THE INFLUENCE OF VEGETATION ON CHANNEL FORM OF SMALL STREAMS

R. C. ZIMMERMAN [1], J. C. GOODLETT [2], and G. H. COMER [1]

ABSTRACT

Data on channel width of several small streams in the Sleepers River basin of northern Vermont have provided some measure of the influence of vegetation on channel form. Along 5 streams, for which there are complete records of variation in channel width, width does not increase in a downstream direction as far as points with drainage areas of 0.2 to 0.8 square mile, presumably as a result of disturbance and encroachment by vegetation. In one basin with an area of 0.8 square mile, channel width is clearly related to type of vegetation, as the channel is alternately wide under forest, and narrow in sod. Along one stream, width increases in response to increases in discharge where the drainage area exceeds 0.3 square mile, but the variability in width (expressed as the standard deviation from mean and as a coefficient of relative variability) also increases, reaching a maximum where the drainage area is about 2 square miles. Relatively uniform channel widths occur, on the other hand, where the drainage area is about 6 square miles. Similar relationships were found in other streams sampled. In one stream, however, the mean channel width under forest where the drainage area is about 1.3 square mile exceeds by more than 5 feet the mean width of the same stream where the drainage area is 2.8 square miles and the vegetation along the stream is predominantly sod.

In the Sleepers River basin there are apparently two thresholds along streams. In a downstream direction, the first threshold occurs at points with drainage areas of 0.2 to 0.8 square mile. Upstream from these points, width does not increase in a downstream direction, living tree roots cross the channel, and dams of organic debris are common. The flow is commonly underground. Points with drainage areas of 0.2-0.8 square mile have annual high flows of 10 to 20 cfs. With drainage areas exceeding 0.2-0.8 square mile widths increase, but channel form is highly variable, and mean widths may vary by as much as 5 feet depending upon the type of vegetation. Relatively uniform widths occur, regardless of vegetation, where the drainage area exceeds 4 to 6 square miles. Points with drainage areas of about 5 square miles are apparently the second threshold. These points have annual high flows in the range of 100 to 150 cfs. Beyond these points, the influence of vegetation on channel form is marginal compared with that of geologic differences and the sinuousity of the flow itself.

Vegetation influences channel form by altering the roughness and shear strength of bed and banks. In addition, non-fluvial processes such as the windthrow or frost-heaving of streambank trees may locally double or triple the channel dimensions that would occur with the same discharge regimen in the same geologic setting.

RÉSUMÉ

Des données sur la largeur du chenal de plusieurs petits cours d'eau du bassin de la rivière Sleepers du nord Vermont ont fourni quelques mesures de l'influence de la végétation sur la forme du chenal. Le long de 5 cours d'eau, pour lesquels on possède des données complètes sur la largeur du chenal, on observe que la largeur n'augmente en direction aval qu'en des points avec des étendues de drainage de 0,2 à 0,8 mille carré, probablement par suite du trouble et de l'envahissement par la végétation. Dans un bassin avec une surface de 0,8 mille carré, la largeur du chenal est clairement en relation avec le type de végétation, le chenal étant alternativement large sous la forêt et étroit en terrain gazonné. Le long d'un des cours d'eau, la largeur augmente avec le débit là où la surface de drainage dépasse 0,3 mille carré, mais la variabilité de la largeur (exprimée par la déviation standard de la moyenne et comme un coefficient de variabilité relative) augmente également; atteignant son maximum quand l'étendue du bassin est de 2 milles carrés. Par contre, une largeur relativement uniforme quand la

(1) Soil and Water Conservation Research Division, Agricultural Research Service, U.S. Department of Agriculture; present address of senior author is Harvard University Forest, Petersham, Mass.

(2) Late professor of geography, The Johns Hopkins University, Baltimore, Maryland.

surface de drainage atteint 6 milles carrés. Des relations analogues ont été trouvées pour d'autres cours d'eau étudiés. Dans un cours d'eau cependant, la largeur moyenne sous forêt, quand la surface de drainage est d'environ 1,7 mille carré, dépasse de plus de 5 pieds la largeur moyenne du même cours d'eau avec une étendue de bassin de 2,8 milles carrés, la végétation étant constituée par une prédominance du gazon.

Dans le bassin de la rivière Sleepers, il y a apparemment deux seuils le long des rivières. En direction aval, le premier seuil se produit aux points avec des aires de drainage de 0,2 à 0,8 mille carré. En amont de ces points, la largeur n'augmente pas en direction aval, des racines d'arbres vivants traversent le chenal et des barrages de débris de matières organiques sont communs. Les points avec des surfaces de drainage de 0,2 à 0,6 mille carré ont des débits maximaux annuels de 10 à 20 pieds cubes/sec. Avec des surfaces de drainage de 0,2 à 0,8 mille carré, les largeurs augmentent, mais la forme du chenal est grandement variable et la largeur moyenne peut varier jusqu'à 5 pieds, dépendant du type de végétation. Des largeurs relativement uniformes se produisent, indépendamment de la végétation, là où la surface de drainage dépasse 4 à 6 milles carrés. Les points avec des surfaces de drainage d'environ 5 milles carrés constituent le second seuil. Ces points ont un débit annuel maximum de 100 à 150 pieds cubes/seconde. Au-delà de ces points, l'influence de la végétation sur la forme du chenal est marginale comparée à celle du différence géologique et de la sinuosité de la rivière.

