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Source Areas of Storm Runoff in a Pasture Catchment

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ABSTRACT

The processes of storm runoff in an improved ryegrass-clover catchment were examined by weekly mapping of saturated soils and by hydrograph analysis. Areas categorised as permanently saturated made up 3-5% of catchment area, seasonally saturated 8-14%, and temporarily saturated up to 100% of catchment area in large storms.

Quickflow tended to originate solely from permanently or seasonally-saturated areas in rainfalls of 2-5 mm and mainly from these areas in events of 5-25 mm. Temporarily-saturated areas contributed a major proportion of quickflow in rainfalls greater than 25 mm, especially in winter when heavy rainfall exceeded infiltration and surface detention over large areas of the catchment. Quickflow patterns in heavy rainstorms are determined mainly by the properties of the soil surface, which are strongly influenced by stock trampling. Areas of permanent and seasonal saturation appeared to generate about one third of total quickflow; about half the catchment area generated 95% of the quickflow. Land management aimed at limiting nutrient or pollutant losses in overland flow should be directed to the source zones of predominant runoff rather than to the whole catchment.

Soil surface saturation correlated well with soil properties (pugging, structure, mottling and gleying), vegetation type and geomorpholoy. Mapping of soil saturation and soil and vegetation surveys may prove useful in identifying runoff source areas in New Zealand hill pastures.

Key words: hydrology, surface runoff, water quality, source areas, water balance, overland flow, quickflow, infiltration, topsoil properties, non-point pollution.

INTRODUCTION

A requirement in land and water resource management is an understanding of how storm runoff is generated. Flood and erosion control, water quality and even forest and farm productivity may be improved if areas of differing hydrologic behaviour within a catchment are known.

The generation of storm runoff at land surfaces is very complex and a number of runoff concepts have been developed. The Horton (1933) model considers average conditions in a catchment and proposes that surface runoff occurs when, during rainfall, and after interception and detention stores are filled, the rate of infiltration becomes less than the rate of rain falling. The partial-area model of Betson (1964) proposes that only parts of the catchment generate surface runoff in this way, the major source of runoff being from permanently-saturated areas or areas of lower infiltration rate. The Hewlett (1961) model proposes that storm flow is generated as surface runoff and as subsurface flows from saturated zones around the catchment channel system. These zones grow in area during rainfall, as their limited storage capacity is filled by rainfall and subsurface water flow from upslope. These areas are referred to as variable source areas. Because infiltration rates commonly exceed rainfall rates in many catchments, especially forest catchments, the Hewlett model offers a more satisfactory explanation of storm runoff than the Horton model.

The concept of limited areas of a catchment contributing to flood flow is a vital one for water quality studies and for water and land management because it implies that management may be concentrated more profitably and economically in areas of limited size. For example, Engman (1974) suggests that this knowledge can be used to indicate where fertilisers could be applied safely and where heavy use of pesticides should be avoided.

In New Zealand, Pearce and McKerchar (1979) have inferred runoff mechanisms in a range of storms for 17 small catchments by examining the change in ratio of quickflow to rainfall with storm size. Saturation overland flow on small portions of the catchment appeared to explain storm runoff in small rain storms (1 day-100 day return period) in all catchments. In larger storms, either overland flow of the Hortonian type or rapid subsurface flow could explain storm runoff, depending on soil and topography.

So far there have been few field descriptions of runoff source areas. Dunne *et al* (1975) found that topography, baseflow, an antecedent-moisture index, and soil type were the most useful indicators of the location or likely area of the saturated zone. Vegetation was useful as a rough indicator in some areas. In a New Zealand study, Taylor and Pearce (1982) found that, where subsurface flow and saturation overland flow were both important contributors to quickflow, topographic and soil indicators were not useful in identifying runoff source areas.

In this field study we investigated the generation of storm runoff in a small pasture catchment in terms of the three models referred to above. Hydrograph analysis provides quickflow:precipitation ratios which may be compared with saturated area:total catchment ratios; the relationships between these ratios will differ for the models under investigation. We also attempt to relate the runoff source areas identified to soil morphology, topography and vegetation.

SITE DESCRIPTION

The area selected for study is a 4.27 ha catchment at Judgeford, 23 km northeast of Wellington, New Zealand, map reference NZMS 1 N160/483436 (Fig. 1). The nearest climate station is at Pauatahanui, 4 km from the catchment.

Mean annual rainfall for the period 1941-70 was 1200 mm. Rain is well distributed, with enough summer rainfall so that stored moisture plus rain usually exceeds evapotranspiration. Mean windrun for the period 1969-76 was 317 km/day. Mean daily air temperature (1941-70) was 12.9°C with mean daily maximum 16.9°C and mean daily minimum 9.4°C. Mean daily total incoming short wave radiation was $1.43 \times 10^7 J/m^2$.

The catchment is underlain by greywacke. The surficial deposits consist of colluvium derived from underlying sediments mixed with Quaternary loess. A fuller description of the geology is given in Healy (1980).

