the shape of the quickflow hydrograph. Flow from the pipe source area is generated as subsurface flow by rapid infiltration and lateral flow in the soil macro-pore network. In contrast, the quickflow generated from the stream head source area is generated as saturation excess overland flow.

(2) Terminology applied to dynamic source areas

The two types of dynamic source area, termed so far stream head and pipeflow, found in the study catchment are difficult to describe using terms commonly applied to dynamic source areas. The saturated (surface saturation) area in the catchment is not equivalent to the total source or contributing area. In drawing attention to a similar spatial pattern of source areas Jones (1979) has suggested a variety of terms, emphasising the necessity of a link between channel and zones of saturation for such areas to contribute to the storm hydrograph. In the study example, however, such terms are largely redundant since the extensive pipe network ensures contribution from all pipeflow source areas.

It is desireable to differentiate between types of source area on the basis of their nature and location. The source area types identified here are, therefore, most usefully termed; surface saturated (stream head) and subsurface saturated (slope summit) source areas. The types of flow generated in these areas can be equally well described as surface and subsurface quickflow.

(3) Implications for the measurement and modelling of dynamic source areas

Simply mapping, the extent of saturated areas to estimate quickflow contributing areas will be inaccurate when significant subsurface saturated source areas exist in a catchment. The error introduced will lead to an underestimate of quickflow volumes if the measured area is used in a simulation model. For example, the model developed by Bevan and Kirkby (1979) generally underestimates quickflow but gives its best results for very wet antecedent conditions when a greater proportion of areas which generate subsurface quickflow will be completely saturated.

In catchments where areas capable of subsurface quickflow generation may exist (these will essentially be limited to those with extensive natural pipe networks) field mapping should be combined simple hydrograph analysis to determine the extent of quickflow contributing areas.

An attempt to model the location and extent of source areas has been included by Bevan and Kirkby (Bevan and Kirkby, 1978) in their catchment simulation and have shown, in a number of different catchments, that

$$S \propto \ln a/s$$

where S = frequency of surface saturation

a = area drained per unit contour length

s = tangent of slope gradient.

For any particular discharge the saturated area is correlated with the area in the catchment which exceeds the threshold ln a/s value associated with that discharge.

A wholly topographic variable such as this though, will only be a good indicator of both the extent and location of quickflow source areas if the slope soil cover is homogenous. Where this is not the case and the nature of the soil changes with slope conditions (eg. the study catchment where peat develops on the gentler gradient of the slope summit) or lithological changes occur the 'soil component' must be accounted for. A first step towards this would be the correlation of soil moisture level for a variety of discharges, with ln(a/s) values in different soil mapping units.

(4) Conclusion

The results presented in this paper show that descriptions of the nature and pattern of dynamic source areas in small catchments have, to date, been over simple. It is clear that the physiography of a drainage basin exerts a control on both, which is reflected in the types of flow processes found. It is encouraging to note though that simple topographic and pedologically determined indices should be capable of modelling the distribution and dynamic changes in size of all types of quickflow source areas in small catchments.

References

Albertson, M.L. and Simons, D.B. (1964) Fluid mechanics, Ch. 7 in Chow, U.T. (ed.) Handbook of applies hydrology, McGraw-Hill, New York.

Anderson, M.G. and Burt, T.P. (1978) Experimental investigations concerning the topographic control of soil water movement on hillslopes, J. Geomorph. N.F. Suppl. Bd. 29, 52-63.

Bello, A., Day, A., Douglas, J., Kin-Che Lan and Soh, Z.B.H.A. (1978) Field experiments to analyse runoff, sediment and solute production in the New England region of Australia, J. Geomorph. N.F. Suppl. Bd. 29, 1980-90.

Betson, C.P. (1964) What is watershed runoff? J. Geophys. Research, 69, No. 8, 1541-52.

Beven, K.J. and Kirkby, M.J. (1979) A physically based, variable contributing area model of basin hydrology, Hydrological Sciences Bulletin, 24(1), 43-69.

Day, D.G. (1979) Drainage density changes during rainfall, Earth Surf. Processes, 3, 319-26.

Dickinson, W.P. and Whitely, H. (1970) Watershed areas contributing to runoff, General Assembly Int. Assoc. Sci. Hydrology, New Zealand, 12-16.

Dunne, T. (1978) Field studies of hillslope flow processes, in Kirkby, M.J. (ed.) Hillslope hydrology, Wiley, London, 177-222.

Dunne, T. and Black, R.D. (1970) An experimental investigation of runoff production in permeable soils, Water Res. Res., 6, 478-90.

Dunne, T., Moore, T.R. and Taylor, C.H. (1975) Recognition and prediction of runoff-producing zones in humid regions, Hydrological Sciences Bulletin, XX(3), 305-25.

Emmett, W.W. (1970) The hydraulics of overland flow on hillslopes, U.S. Geol. Survey Professional Paper 662-A, 45pp.

Emmett, W.W. (1978) Overland flow, in Kirkby, M.J. (ed.) Hillslope hydrology, Wiley, London, 145-76.

Finlayson, B. (1977) Runoff contributing areas and erosion, Res. Paper 18, School of Geography, University of Oxford.

Gilman, K. and Newson, M. (1980) Soil pipes and pipeflow - a hydrological study in upland Wales, Monograph No. 2, Geobooks, Norwich.

Hack, J.T. and Goodlett, J.C. (1960) Geomorphology and forest ecology of a mountain region of the Central Appalachians, U.S. Geol. Survey Prof. Paper 347, 65 pp.

Hewlett, J.D. (1961) Soil moisture as a source of base flow from steep mountain watersheds, South Eastern Forest Experiment Station, U.S. Forest Service, Station Paper 132, 11 pp.

Hewlett, J.D. and Nutter, W.L. (1970) The varying source area of streamflow from upland basins, Paper presented at the Symposium on Interdisciplinary Aspects of Watershed, Management, Montana State University, Boseman A.S.C.E., New York, 65-85.

Horton, R.E. (1933) The role of infiltration in the hydrological cycle, Trans. Am. Geophys. Union, 14, 446-60.

Horton, R.E. (1935) Surface runoff phenomena, Part I, Analysis of the hydrograph, Horton Hydrological Laboratory Publication 101, Vorheesville, New York, 73 pp.

Ingram, H.A.P. (1967) Problems of hydrology and plant distribution in mires, J. Ecol., 55, 711-24.

Jones, J.A.A. (1979) Extending the Hewlett model of stream runoff generation, Area, 11(2), 110-14.