La végétation influence la forme du chenal en modifiant la rugosité et la tension tangentielle des lits et des rives. En addition, des influences non hydrauliques comme l'action du vent et celle de la gelée des rives sur les arbres peuvent doubler ou tripler localement les dimensions du chenal qui se produiraient avec le même régime de débit dans la même formation géologique.

Introduction

The form of channels of small streams flowing through forest or sod is influenced by growing and dead vegetation. Processes such as tree-throws, formation of blowdown mounds across channels, accumulation of organic debris, and the extension of roots and sod into the channel cause channel form to vary greatly over short distances. In a basin of northern Vermont these processes are apparently so active that, to points with drainage areas of 0.2 to 0.8 square mile, channel width does not increase with increasing drainage area and discharge. Farther dowsntream channel width increases but the variability in width also increases. Relatively uniform channels occur, on the other hand, where drainage areas exceed 4 to 6 square miles and presumably discharges are of sufficient magnitude to eliminate most of the disturbance caused by vegetation growing and decaying near the channel. The stabilizing or disrupting influence of vegetation on bank and bed material is also such that mean channel width may be the same in two reaches with drainage areas differing by more than 2 square miles.

The small streams studied are in the Sleepers River basin, in Caledonia County, northeastern Vermont (fig. 1). The Sleepers River basin, a watershed instrumented by the USDA Agricultural Research Service (see Holtan and Whelan, 1965, pp. 353-356), is part of the Passumpsic-Connecticut drainage system. One of the streams studied in detail is Pope Brook, a watercourse about 4.5 miles long and with a drainage area of 6 square miles (fig. 1). The lower one mile of Pope Brook is shown on the St. Johnsbury topographic sheet as part of a shorter North Brook; for the purposes of the study this lower reach was considered part of the mainstem of Pope Brook. Data were also collected along the first right-hand tributary of Pope Brook (reach 1*a*; fig. 1). The second stream studied in detail is an unnamed tributary of the Sleepers River, hereafter referred to as stream W-12 (fig. 1). Stream W-12 is about 2.2 miles long, and drains 0.8 square mile. Supporting data were also obtained in several other streams of the Sleepers River basin (fig. 1).

The description of Pope Brook is based on five sample reaches the length of which was determined mainly by the need to avoid backwater from weirs, trampling by cattle, skid trails, and other man-caused disturbance. The first right-hand tributary of Pope

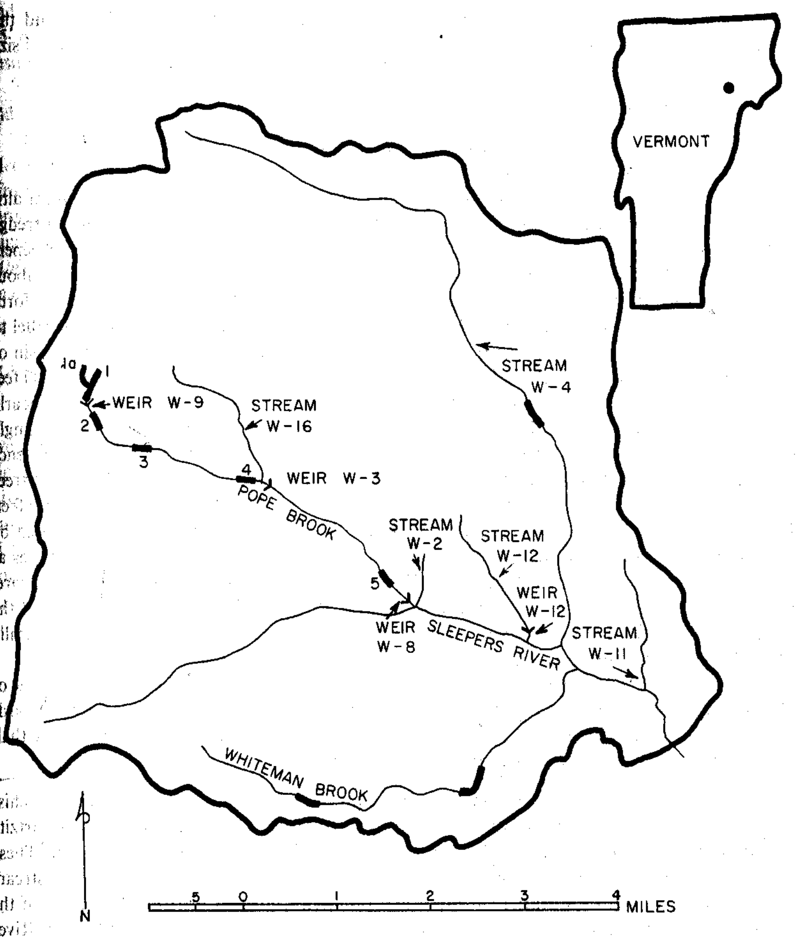

Fig. 1 — Map of the Sleepers River basin showing streams sampled. Bold lines indicate reaches sampled; length of reaches is exaggerated. Other streams, except Sleepers River, were sampled along their entire course.