Soils of the catchment were named as Judgeford stony hill soils (JgH) by Gibbs (in Northey and Gibbs, 1974). These are yellow-brown earths in the New Zealand classification (Taylor and Pohlen, 1979).

The catchment is 45 m asl at its lowest point, rising to 96 m asl in the northeastern corner. The topography can be classed as rolling to steepland. Erosion severity is moderate with some slumps on wetter south-facing slopes, sheep tracks and terracettes on steep slopes and sheet erosion associated with porina (*Wiseana* sp.) damage to pasture on gentler slopes. Streambanks are actively eroding in permanent watercourses.

The study area probably was cleared of forest before 1900. Some scrub clearance is believed to have been carried out later on, with giant disc harrowing on the gentler slopes in the period 1948-55. The catchment is now under improved ryegrass-clover pasture with rush vegetation in wet hollows and marshy patches near stream channels. The area is stocked mainly with sheep and occasionally with cattle. During the study period the area was intermittently heavily stocked, with an average stocking rate of 22 stock units/ha. From May to September soil pugging was severe in the wetter parts of the catchment.

FIG. 1—Photograph of experimental catchment, Judgeford, near Wellington, looking north-east.

TABLE 1 — Legend to the geomorphological map (Figure 2a)

Landform Class	Description Site Characteristics	Slope Angle	Slope Form	Microtopography	Erosion (1-10)+	Dalrymple's** Class
1 Interfluve	Convex ridges	4-12°	Convex	—	2	1
2 Sideslope	Above toeslopes. Transportation zone, colluvial wash and water*	7-27° (av 19°)	Predominantly planar	Some terracettes	3	2 3 5
3 Complex sideslope	Steep slopes: bare ground treads and seepage zones; variable depth of soil	Variable treads and risers. Overall 27-37°	Concave and convex some planar	Many terracettes	3-5	4 5
4 Toeslope	Lower part of hill slope: zone of accumulation of colluvial wash and of subsurface overland flow	6-12°	Concave with some convex areas	Mounds and hollows (puddling)	3	6
5 Alluvial toeslope	Terrace edge, above incised stream channel	8-9°	Convex	—	2	7
6 Slump	Occurs on steeper slopes in the base of seepage zones on sideslopes	12-18°	Convex (cross) Concave (long)	Hummocks and terracettes	Deposition +3	4 8
7 Stream channel	Permanently-saturated alluvial and colluvial deposits in and beside stream channel	5°	Planar	Hummocky zone	Deposition	9

* Upper part of sideslopes may be temporarily wet after high-intensity rain, lower part may be wet by end of winer as water accumulates.

** Dalrymple *et al* (1968).

\+ Erosion class estimated visually on 1 (low) — 10 (high) scale.

FIELD METHODS

Stream level was continuously measured at a compound 'V' notch weir with a Lea water-level recorder serviced weekly. Rainfall was measured using a Lambrecht recording rain-gauge and a manual check gauge.

Runoff volumes were computed for selected flow events with separation of the hydrographs into quickflow and baseflow using the Hewlett and Hibbert (1967) method, at a slope of 0.0055 l sec^{-1} ha^{-1} h^{-1}. A flow event was defined as a period of continuous quickflow production and often included several periods of rain.

Missing record was 14% for streamflow and 19% for rainfall at different times, giving complementary record for only 67% of the study period. Daily rainfalls for periods of lost rainfall record were available from a rain gauge about 2 km away; a correction of ×1.02 was applied to these values.

The surface-saturated areas of the catchment were mapped weekly on foot, by visually identifying the boundary between saturated and unsaturated soils. A series of pegs each 15 m distance from the stream channel aided the estimation of map distances. Criteria for saturation were obvious surface water or liquid mud, or release of water on light pressure from the gumboot.

The morphologies of the soil profiles at 16 sites in the catchment (Fig. 2) were recorded and described. Soils of the catchment were tentatively classified to subgroup level using Soil Taxonomy (Soil Survey Staff 1975) (Fig. 2, Table 1).

The intensive study area was sited on the largest toeslope in the south-west quadrant of the catchment. Here a detailed survey of 43 sites was made using a soil auger to determine the distribution of the two main soils — Aquic Dystrochrepts and Aeric Haplaquepts, and their association with vegetation (Fig. 2).