Kirkby, M.J., Callan, J., Weyman, D.R. and Wood, J. (1976) Measurement and modelling of dynamic contributing areas in very small catchments, Working Paper 142, School of Geography, University of Leeds.

McCaig, M. (1980) Erosion of stream head hollows, Ph.D. thesis, School of Geography, University of Leeds, 427 pp.

Moss, J. (1913) Vegetation of the Peak District, Cambridge.

NERC (1975) Flood studies report, I. Hydrological Studies, NERC, London.

Newson, M.D. and Harrison, J.G. (1978) Channel studies in the Plynlimon experimental catchments, Institute of Hydrology Report 47, 61pp.

Pilgrim, D.H., Huff, D.D. and Steele, T.D. (1978) A field evaluation of subsurface and surface runoff, II. Runoff processes, J. Hydrology, 38, 319-41.

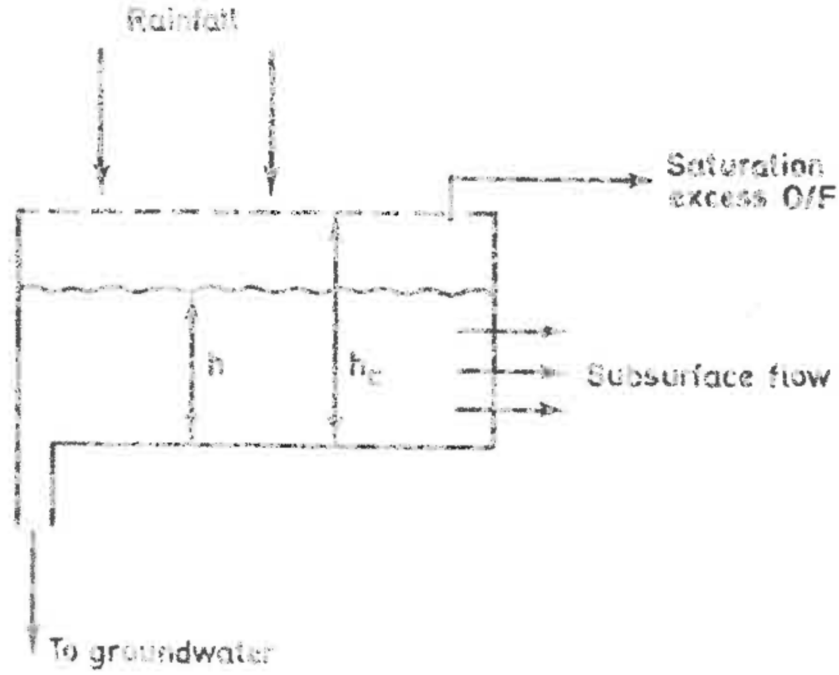
Tagg, A. (1981) Personal Communication.

T.V.A. (1963) A water yield model for analysis of monthly runoff data, Res. Paper No. 2, Knoxville, Tenn., 78 pp.

Weyman, D.R. (1971) Surface and subsurface runoff in a small basin, Ph.D. thesis, University of Bristol, 243pp.

Whipkey, R.Z. (1967) Storm runoff from forested catchments by subsurface routes, International Symposium on Floods and their Computation, UNESCO, Leningrad.

Wray, D.A., Stevens, J.V., Edwards, W.N. and Bromehead, C.E.N. (1930) The geology of the country around Huddersfield and Halifax, Memoir of the Geological Survey of England and Wales - explanation of sheet 77, 221 pp.