Brook was sampled from point of first flow to confluence with the mainstem. Within the reaches sampled, channel dimensions were measured every 25 feet; use of this interval is a compromise between the attempt to obtain as continuous a record of variation in channel form as possible and the necessity to cover representative portions of the streams. Stream W-12 was sampled from the point of first flow to the confluence with the Sleepers River, also at intervals of 25 feet. The study emphasizes channel width as in the streams of the Sleepers River basin as elsewhere width is the parameter most accurately and rapidly determined. Widths were measured, for consistency's sake, between breaks-in-slope between bank and bed. At these breaks-in-slope there is also commonly a color and textural change from greyish sand and gravel to brownish finer material. The few channel depths cited are average depths, at a cross-section, to the top of the bank. Determination of an average depth was relatively easy where the channel was box-shaped, but somewhat arbitrary where the channel was bouldery and the bank poorly defined. Channel depths are mentioned to convey an idea of the total size of the channel.

BASIN CHARACTERISTICS OF POPE BROOK AND STREAM W-12

Topography. Pope Brook has an oblong basin with minimum and maximum altitudes of about 920 and 2,260 feet. The brook rises at about 1,950 feet in the Kittredge Hills, a north-south trending ridge that forms the western boundary of the Sleepers River basin. Pope Brook rises parallel to the main ridge, and flows southward for about 3/4 mile before turning towards southeast. The brook joins the Sleepers River at North Danville. The first right-hand tributary (reach 1*a*) of Pope Brook also rises parallel to the Kittredge Hills, upslope from the headwaters of Pope Brook. The upper basin of Pope Brook rises from about 1,700 to 2,200 feet in half a mile. The upper 50 to 100 feet of the basin, just below the summit of the Kittredge Hills, usually consist of nearly vertical cliffs of quartzite. Below these cliffs are commonly talus slopes with an angle of about 40 degrees. The talus slopes are currently active as indicated by the presence on them of boulders with sharp, unweathered sides, and by scarred and trained trees at their base. Below the cliffs and talus slopes, at altitudes between 1,800 and 2,000 feet, are upper slopes with angles of 20 to 30 degrees. These upper slopes are marked by pronounced mound-and-pit microrelief, locally of as much as 5 feet, and by chutes as much as 30 feet wide and 6 feet deep. The slopes of the thalweg of Pope Brook are, however, more gentle. To a point about 2 miles from the basin divide they are of the order of 0.04 to 0.10 feet over feet. At about 4 miles from the divide slopes are generally of 0.01-0.02 feet over feet.

Stream W-12 has an elongated basin with minimum and maximum altitudes of about 740 and 1,400 feet. Stream W-12 rises at about 1,210 feet, and flows towards southeast and the Sleepers River in avalley generally half a mile wide. Slope of the thalweg of stream W-12 is generally 0.03-0.06 feet over feet.

Geology and soils. Most of Pope Brook basin is underlain by the interbedded schist and limestone of the Waits River formation (Hall, 1959, plate 1). Micaceous quartzite and quartz mica schist of the Gile Mountain formation occur above 1,700 feet. These more resistant rocks form the main ridge of the Kittredge Hills. The basins of stream W-12 and of the other streams sampled are underlain almost entirely by rocks of the Waits River formation (Hall, 1959, plate 1). The surficial deposits in the Sleepers River basin are mainly till. On lower slopes and on valley floors, the till is generally grey-blue, compacted clay and sand, locally tens of feet thick.

The soils in the basins of Pope Brook and stream W-12 are loams, ranging from silty to very rocky. On valley floors of all the basins in which data were collected, the soils are mainly silty loams (Typic and Humic Fragiaquepts) of the Cabot and Calais series (U.S. Soil Cons. Service, unpub. soil survey of the Sleepers River basin, 1959-1962).

Climate. The climate in the basins is continental, with temperatures ranging from about −45 to 98 degrees F; mean annual temperature is about 40 degrees F (USDA-ARS, Danville, Vermont, unpub. station data). The mean annual precipitation is about 35 inches at the lowest, and 40 inches at the highest altitudes cited. Snow constitutes one-third to one-half of the annual precipitation. A snow cover is generally present from early December through late April.

Land use. Forests cover about 67 percent of Pope Brook basin; the upper one square mile is completely forested. The rest of the basin is mainly in pasture (19 percent), and in cultivated fields (11 percent). Pope Brook flows through forest for about 3.5 miles of its 4.5-mile course; the lower one mile of the stream is flanked by pasture, but the banks are lined with trees.

The basin of stream W-12 is about 35 percent forested, and 65 percent in pasture and fields. About half of the 2.2-mile course of stream W-12 is under forest.

The main woody species on the valley floors of the streams studied are sugar maple (*Acer saccharum* Marsh.), yellow birch (*Betula lutea* Michx. f.), white and black ash (*Fraxinus americana* L.; *F. nigra* Marsh.), balsam fir (*Abies balsamea* (L.) Mill.), white spruce (*Picea glauca* (Moench.) Voss), northern white cedar (*Thuja occidentalis* L.), American elm (*Ulmus americana* L.), mountain maple (*Acer spicatum* Lam.), alder (*Alnus rugosa* (Du Roi) Spreng.), red osier (*Cornus stolonifera* Michx.), and willow (mainly *Salix discolor* Muhl.).