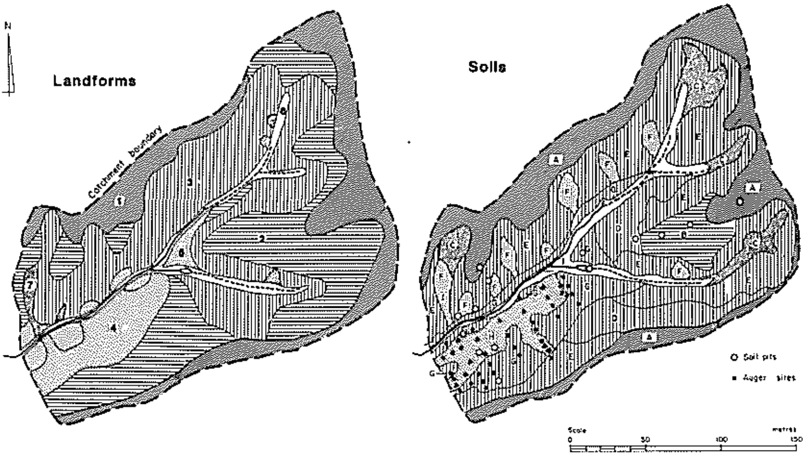

FIG.2—Distribution of (a) landforms and (b) soils of the experimental catchment. Legends for these maps are given in Tables 1 and 2 respectively.

TABLE 2 — Legend for soil map (Figure 2b)

Classification of these soils is to subgroup level of USDA Taxonomy (Soil Survey Staff 1975) and is tentative based on soil-profile criteria alone. Map units are dominated by the soil listed but also contain several other soils.

Class No.	Landform Class (Table 1)	Most Extensive Soil on Landform Class	Characteristics of Most Extensive Soil	Drainage Class (Taylor & Pohlen 1970)	Map Code (Figure 2)
1	Interfluves	Typic Dystrochrept	Friable, brown, silty and fine sandy subsoils, no mottles, no gravels	Well drained	A
		Aquic Dystrochrepts	Firm, brown, silty, subsoils, faint mottles above 60 cm, no gravels	Imperfectly drained	B
2	Sideslopes	Typic Hapludult	Very firm, brown, clayey subsoils, no true mottles, no gravels.	Moderately well drained	C
		Aquic Dystrochrept	(as for Aquic Dystrochrept above)	Imperfectly drained	D
3	Complex Sideslopes	Aquic Dystrochrept	(as above)	Imperfectly drained	E
		and Aeric Haplaquept	Firm, grey, silty subsoils, reddish-brown mottles above 30 cm, no gravels.		
4	Toeslopes	Aeric Haplaquept	(as for Aeric Haplaquept above)	Poorly drained	H
5	Alluvial Toeslopes	Aquic Dystrochrept	(as for Aquic Dystrochrept above)	Imperfectly drained	G
6	Slumps	Tupic Haplaquent	Firm, very clayey subsoils, many reddish-brown mottles, no gravels.	Very poorly drained	F
7	Stream Channels	Typic Fluvaquent	Soft, very grey, silty soil, no mottles, no gravels.	Very poorly drained	I

The morphological criteria was used in this study to separate these soils were:

	Aquic Dystrochrepts	Aeric Haplaquepts
Topsoil:	reddish-brown mottles or coatings absent	reddish-brown mottles or coatings present
Subsurface horizons:	20-60 cm yellowish-brown matrix, common faint reddish-brown mottles	20-80 cm greyish-brown matrix, many distinct reddish brown mottles
	> 60 cm yellowish-brown matrix, common reddish-brown and few grey mottles	> 80 cm dominantly grey matrix many distinct reddish-brown mottles

Seven landform units were identified (Fig. 2) and, in Table 2, have been related to theoretical landform units of Dalrymple *et al* (1968).

Infiltration measurements were made using a single-ring infiltrometer. Water movement over saturated surfaces and down soil profiles was traced using dyes.

RESULTS

Rainfall

Total rainfall during the study period, 27 April 1979 to 17 October 1980 (540 days), was 2587 mm. Rainfall was well distributed throughout the period

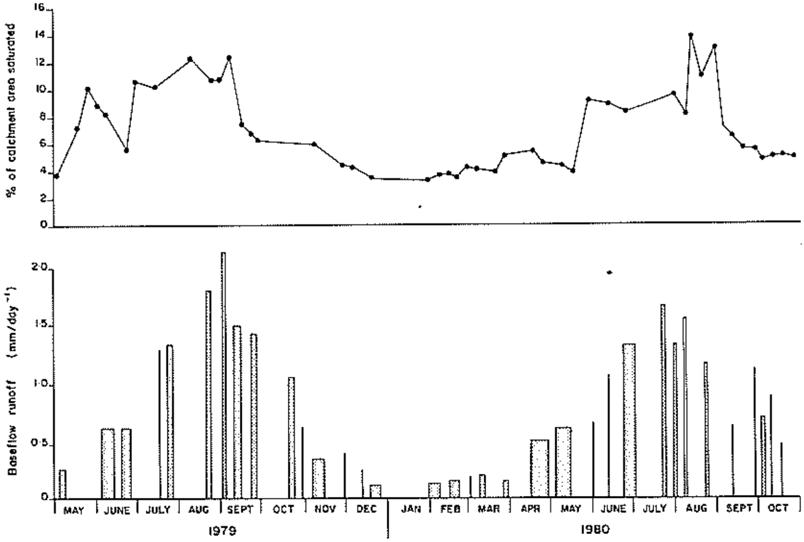

FIG.3—Percentage of catchment area saturated (excluding rainstorm-influenced data) and baseflow discharge (mm/day). Histograms show duration of baseflow.