h = Storage level
h_c = Storage capacity

Figure 1. The saturation excess model of runoff generation

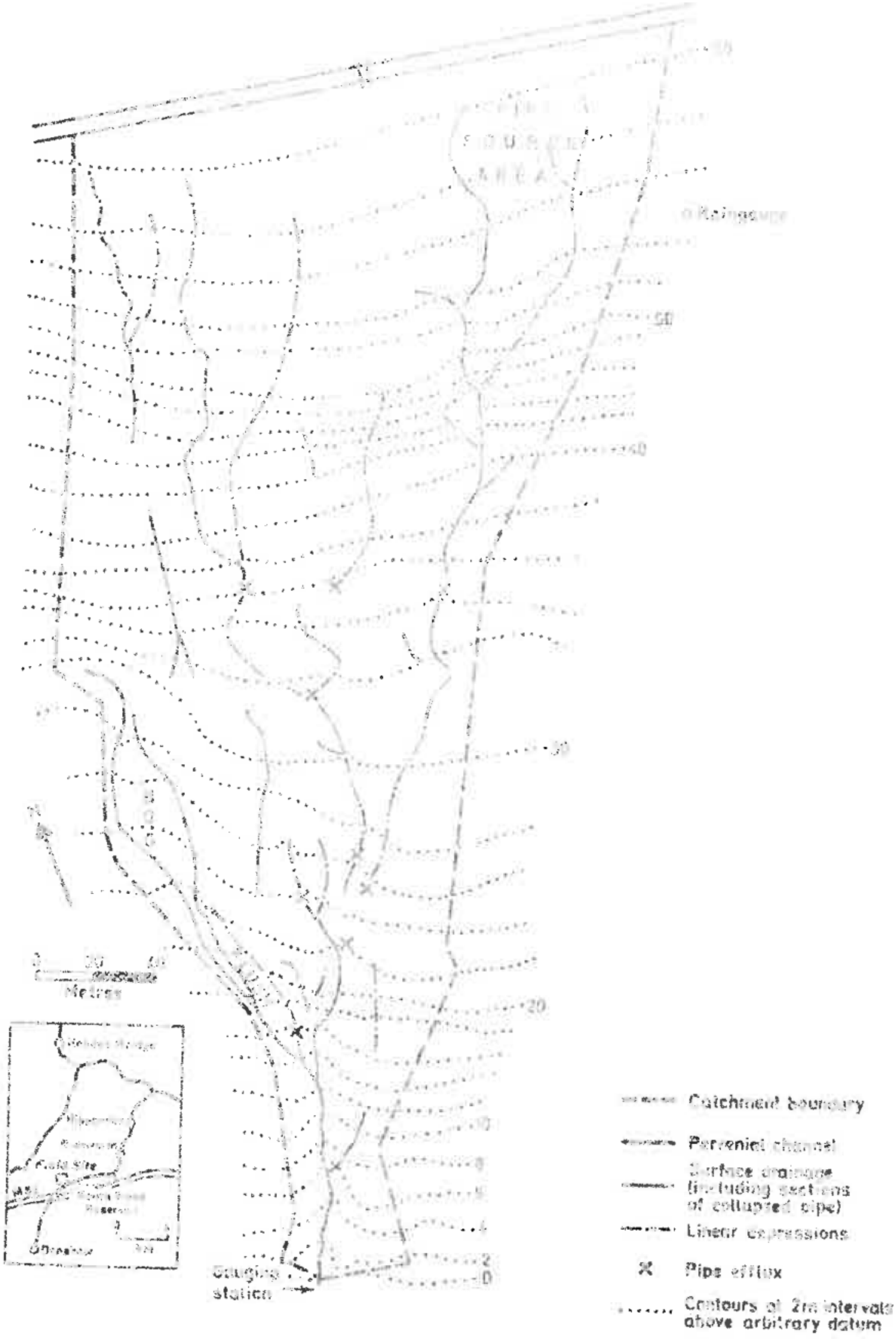


Figure 2. Map of experimental catchment

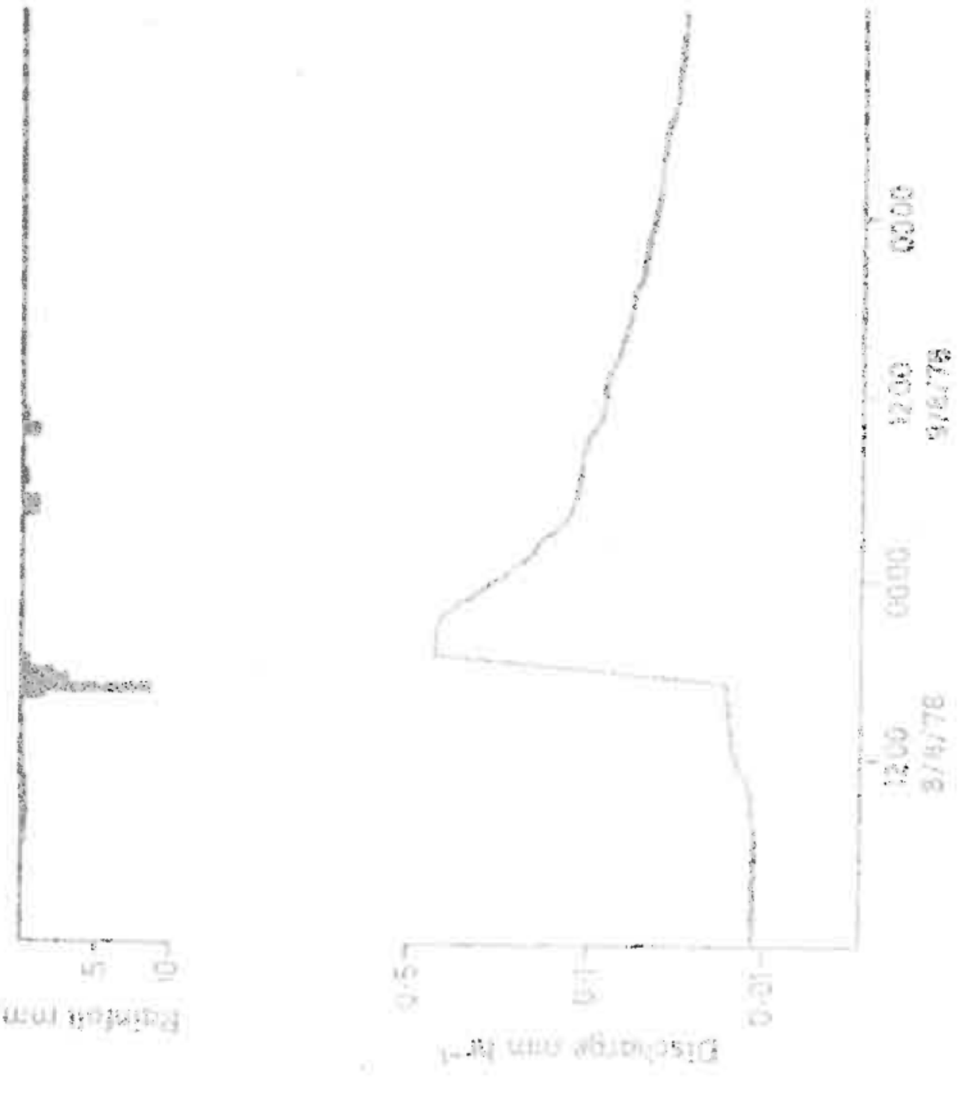
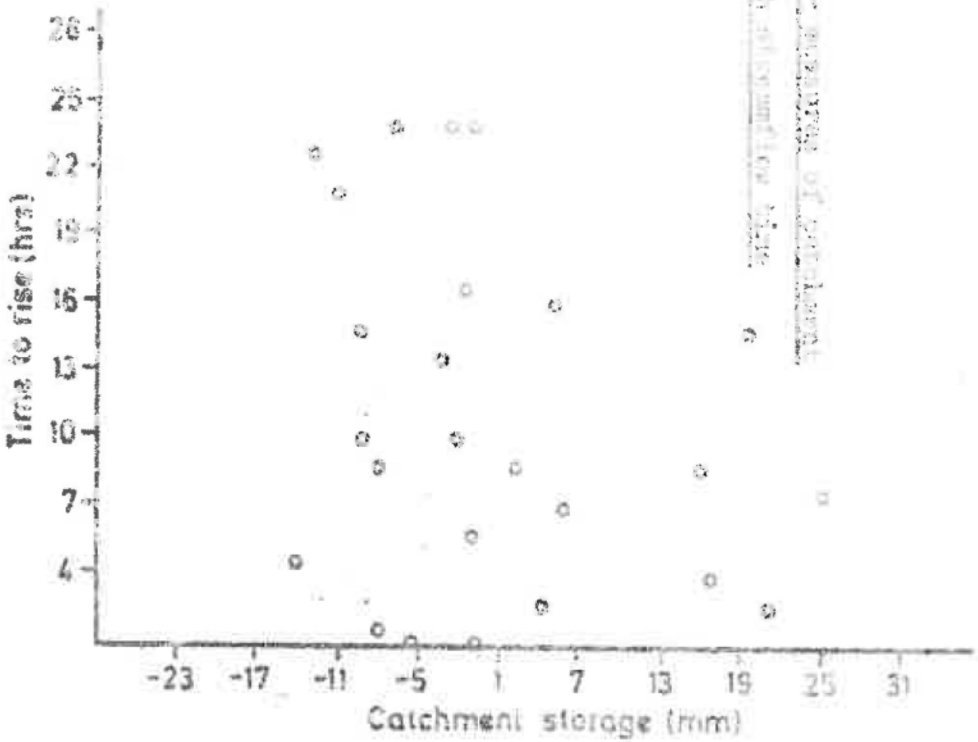
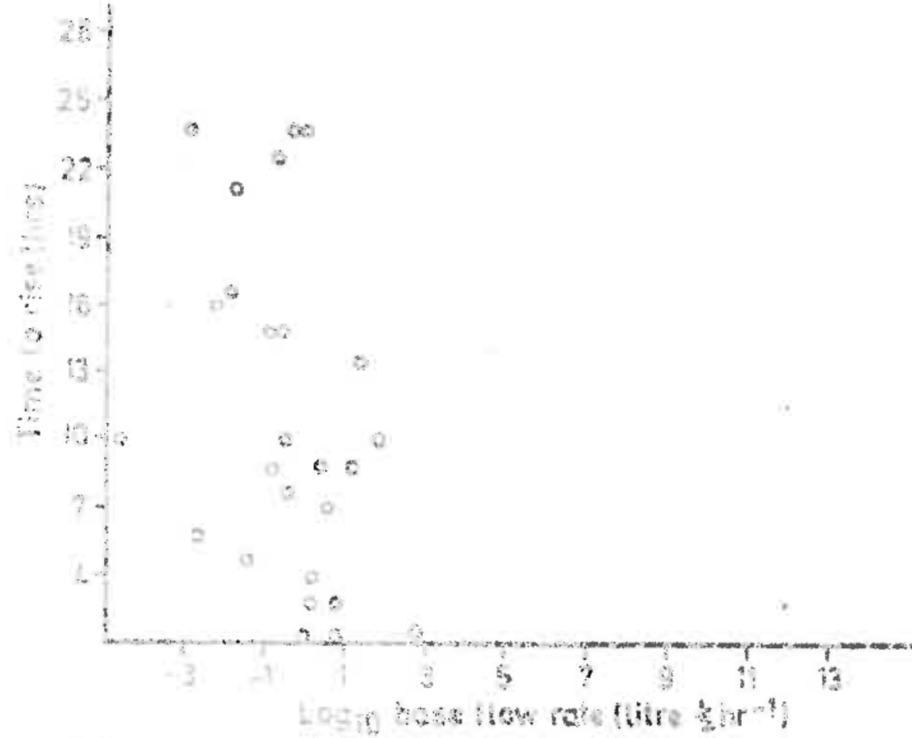