Flow regimens of Pope Brook and stream W-12

Pope Brook is gauged at points about 0.5 (weir W-9), 2.7 (weir W-3), and 4.5 miles (weir W-8) from the divide, and stream W-12 at a point about 2.1 miles from the divide (fig. 1); discharge data for these points are shown in table I. The streams in the Sleepers River basin generally have their maximum annual discharges in April as a result of snowmelt, their minimum flows in late August-early September, and a secondary peak of high flows in October and November. Descriptions of selected runoff events in Pope Brook and other streams in the Sleepers River basin have been published (U.S. Agricultural Research Service, 1963; 1965).

TABLE I

*Hydrologic characteristics o*r *Pope Brook and stream W'12.*
Data from USDA-ARS, Danville, Vermont, unpub. gauging records.

	Gauging stations			
	Pope Brook			Stream W-12
Weirs:	W-9(1)	W-3(2)	W-8(3)	W-12(4)
Drainage area, sq.mi.	0.2	3.3	6.0	0.8
Mean annual discharge, cubic feet per second (cfs.)	0.3	5.2	7.5	*n/a*
Maximum peak discharge on record, cfs.	8.2	158	240	21

(1) Period of record 1962-66.
(2) Period of record 1960-66.
(3) Period of record 1961-66.
(4) Period of record 1963-66.

TABLE II

Channel characteristics of Pope Brook in reaches sampled

Reach	n(1)	Channel width, feet				Width's v(3), percent	Channel depth, feet(4)			Mean depth of flow, feet (5)
		max.	min.	mean	s(2)		max.	min.	mean	
1*a*	37	7.1	0.6	2.3	1.5	64	0.9	0.2	0.5	*n/a*)
1	52	6.1	1.1	2.8	1.3	46	1.7	0.2	0.8	0.2
2	36	10.3	1.2	5.3	2.0	38	1.9	0.4	1.1	*n/a*
3	55	17.1	3.9	8.5	2.2	26	2.5	0.8	1.6	*n/a*
4	41	21.3	6.2	12.2	9.1	75	4.2	0.8	1.7	*n/a*
5	25	21.1	14.8	17.7	1.6	9	5.4	2.4	3.8	0.6

(1) Number of cross-sections measured.
(2) Standard deviation: $s = \sqrt{[\Sigma(x-\bar{x})^2]/n}$
(3) Relative variability (Pearson's v): $v = 100s/\bar{x}$.
(4) Data fair to poor.
(4) Data for Oct. 21-24, 1966; data poor.

Pope Brook. Channel and valley-floor characteristics of Pope Brook in the reaches sampled are shown in tables II and III. The aspect of Pope Brook at the point of first flow on October 13, 1966, is shown in figure 2.

TABLE III

Channel and valley-floor characteristics of Pope Brook at selected locations

Distance from divide, feet	Description
337.5	Valley head is a swale floored by spongy litter and duff about 0.7 feet thick. Width and slope of swale floor are about 16 feet and 0.08 feet/feet. Blowdown mounds and fallen trees are across the entire swale.
580	Swale floor is 18.5 feet wide. Densely forested.
897.5	First well-defined channel, about 1.3 feet wide and 0.2 feet deep. Channel heads in tunnel 2-3 inches wide and 2-3 inches below the swale floor.
997.5	Point of first flow on October 13, 1966; flow emerges from tunnel in organic debris.
2,700	First well-defined floodplain, about 1.5 feet above the channel bed, and 30 to 50 feet wide. Drainage area 0.3 square mile. Highest discharge measured in 5 years at a point 100 feet farther upstream is 8.2 cu.ft.
3,125	Last point sampled where blowdown mound has recently blocked the channel.
5,150	Last point where living tree roots were observed across the entire channel. Drainage area 0.8 square mile.
12,970	Last point sampled where living tree roots extended to the middle of the channel.
14,570	Last point sampled where logs and other debris dammed the entire channel. Drainage area about 3.4 square miles.

In reach 1 and in tributary 1*a*, width does not increase in a downstream direction (fig. 3). On October 13, 1966, discharge in Pope Brook increased from 0.03 cubic feet per second (cfs.) at the point of first flow, about 1,000 feet from the divide, to 0.19 cfs. at weir W-9, 2,600 feet from the divide. In reach 1, channel widths and channel depths measured are essentially unrelated; only 5 percent of the variation in channel depth was explained by the regression of depths on widths. In contrast to rivers, narrow channels in reach 1 of Pope Brook are commonly shallow, and wide channels deep, especially where debris have dammed the channel. In the headwaters of Pope Brook slope is probably independent of discharge, primarily because the stream is flowing at a short distance above resistant bedrock. In any stream, however, the continuity of flow must be maintained. In reach 1 of Pope Brook, as in other small mountain streams, the adjustement of flow to changes in channel form apparently occurs mainly through velocity, as partially confirmed by the acceleration of floating objects in narrow and shallow reaches. As measured, the channel depths in reach 1 do not increase in a downstream direction, as the greatest depths occur in the upper part of the reach.