TABLE 3 — Summaries of rainfall and quickflow for the period 27 April 1979 — 17 October 1980 at the experimental catchment, Judgeford

Rainfall Summary for Full Period				Rainfall and Quickflow Summary for Events with Complete Records				
Rainfall Class (mm)	Total for Period (mm)	Total Number of Events	Return Period* (days)	Number of Events	Rainfall (mm)	Quickflow (mm)	Mean Proportion of Rainfall as Quickflow (%)	Standard Deviation
0-2	54	87	6	0				
2-5	120	37	15	24	78	3.9	4.9	2.5
5-10	257	34	16	19	141	11	7.8	5.0
10-25	440	28	19	19	297	37	12.8	7.0
25-50	750	21	26	13	463	179	37.9	14.8
50-100	725	10	54	4	296	161	54.0	13.6
100+	241	2	270	2	241	170	72.2	21.2

* Assessed by relative frequency within the study period.
Total 2587

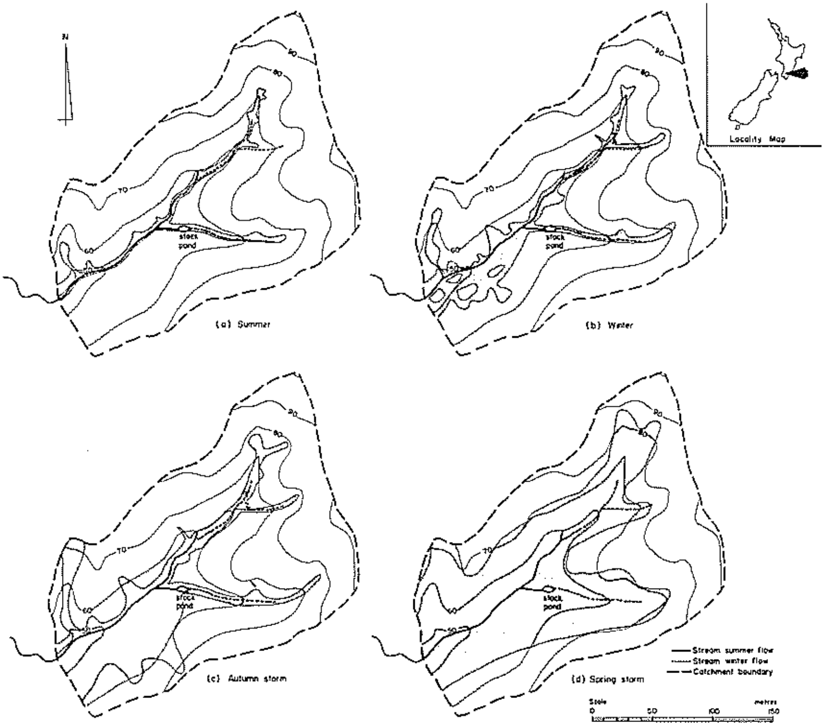

FIG.4—Saturation maps, experimental catchment, Judgeford.

with about 145 mm/month in winter (June-August), 120 mm/month in spring (September/November), 130 mm/month in summer (December-February) and 180 mm/month in autumn (March-May). Maximum intensity recorded in 10 minutes was 26 mm/h, and in one hour 8.5 mm/h.

Runoff as Baseflow

Streamflow was continuous throughout the study period; flow occurred within the stream channel and from permanent and winter surface-saturated areas caused by seepage on the valley sides. Fluorescin dye showed up surface water movements of 1-8 m/h across some winter saturated surfaces under baseflow conditions. Baseflows (defined as flows occurring at least four days after > 1.5 mm rain, but taking into consideration residual effects from larger storms) showed smooth seasonal variation, from 1.9 mm/day in mid-winter to 0.11 mm/day in summer (Fig. 3).

Runoff as Quickflow

Events for which rainfall and runoff were measured (81 during the study period) were grouped in six rainfall classes. Quickflow as a proportion of rainfall was calculated for each event and averaged for each of the six classes (Table 3). The proportion of rainfall appearing as quickflow increased from only a few percent for small events to as high as 90% for the largest events. Quickflow accounted for about 35% of total rainfall.

The shape of the hydropgraph peaks and the time to peak show that stream response to rain is rapid.

Description of Surface-Saturated Areas

Four selected maps of surface-saturation are shown in Figure 4. The summer map (March 1980) indicates areas near the stream channel and on the valley sides which were permanently saturated. The winter map (August 1979) indicates the enlarged areas commonly saturated during winter months, including permanently wet areas plus additional areas on the valley sides. These areas are referred to in this paper as the *permanently-saturated areas* and the *seasonally-saturated areas* respectively. The other two maps made during or shortly after rain storms show the presence of additional *temporarily-saturated areas.*

Permanently-saturated areas

The areas of the catchment permanently saturated were the streambed, the streamside or riparian zone, and several seepage areas on the valley sides (Fig. 4a). These streamside and seepage areas were characterised by wet, massive, and soft topsoils over wet, grey, massive subsurface material showing little horizon development. The soils were heavily damaged in places by animal treading, and supported vegetation species adapted to wetland conditions (Table 4). Soils were classifed as Typic Haplaquents and Typic Fluvaquents. Landforms tended to be geomorphic classes 6, slump and 7, stream channel (Fig. 2).