Figure 1. Example quickflow event





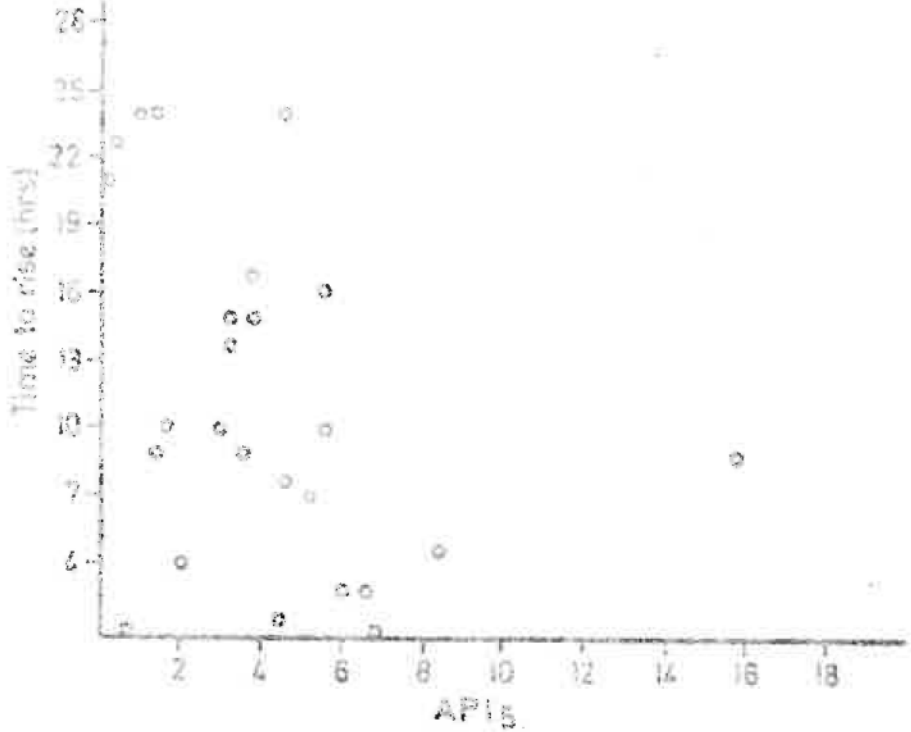


Figure 4. Scattergrams - measures of catchment wetness with streamflow time to rise