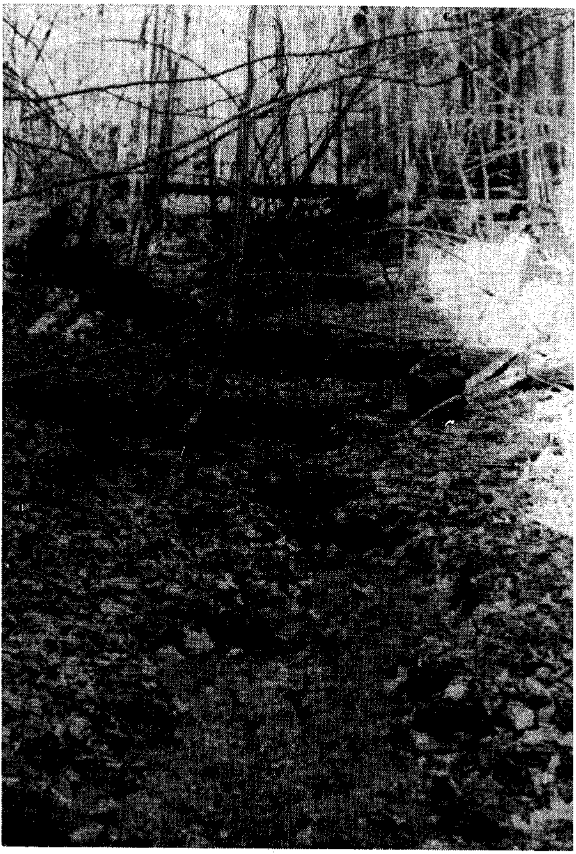

Fig. 2 — Pope Brook at the point of first flow on October 13, 1966, about 1,000 feet from the divide. The channel is 1.1 to 2.5 feet wide, and 0.5 to 0.8 feet deep.

The widths in reach 2, which begins 100 feet downstream from weir W-9, probably reflect the increase in discharge as they differ significantly ($p = 0.01$) from those in reach 1. The drainage area at about the end of reach 2 is 0.8 square mile. The data for width in reach 2 show, however, considerable scatter about the mean (table II). On the other hand, the variability of width in reach 2 is smaller than in reach 1 (table II). Reach 3 is also marked by great variability in channel width, but again this variability is smaller than in reach 1 (table II).

Widths in reach 4, about 2.5 miles from the divide and where the drainage area is about 2 square miles, deviate considerably from a mean of 12.2 feet. The relative variability in this reach is the greatest measured in Pope Brook (table II). Log dams occur in reach 4, despite widths nowhere less than 6 feet. Where these and other obstructions are present in the channel, lateral scour and undercutting of banks of

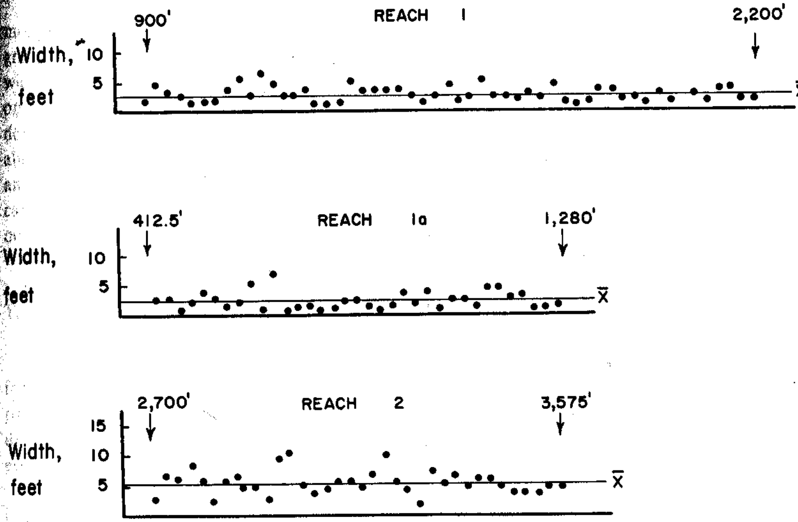

Fig. 3 — Channel widths of Pope Brook in reach 1, 1*a*, and 2. Figures above arrows are distances in feet from the basin divide.

3 to 5 feet are common. Thus the greatest variability in width seems to occur at some distance from the divide, presumably at the point where discharge is too large to circumvent easily obstructions, yet not large enough to float or wash away these obstructions rapidly as occurs farther downstream. The turbulence and instability imparted to high flows in the range of 70 to 140 cu.ft by logs and snags are probably also responsible for the lateral scour characteristic of reach 4. The average velocity measured in reach 4 in 1965 and 1966 was the highest recorded in the Sleepers River (d.a. 44 square miles) and in Pope Brook (Brooks, 1967, p. 46).

In reach 5, about 4 miles from the divide, the relative variability of width is the lowest measured in Pope Brook, despite the small sample, and the presence of boulders 3 to 6 feet long in the channel. Reach 5 has banks usually more than 3 feet high, which presumably hold tree trunks wholly or partly off the water should a tree fall across the stream. Trunks and other debris are probably removed from the reach every year by high flows in the range of 100 to 200 cu.ft. In October 1966, reach 5 was clear of tree trunks and branches more than 3 inches in diameter. The roots of trees lining reach 5 are sheared off at 1 to 1.5 feet from the bank.