TABLE 4 — Some plants of the experimental catchment, Judgeford

Species throughout the pasture area	*Lolium perenne* L. *Trifolium repens* L. *T. dubium* Sibth.
Species apparently restricted to drier areas	*Cerastium* sp. *T. subterraneum* L.
Species of drier areas apparently tolerating temporary waterlogged conditions	*Taraxacum officinale* Weber *Plantago major* L. *Cynosurus cristatus* L. *Hypochaeris radicata* L. *Mentha pulegium* L. *Rumex* sp.
Species restricted to seasonally saturated areas	*Juncus articulatus* L. *J. bufonius* L. *J. gregiflorus* L. Johnson *Juncus* spp. (tall rushes)
Species of permanently saturated areas	*Blechnum minus* (R. Br.) Allan *Epilobium insulare* Haussk. *Myosotis sp.* *Veronica sp.* *Nasturtium sp.* *Juncus spp.* *Eleocharis sp.* *Schoenus maschalinus* Roem. et Schult

Seasonally (winter)-saturated areas
The additional catchment surfaces commonly saturated in winter included areas adjacent to permanently-saturated areas, plus areas on the valley sides (Fig. 4b). These area were characterised by a poorly-structured surface layer, a muddy pugged surface, either saturated or incipiently saturated topsoil (ie, with minimal rain storage potential) and by pasture plants and plant species adapted to wetland or waterlogged conditions (Table 4). The distribution of tall rush vegetation (Fig. 5) correlated well with these areas (cf, Fig. 4b). The soils of these areas tended to be dominantly Aeric Haplaquepts (Fig. 2). Ferrous ions in the upper soil horizons were a useful indicator of previous waterlogging. In this study we detected ferrous ions using the field test kit described by Childs (1981). The seasonally-saturated areas tended to belong to geomorphic classes 3, parts of complex toeslopes, and 4, sideslopes (Fig. 2).

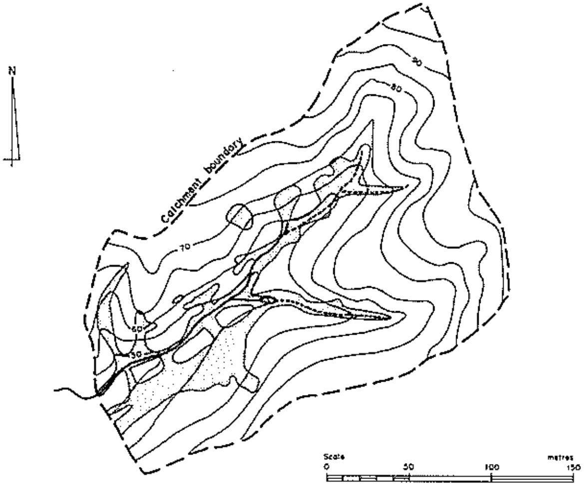

FIG.5—Distribution of tall rush vegetation (*Juncus* spp.) in the experimental catchment.

Temporarily-saturated areas
Large, temporary increases in surface-saturated areas occurred during many of the larger rain storms. The temporarily-saturated area could include all soils outside the permanently and seasonally-saturated areas. Of the temporarily-saturated areas the convex headslopes became saturated most rarely, the sideslopes most commonly, and the flatter-topped interfluves occasionally. The characteristics of these soils were moderately-developed topsoil structure, with some evidence of surface sealing caused by stock trampling. The vegetation comprised typical pasture species with no special adaptations to waterlogging (Table 4).

Soils of these areas tended to be dominantly Aquic Dystrochrepts, but with Typic Dystrochrepts and Typic Hapludults on the well-drained and moderately well-drained portion of the landscape. These areas belong to geomorphic classes 1, interfluves; 2, sideslopes; 3, parts of complex sideslopes, and 5 alluvial toeslopes (Fig. 2).