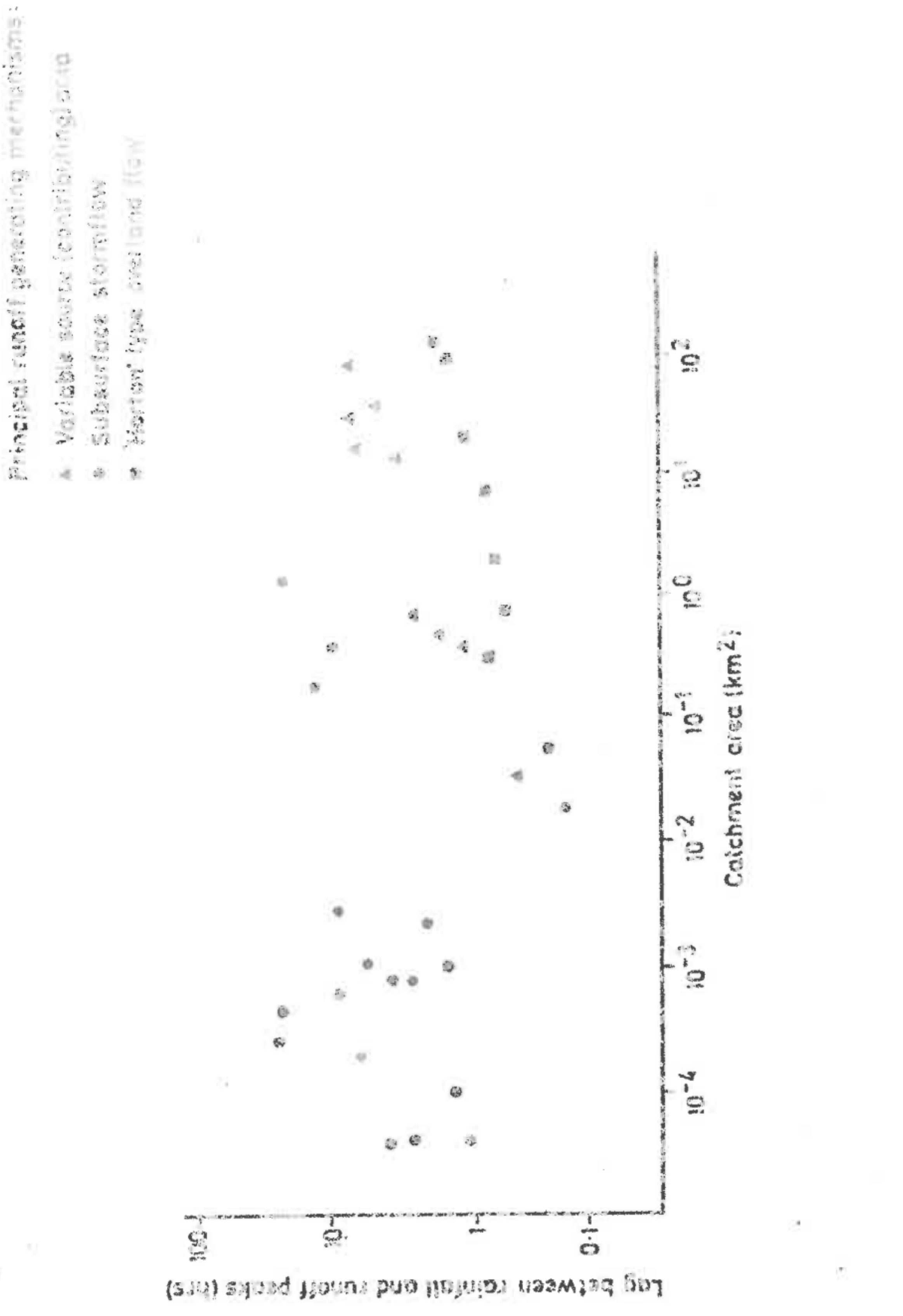


Figure 5. Times to peak for catchments with different types of quickflow generation (Redrawn after Dunne, 1978)

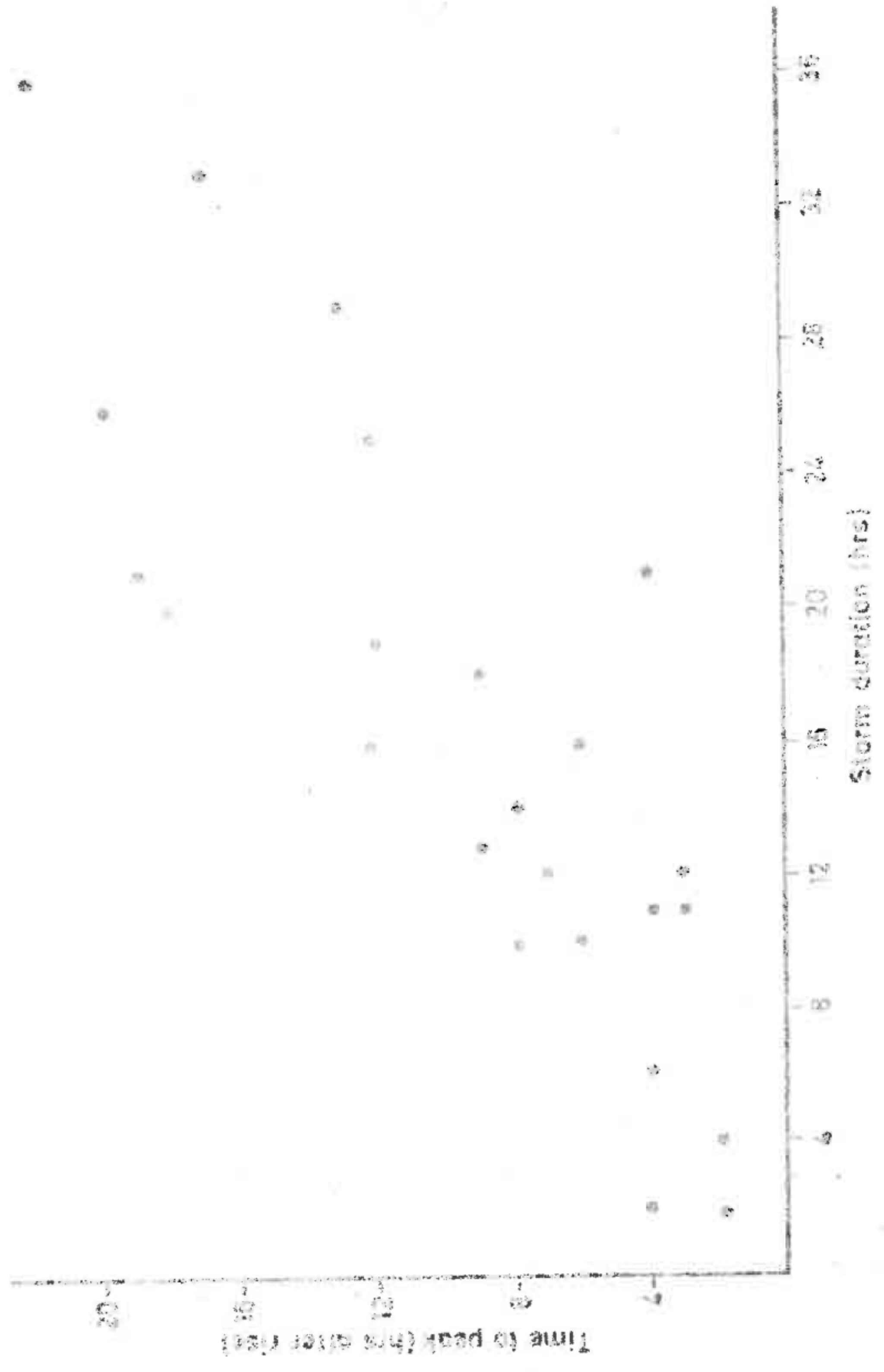


Figure 6 Relationship of time to peak with storm duration

Velocity (ms^{-1})	Average Slope	Vegetation cover	Source
[illegible] - [illegible]	–	–	Emmett, 1970
0.006 - [illegible]	15°	Grasses (90% surface cover)	Emmett, 1970
[illegible]	9°	Juncus/Grass bog community	[illegible] and Harrison, 1978
[illegible]	5°	Unimproved pasture	Tagg, 1981
[illegible]	[illegible]	Moorland grasses	Tagg, 1981
0.01 - 0.07	5°	Unimproved pasture	Present study