Stream W-12. The range of variation in channel width of stream W-12 is shown in figure 4. Average width of this stream is 3.0 feet, or about the same as the average width of Pope Brook in reach 1 (table II). The widths of stream W-12 vary primarily with type of vegetation as the channel, regardless of distance from divide, is narrow in sod and wide under forest or thickets. Bank material consolidated by grass roots is apparently more resistant to lateral stream erosion than the material criss-crossed by tree roots under forest. Sod may also encroach more rapidly on the channel during periods of low or no flow than tree roots or understory plants in the forest. Under the forest, tree-throws and solid plant remains are, on the other hand, more likely to cause variation in channel form by weakening the banks or by damming the channel.

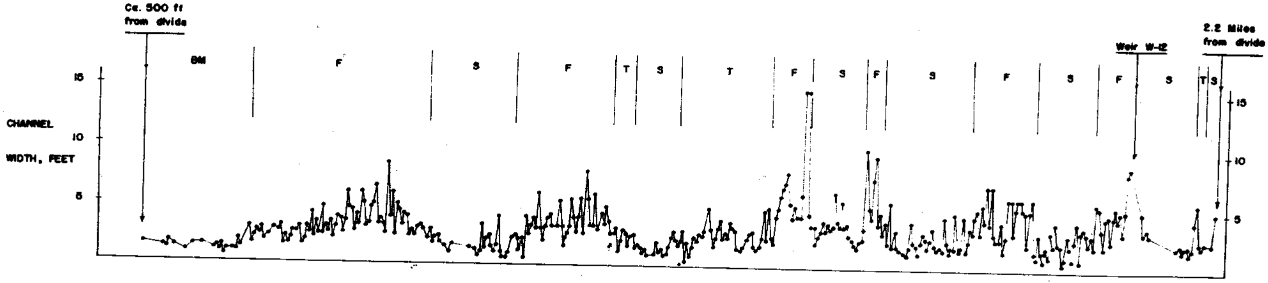

Fig. 4 — Channel widths of stream W-12 from the point of first flow at about 500 feet from the divide to the confluence with the Sleepers River, about 2.2 miles from the divide. The channel is narrow in a boggy meadow (*BM*) and in sod (*S*), and wide under forest (*F*) and thickets (*T*).

The data for stream W-12 illustrate the difficulty in selecting statistics in fluvial morphology. For example, the mean width of stream W-12 would be considerably greater if sampling had been limited to reaches under forest. A relationship between width and drainage area, or between width and discharge in stream W-12 also depends on the selection of cross-sections. If only the data for reaches in sod are used, then a downstream increase in width—presumably caused by an increase in discharge—from about 1.5 to 2.0 feet seems to occur between a reach 500 to 1,000 feet from the divide, and the confluence with the Sleepers River, about 2 miles farther downstream. Under a canopy of trees and shrubs, on the other hand, a net downstream increase in width does not seem to occur.

THE INFLUENCE OF VEGETATION ON CHANNEL FORM

The illustrations shown and discussed below are a few examples of how ordinary forest processes, such as uprooting of trees, collapse of trees that died on the stump, or root growth in the channel, have affected the form of the channel. The examples are drawn from the upper reaches of Pope Brook; similar examples could be shown, however, for all the other streams examined.

At about 1,050 feet from the divide, living roots and material consolidated by the roots form a bridge across the channel of Pope Brook (fig. 5*A*). The flow on October 13, 1966 (probably all base flow), went under the bridge. At high flows, the resistance caused by the bridge has probably indirectly caused the widening of the channel immediately upstream from the bridge.

Where living roots occur in the channel, the channel is generally narrow, whatever the cause-and-effect or "feedback" relationship between the two. At about 1,500 feet from the divide, where a sugar maple with a stem diameter of 3 feet sends roots 1 to 2 inches thick across the channel of Pope Brook, the width is 1.0-1.5 feet and the depth about 0.6 feet (fig. 6).

At about 1,725 feet from the divide, soil and other material shed from the root mass of an uprooted tree have blocked the channel (fig. 5*B*). The stream, however, has continued to flow in the same channel by opening a tunnel in the accumulated material. The tunnel is apparently stabilized by roots remaining in the material. High flows have opened, on the other hand, a secondary channel around the blowdown mound and through the decaying log.

The effect of tree-throw on the position and shape of the channel is also shown in figure 5*C*. At this location about 3,125 feet from the divide, fallen trees have dammed the channel and caused, indirectly, considerable deposition of sand and gravel, locally of as much as 1.5 feet. High flows have apparently opened a new channel, as well as a tunnel under the island between the old and new channel; the entire flow on October 14, 1966, went through this tunnel. High flows, however, are probably still carried in the old channel, as suggested by the pools located downstream from the fallen trees.

Where a fallen tree dams the channel, a shift in channel need not occur. As shown in figure 5*D*, the stream may circumvent the obstruction through lateral scour. This scour is probably retarded by the presence of living trees and roots along the cut bank.