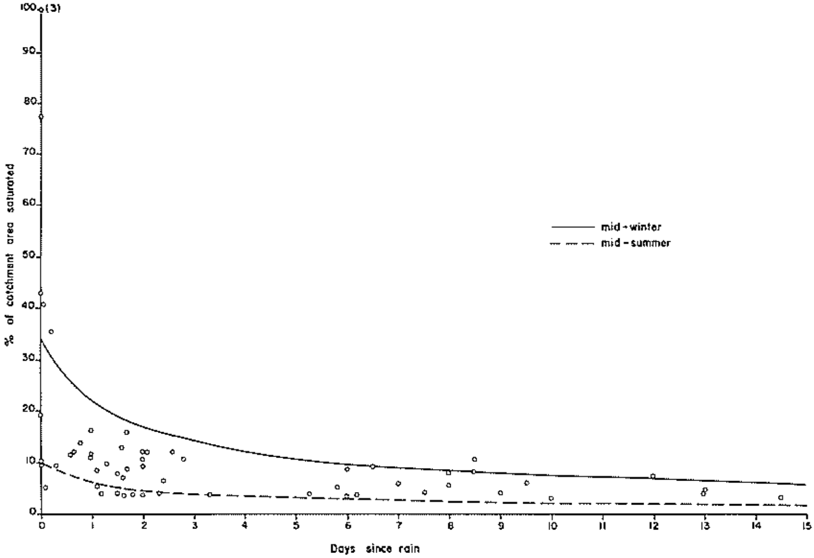

FIG.6—Rate of shrinkage of saturated area after rainstorms. The regressions lines for mid-winter and mid-summer are plotted using a regression of saturated area on a season factor and days since rain (see text).

Variation in surface-saturated areas

The rate of shrinkage of saturated areas is indicated by a plot of saturated area (measured in the weekly visits) against the number of days since rain (Fig. 6). Multiple regression analysis of the percentage of the catchment saturated as a function of days since rain, a season factor, an index of effective rain (ratio of rain amount:days since rain), and prior saturation, explained about 69% of the variation in saturated area. Days since rain and season alone explained 64% of the variation according to the following regression formula:

$$\text{Log } A=1.2651-0.2737\,(S)-0.6480\,\text{Log}(D+1)$$

where A=the percentage of the catchment area saturated,

S=a season variable, sine ((week number-25)×3.142/26), with week number starting 22 April 1979, and

D=number of days since rain.

This equation was used to plot the mid-summer and mid-winter lines in Figure 6. A logarithmic transform of time since rain helps to model the relatively quick reduction in saturated area following a storm and the slower shrinkage in saturated area associated with permanent summer or winter saturation.

In this catchment temporarily-saturated areas disappear within about 1-1.5 days in summer and within about 3-4 days in winter (Fig. 6). Periods when total saturated area exceeded 30% of the total catchment area appeared to last no more than a few hours.

Using this information, maps likely to have included temporarily-saturated areas were removed from the data set, and the remaining data were plotted to show variation in the area of catchment that was saturated seasonally (Fig. 4).

In the summer period 3-5% of the catchment area was saturated, and in the winter period 8-14% of the catchment area was saturated.

Infiltration Measurements

Infiltration rates measured on 16 October 1979 and 20 October 1980 on unsaturated soil surfaces at three valley bottom sites were in the range 1-3.5 mm/h. These soils had been previously winter-saturated and showed stock trampling damage. Measurements on a valley side and on a ridge site were 3 and 39 mm/h respectively.

Measurements of infiltration at the same sites on 23 April 1980 ranged from 22-128 mm/h (mean 81 mm/h) showing permeability had recovered during summer.

Low infiltration rates in winter and spring resulted from sealing of the soil surface by stock trampling. When the top 10 cm of soil was removed and the infiltrometer ring was set up on the exposed surface, measurements of 31 mm/h and 200 mm/h were recorded at sites with surface values of 1 and 37 mm/h respectively.

DISCUSSION

The results of this study enable quickflows and baseflows from a small hill pasture catchment to be compared with the distribution of surface-saturated areas in the catchment, and then in turn for those areas to be compared with the topography, soil and vegetation of the catchment.

Relationships Between Runoff and Saturated Soils

Baseflow

Baseflow and the area of catchment saturated were highly correlated (Fig. 4). The extent of permanently and seasonally-saturated soils probably determined baseflows for this catchment. On this assumption baseflow generation per unit of saturated area was about 7 litres m^{-2} day^{-1} in summer and about 12 litres m^{-2} day^{-1} in winter. Baseflow may give a useful guide to area of permanently and seasonally-saturated soils and *vice versa*.

Quickflow

In this study, four quickflow categories were defined, based on the ratio of *quickflow to rainfall* (Qf/P) and the proportion of catchment saturated (A) prior to the event:

Type *a*, where $Qf/P < A$ — interception, detention and infiltration dominate and there is little quickflow. Rainfall events are small and Qf/P is not related to the proportion of catchment surface-saturated.

Type *b*, where $Qf/P \cong A$ — quickflow is related to antecedent (ie, permanently and seasonally) saturated area, and there is no significant development of temporarily-saturated areas.

Type *c*, where $Qf/P > A$ — quickflow comes mainly from the permanently and seasonally-saturated areas plus some areas temporarily saturated.
Type *d*, where $Qf/P \gg A$ — quickflow comes from a greatly-enlarged saturated area as a result of rainfall exceeding infiltration.