Figure 1. Overland flow velocities

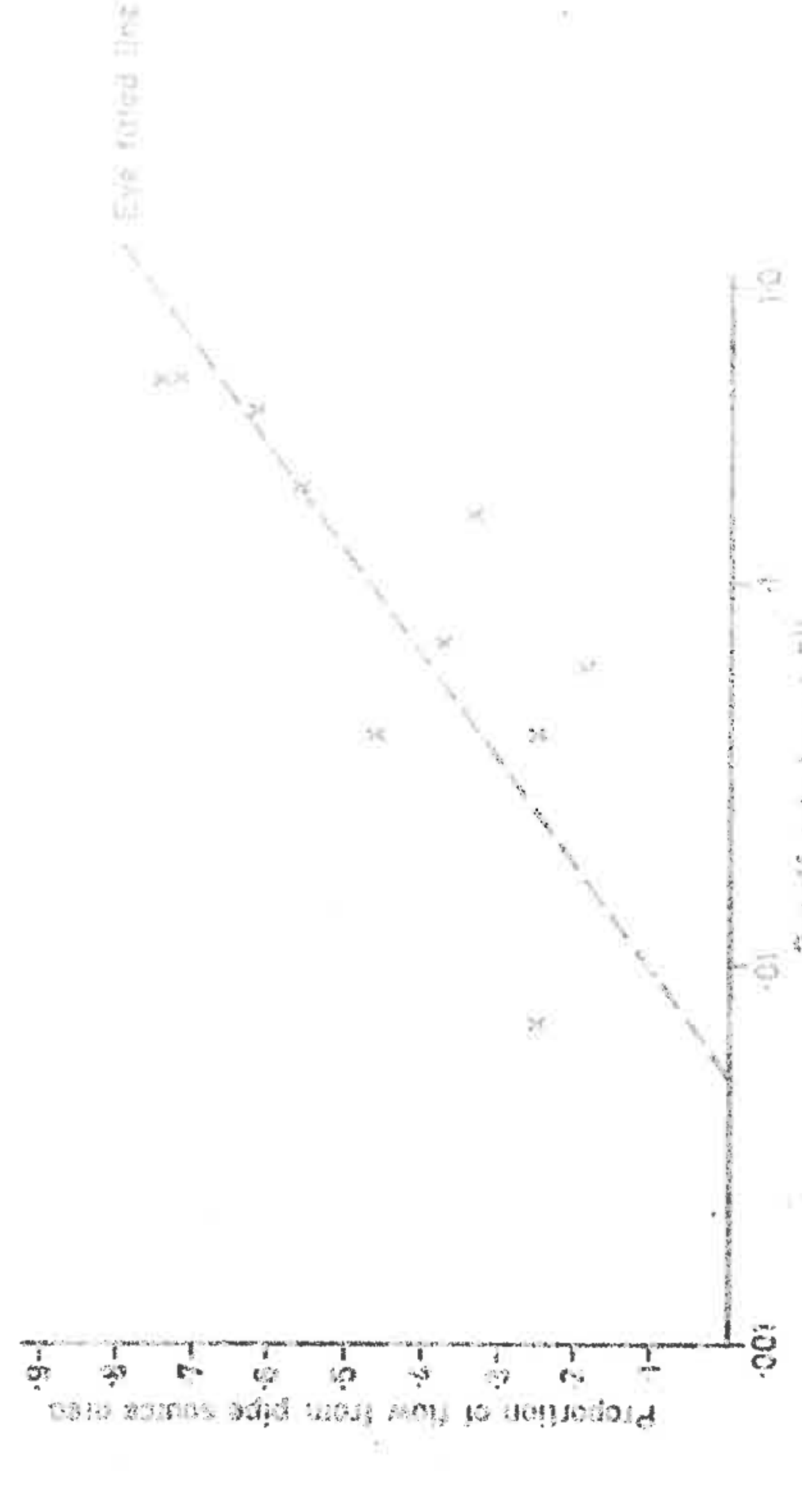


Figure 8. Relationship between flow from different source areas and runoff rate

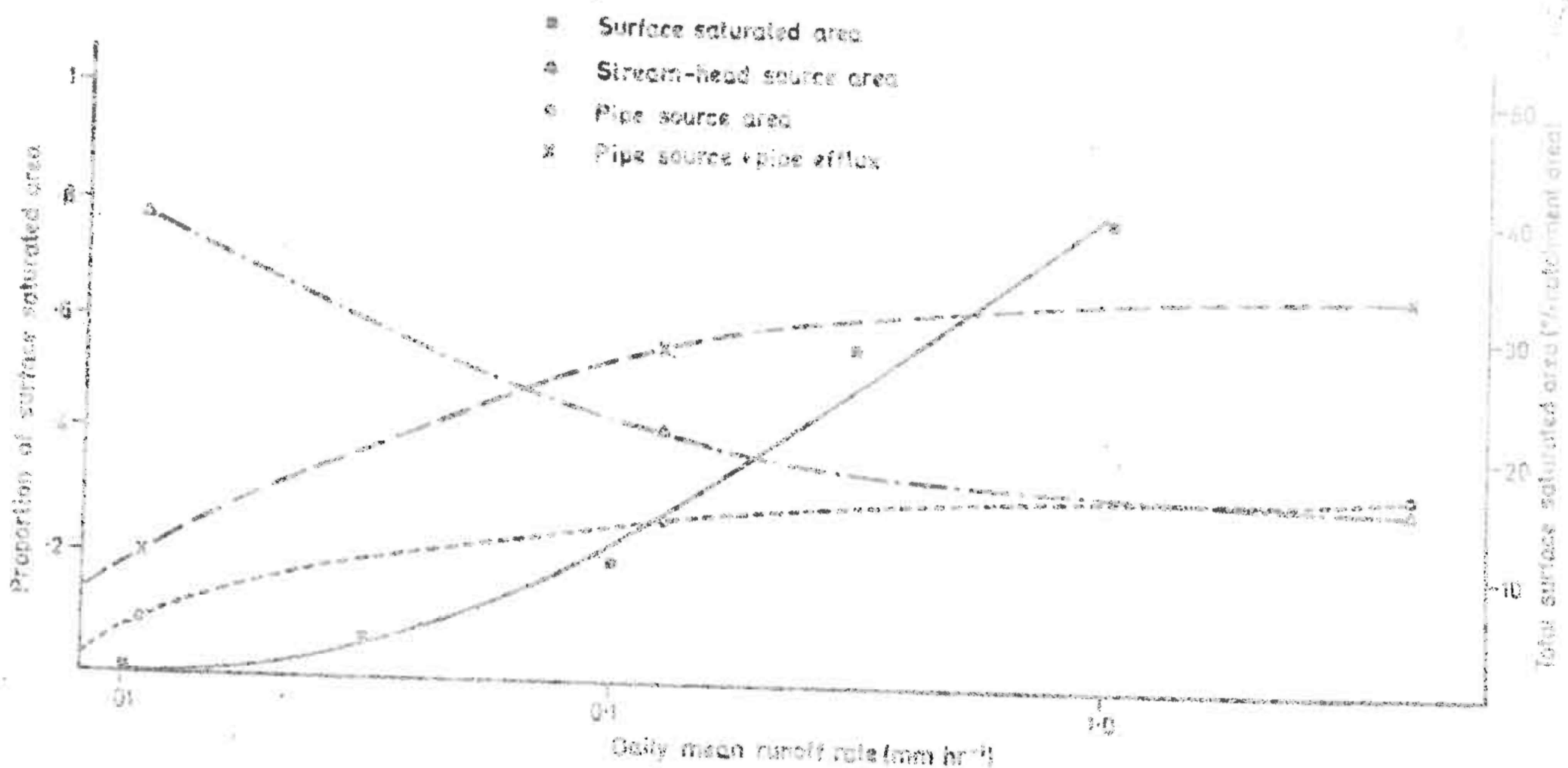