There are many more ways in which forest processes can change the form of the channel of a small stream. However, the most common relationships are a widening of the channel upstream from dams of organic debris, widening of the channel where a tree is thrown in a direction away from the stream, narrowing of the channel where roots or living plants are in or along the channel, and meandering wherever a fallen tree does not span the entire channel or spans the channel but channel shitting cannot occur because of other obstructions. This does not imply that all meanders under forest are caused by obstructions. Other common adjustements of the stream to forest

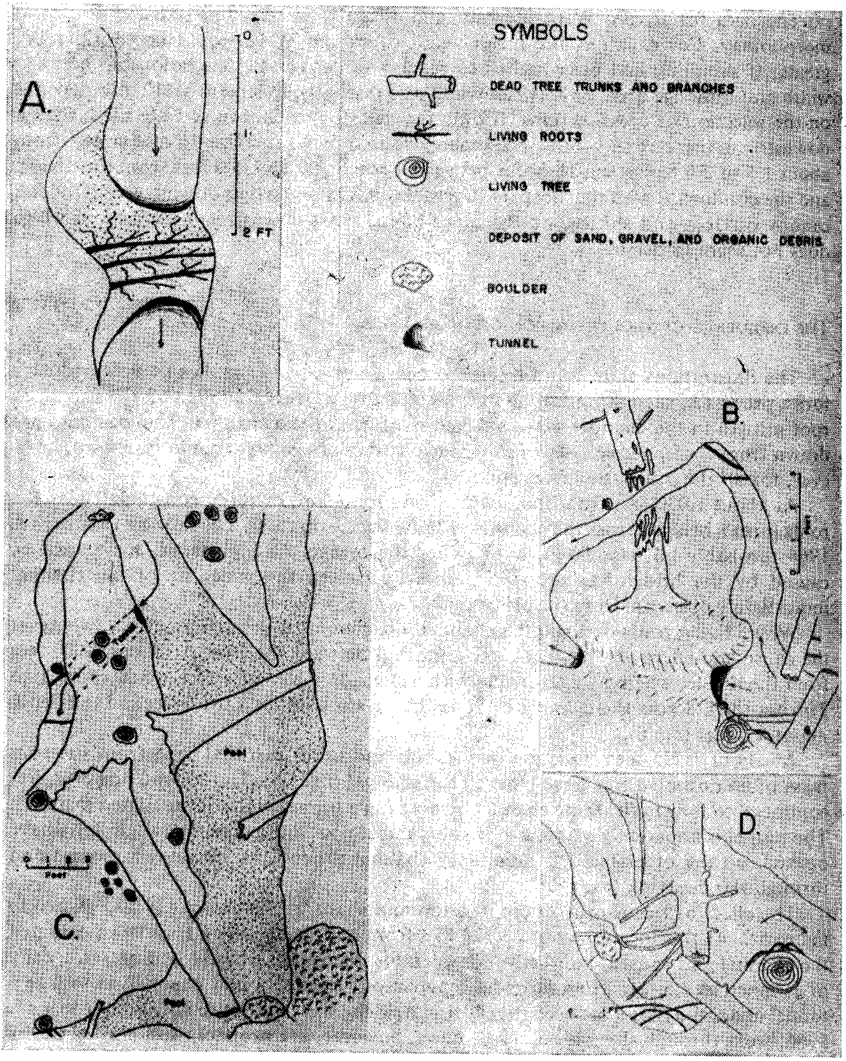

Fig. 5 — Channel form of Pope Brook at selected locations in reaches 1 and 2. See text for explanations.

processes are tunnelling or channel-shifting where blowdown mounds or large amounts or organic debris have completely blocked the channel.

Characteristics of other streams in the Sleepers River basin

Data on channel form of other streams in the Sleepers River basin generally support the relationships shown for Pope Brook and stream W-12. Data for streams W-2, W-11, and W-16 (fig. 1) also revealed a lack of a net downstream increase in channel width in

Fig. 6 — Roots in the channel of Pope Brook at a point about 1,500 feet from the divide.

reaches with drainage areas of less than 0.2 to 0.8 square mile. These streams were sampled at 25-foot intervals from headwaters to confluence with higher order streams.

In stream W-16, widths are generally less than 3 feet to a point with a drainage area of 0.3 square mile; widths of less than 2 feet are confined to reaches flanked by sod. The widths of stream W-16 then increase to a mean width of 10.0 feet over a distance of about 200 feet where the stream enters a forest, about 0.8 mile from the divide. Widths measured under this forest at 330 cross-sections (drainage area between 0.3 and 1.1 square mile) range from 2.5 to 21.3 feet; the standard deviation is 2.8 feet, and the relative variability (see table II) is 29 percent.

The channel of stream W-16 in the reach under forest described above is considerably wider than the channel of stream W-12, which is flanked by sod and forest. Mean width of stream W-12, which has a drainage area of 0.8 square mile, is 3 feet (see fig. 4). The channel of stream W-16 in the reach under forest is also wide when compared with that of Whiteman Brook where the drainage area is about 2.8 square miles (fig. 1). This reach of Whiteman Brook, which is bordered by pasture and occasional clumps of shrubs, was measured at 66 cross-sections spaced 25 feet apart except where the channel has been disturbed by human activity. Widths at these 66 cross-sections range from 5.7 to 18.0 feet; the mean width is 9.6 feet, the standard deviation 2.0 feet, and the relative variability is 22 percent. Farther upstream, however, where the drainage area is about 1.3 square mile, the channel of Whiteman Brook in a reach under forest is wider. Widths measured at 60 cross-sections spaced 25 feet apart range from 9.3 to 22.8 feet; the mean width is 15.2 feet, the standard deviation 3.0 feet, and the relative variability 20 percent. The aspect of the channel of Whiteman Brook in this reach and in the reach with a drainage area of about 2.8 square miles is shown in figure 7.