To test the relationship between these quickflow categories and rain-event size classes, 59 storms for which maps of antecedent saturated-area existed were selected from the data set. The ratio of (Qf/P):A was calculated for each event and averaged for each rain-event size class. The results (Table 5) show a relationship exists between quickflow category and rain event size. For rainfalls in the ranges 2-5 mm, 5-10 mm and 10-25 mm the mean ratio of (Qf/P):A was 0.92. Quickflow rainfall ratios range up to approximately 15% in those events (Table 3). This suggests that, for small to medium-sized events, quickflow generation can be explained mainly in terms of saturation overland flow (Dunne and Black, 1970) from the antecedent surface-saturated areas of the catchment.

TABLE 5 — The mean ratio of (Qf/P):A for selected rainfalls in different size classes. (Qf/P is the proportion of rainfall as quickflow; A is the proportion of the catchment area surface saturated before the rain event). A ratio of 1:1 would suggest that quickflow is generated mainly from surface-saturated parts of the catchment.

Rainfall Class (mm)	No of Events Selected	Mean Ratio of (Qf/P):A	Rain Event Categories (See Text)
0-2	—	usually no quickflow	a type
2-5	20	0.42±0.28*	a or b types
5-10	14	1.09±0.55	b type
10-25	13	1.50±0.77	b or c types
25-50	7	5.45±2.25	d type
50-100	4	4.55±2.01	d type
100+	1	9.91	d type

* Standard deviation.

For rainfalls greater than 25 mm much quickflow would have to come from temporarily-saturated parts of the catchment as well as the antecedent saturated areas. One such event (14 November 1979, 62 mm total) began during a routine visit for mapping. During heavy rain the saturated area expanded from base level (permanently-saturated areas) to an estimated 50% of the catchment area in 13 minutes (7.7 mm of rain fell) and apparently 100% saturated in a further 15 minutes (1.9 mm of rain fell). After heavy rain ceased flow rate at the weir fell from 100 *l*/s to 13 *l*/s in one hour. This response suggests rainfall exceeded infiltration capacity over wide areas of the catchment. Corroborative evidence is the low infiltration rates (1-3.5 mm/h) measured at valley bottom and sideslope sites in the previous month. These findings are very similar to those of Pearce and McKerchar (1979) for pasture catchments Pukewaenga, Manukau, and Moutere 5.

The degree to which the catchment became temporarily saturated varied with season (Fig. 7) with an average of 54% of rain as quickflow for the months April to September, and of 26% for the months October to March. This, and the higher summer infiltration capacity (around 80 mm/h in late summer/early autumn), suggest that Hortonian overland flow would be less likely in the summer months.

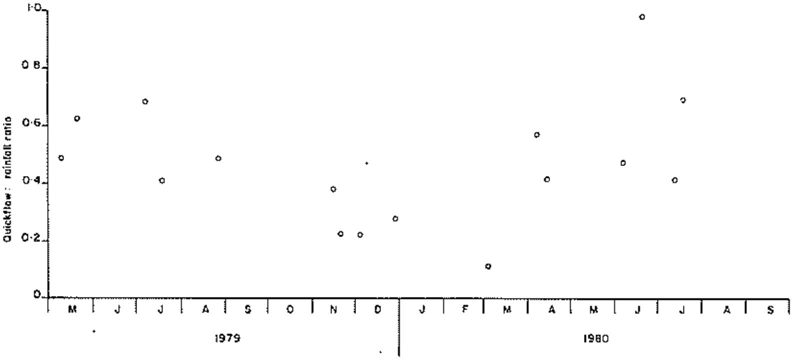

FIG.7—The variation in the proportion of rainfall producing quickflow in large storms (greater than 25 mm of rain) with season, experimental catchment, Judgeford, 1979 to 1980.

The results suggest that quickflow tends to originate solely from permanently or seasonally-saturated areas for low to medium rainfalls (2-25 mm). For larger events, quickflow was generated in temporarily-saturated areas. In winter in particular, when infiltration rates were believed to be low on significant areas of the catchment, large temporarily-saturated areas formed in response to some rainfalls and overland flow was observed. During the summer period (October-April) quickflow:rainfall ratios suggest that temporarily-saturated areas and permanently-saturated areas combined would not have exceeded about one-quarter of the catchment area.

Stock trampling on wet soils, especially during winter, may have a major influence on the hydrological properties of the catchment, by causing marked loss of soil surface structure and porosity. Liquid mud formed at the surface under heavy trampling, and in some areas saturated surface sites were found to be underlain by better-drained unsaturated soils. Infiltration improved during summer, probably through the combination of pasture growth, earthworm activity, and improved bearing strength of the soils when drier.

The effect of trampling on infiltration rates is obvious, but difficult to assess quantitatively. Gifford and Hawkins (1979) have modelled infiltration response to grazing, but such relationships have not been developed for New Zealand soils and conditions.