Figure 9. Mapped extent of surface saturated areas

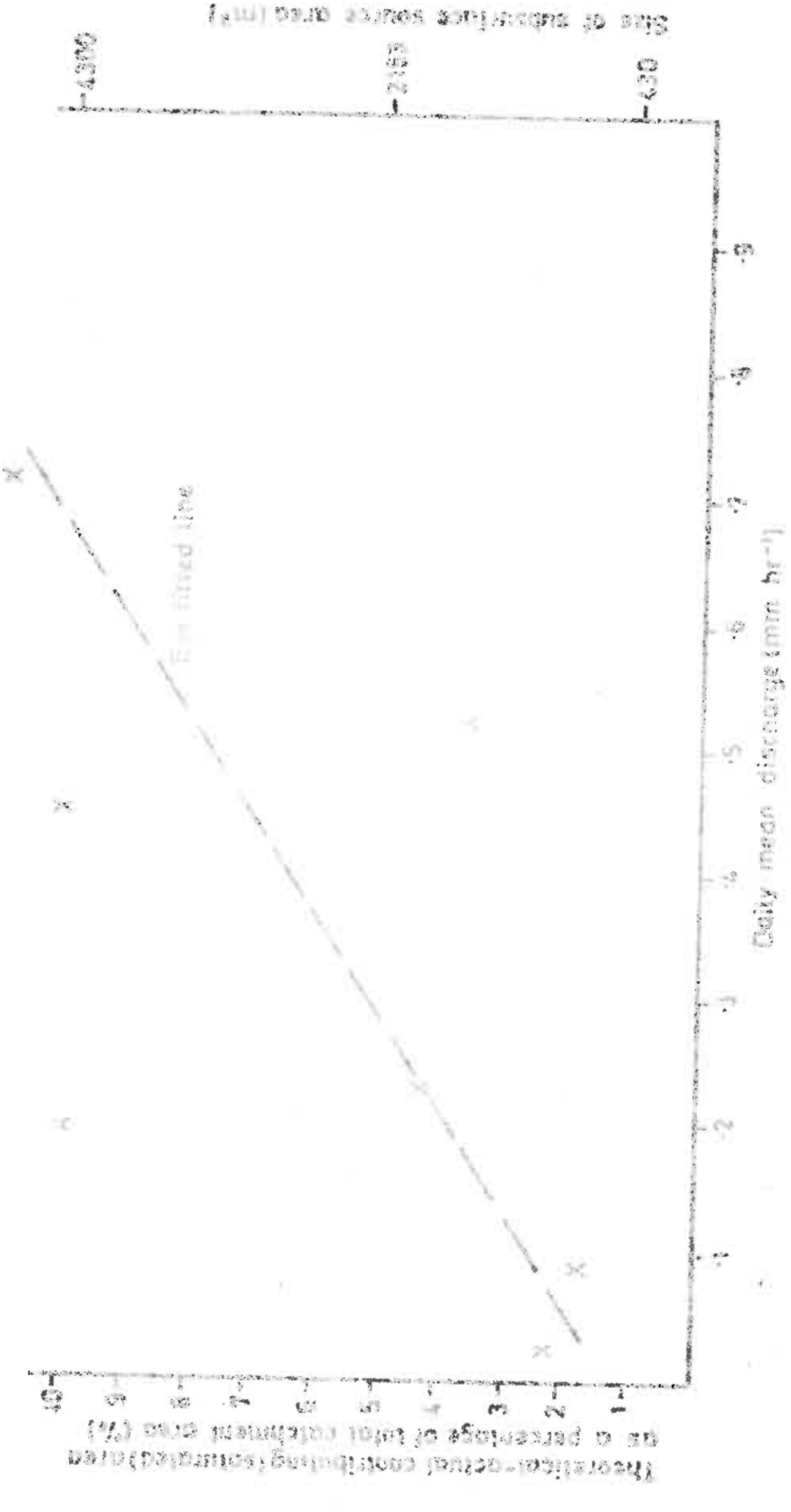


Figure 10. Extent of non-saturated source area - relationship with discharge

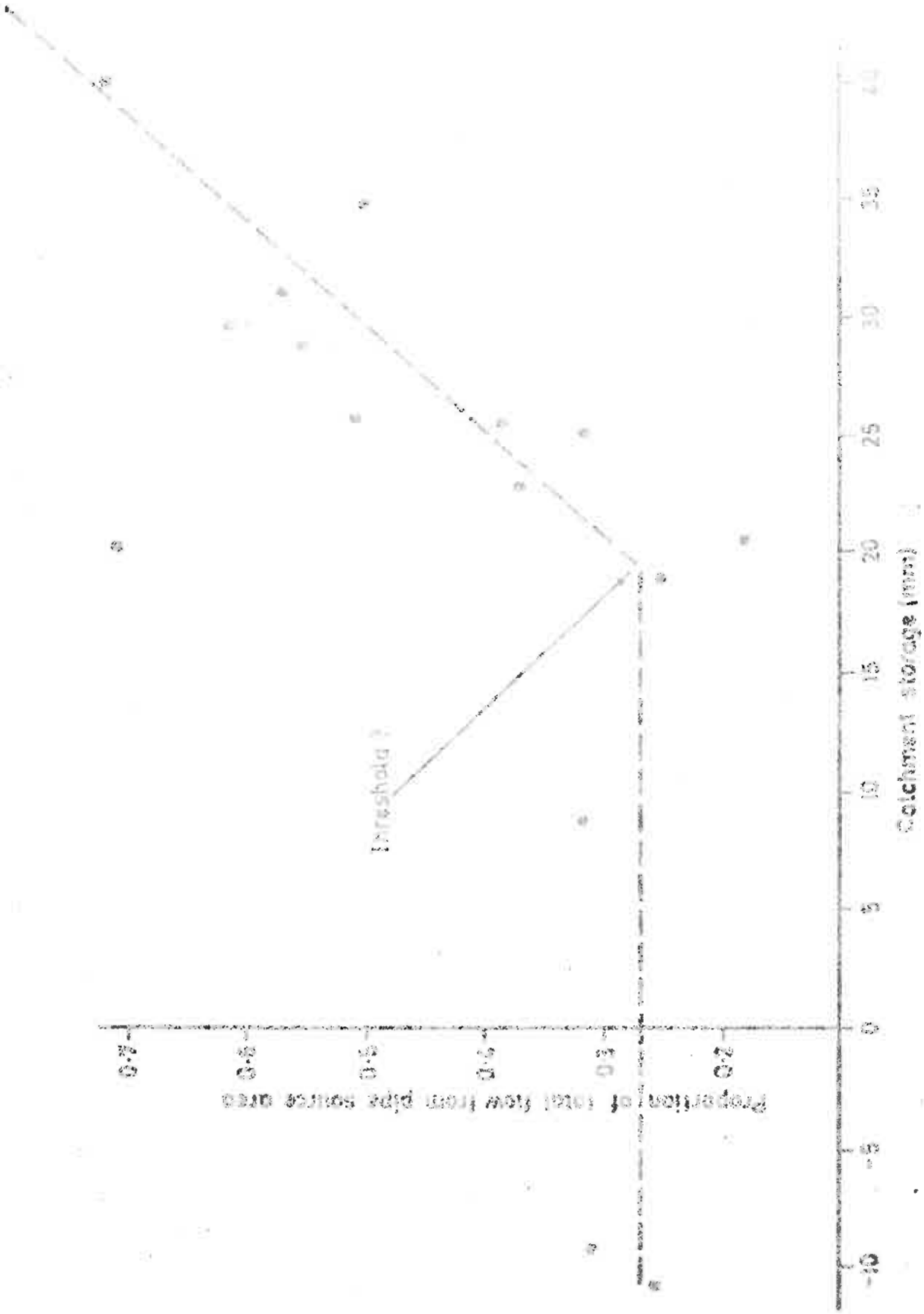