Trampling damage may induce overland flow and, in winter at least, quickflow generation in large storms fits a combined rainfall-excess model (Horton 1933, Betson 1964) and saturation overland flow model (Dunne and Black 1970) better than a subsurface flow model (Hewlett 1961). This may well be common in many New Zealand pasture catchments where the soils suffer significant trampling damage.

Identification and Properties of Saturated Areas

The proportion of total precipitation occurring as quickflow in a storm can be related to the area of surface saturation in a catchment.

If a relationship exists between the extent of surface saturation and soil type or land use, then opportunities for effective land management to control erosion and water quality could emerge. Proper identification of these saturated areas is important.

The permanently and seasonally-saturated areas of the catchment can be visually identified. Survey of the topography, soils and vegetation will also reveal hydrologically-important areas of the catchment. The permanently, seasonally and temporarily-saturated areas had some characteristic species of plants (Table 4), and the distribution of rush (*Juncus* spp) correlated well with that of the seasonally-saturated soils (cf, Figs. 2 and 5). The permanently-saturated areas had poorly-developed soils, the seasonally-saturated areas had soils which showed strong signs of intermittent waterlogging, and some of the temporarily-saturated areas showed minor evidence of waterlogging (Table 6).

TABLE 6 — Summary of the topographic, soil and vegetation features indicative of the surface-saturated zones of the experimental catchment

Surface-Saturated Area	Topography (Table 1)	Soils (Table 2)	Vegetation	Other
Permanently	Stream channel Slumps	Typic Fluvaquent Typic Haplaquent	Plants typical of wet areas, few pasture species	Permanent trampling damage. Very poor drainage.
Seasonally	Concave Toeslopes and some parts of sideslopes	Aeric Haplaquept (many distinct mottles)	Plants adapted to wet soils notably *Juncus* spp plus some pasture species	Heavy winter trampling damage. Poor drainage
Temporarily	Some toeslopes and sideslopes	Aquic Dystrochrept (common faint mottles)	Normal pasture species	Light trampling damage. Moderate drainage
Temporarily (rarely)	Crests of interfluves	Typic Dystrochrept (no mottles)	Normal pasture species	Little trampling damage. Good drainage

The dominant moisture status over a period of years produced a flora characterised by the proportion of species tolerant to waterlogging and a soil with a certain degree of mottling or gleying. These indicate those parts of the catchment that are permanently or seasonally saturated at the surface, and are likely to generate saturation overland flow in low to medium-sized rainfalls. The main indicative features are summarised in Table 6. Such observations could be used by water quality managers as a guide to the areas of a catchment likely to contribute overland flow and, perhaps, diffuse-source pollutants.

TABLE 7 Estimates of the quickflow produced during the study period by increments of catchment area (see Table 4 and text)

Increment of Catchment Area Producing Quickflow (%)	Predominant Surface-Saturation Type	Total Estimated Quickflow from Area During Study Period (mm)	Proportion of Total Quickflow (%)
0-4.9	Permanent	124	13
4.9-7.8	) Seasonal	70	8
7.8-12.8	)	108	11
12.8-37.9	)	431	46
37.9-54.0	) Temporary	156	17
54.0-72.2	)	44	5

* The increment intervals of catchment area producing quickflow are chosen to facilitate calculation of total quickflow from the various rainfall classes, eg, 0-5% catchment area was estimated to contribute all the quickflow when a rainfall event was < 5 mm. The same area also contributes to quickflow from larger storms.

The 12.5-38.7 increment of catchment area corresponds to 25-50 mm rainfall class (see table 4). This increment tends to produce quickflow only in rainfall > 25 mm.

This column gives estimates of total quickflow during study period, including events for which complete quickflow records were not available.

Area of Catchment Producing Quickflow

The proportion of rainfall as quickflow and storm size distribution (Tables 3 and 5) can give some insight to the areas of the catchment normally contributing to quickflow during floods. If it is assumed there is a relationship between proportion of rainfall as quickflow and proportion of catchment area that is saturated, then estimates of quickflow production from the various contributing zones can be made (Table 7). For the study period, it is estimated that the permanently and seasonally-saturated areas (up to about 13% of the catchment) generated about one third of the total quickflow, and around one half of the catchment generated 95% of total quickflow.

These results support the view that land management to reduce nutrient or pollutant losses in overland flow could, with advantage, concentrate on the predominant sources of runoff rather than whole catchments.

Against this, however, is the impact of low frequency but high volume events. The two largest storms measured produced nearly one quarter as much quickflow as the other 79 events (Table 4). Such events may have sufficient energy and impact to defeat the aims of management of selected runoff source zones.

CONCLUSION

Quickflow from the hill pasture catchment studied was derived from permanently and seasonally surface-saturated areas in low to medium rainfalls, and from expanded temporarily surface-saturated areas in larger storms.

Overland flow from the surface-saturated areas was believed to be the main mechanism of quickflow generation.

The saturated zones can be identified by mapping of surface-saturated soils using a simple squeezing test, or inferred by examination of soil type, vegetation features, and topography. Proper identification of these areas is important to land management for water quality.

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