Figure 11. Pipeflow as a proportion of total flow for different catchment water storage levels

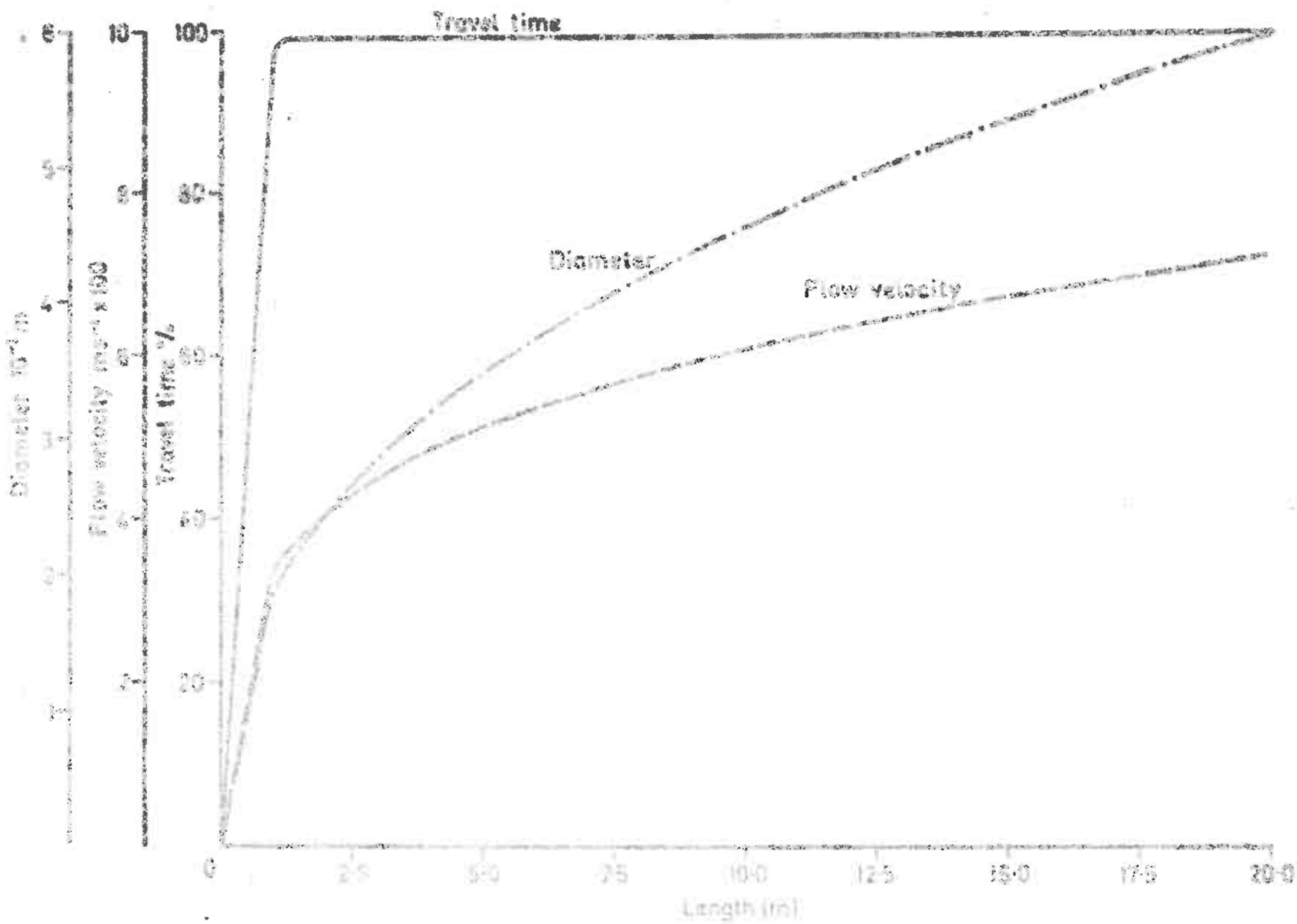


Figure 1[illegible]. Bore diameter, flow velocity and travel time with distance – model results