The two reaches of Whiteman Brook described above are sufficiently well-defined (fig. 7) that width-depth ratios could be computed for them with some accuracy. The ratio for the upper reach (d.a. about 1.3 sq.mi) with mean width and depth of 15.2 and 2.5 feet is 6.1; in the lower reach (d.a. about 2.8 sq.mi), with mean width and depth of 9.6 and 4.7 feet, the ratio is 2.0. Thus the channel form of the lower reach in sod tends to resemble more that of streams with bed and bank material high in cohesive sediment like silt and clay (Schumm, 1960). It is possible, however, that bank material consolidated by grass or tree roots has roughly the same shear strength; if this is true, then the difference in channel dimensions between a forested and a sodded reach may be caused mainly by disturbance under trees.

The channel of Whiteman Brook shows, in addition, that in sod a channel may be narrower and deeper than under forest despite considerably greater discharges. Whiteman Brook is not gauged in the reaches sampled, but discharge records for other streams in the Sleepers River basin show that annual maximum peak discharges with drainage areas of about 3 square miles exceed those at points with drainage areas of about 1.5 square mile by 50 to 70 cu.ft.

A low variability in channel width comparable to that shown for reach 5 of Pope Brook (table II) was measured in the reach of stream W-4 where the drainage area is about 11.5 square miles (fig. 1). In that reach, widths measured range from 21.1 to 36.2 feet; mean width is 26.7 feet, standard deviation 3.3 feet, and the relative variability is 12 percent. These figures are from 33 cross-sections spaced 25 feet apart in a reach of stream W-4 flanked by pasture, thickets, and forest, and in which bedrock crops out in the channel.

The points farthest downstream where living tree roots and dams of organic debris were observed across the entire channel were mapped in 15 streams of the Sleepers River basin (fig. 8). The last points, in a downstream direction, where roots cross the channel were found, with striking consistency, in reaches where the drainage area is 0.8 to 1.2 square mile. Debris dams that span the entire channel were observed as far downstream as points with drainage areas of 3 to 4 square miles. In general, roots cross the channel where the mean width is 10 feet or less, and debris dams span the channel where the mean width is 15 feet or less.

Process and channels of small streams

Data on channel dimensions of several streams of northern Vermont have shown that vegetation strongly influences the form of channels in an area with uniform geology. These data have also suggested the presence of two "thresholds" along these streams. One threshold apparently occurs where the drainage area is 0.2 to 0.8 square mile. Upstream from this threshold there is no net downstream increase in width, the flow is commonly underground, and living tree roots cross the entire channel. Channel shifting, opening of secondary channels, and removal of several feet of bank material caused directly or indirectly by such forest processes as tree-throw and accumulations of debris are also common. In such reaches, annual high flows apparently seldom exceed 10 to 20 cu.ft. Downstream from this first threshold, channel width increases in response to increases in discharge, but the variability in channel form, caused directly or indirectly by vegetation, also increases. In sod, mean channel width may be the same

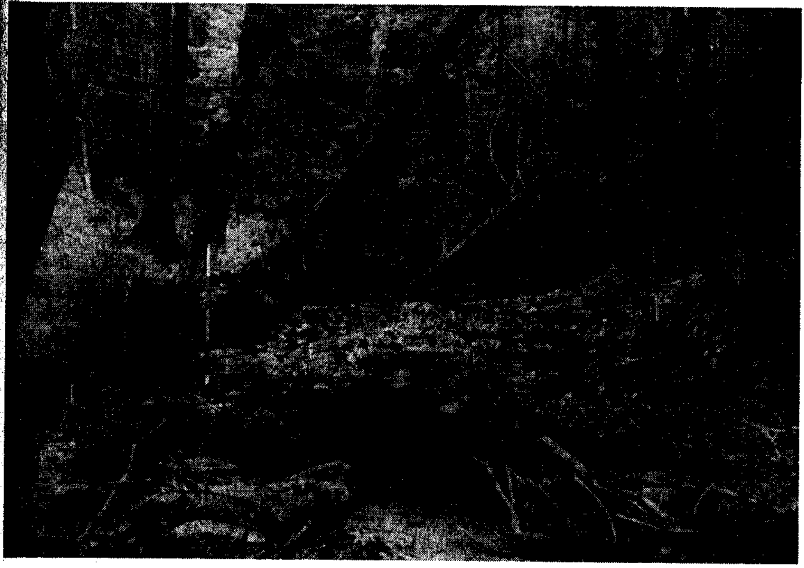

Fig. 7 A

Fig. 7 B

Fig. 7 — Aspect of the channel of Whiteman Brook at points with drainage areas of about 1.3 (*A*) and 2.8 (*B*) square miles. Stakes are marked in feet.

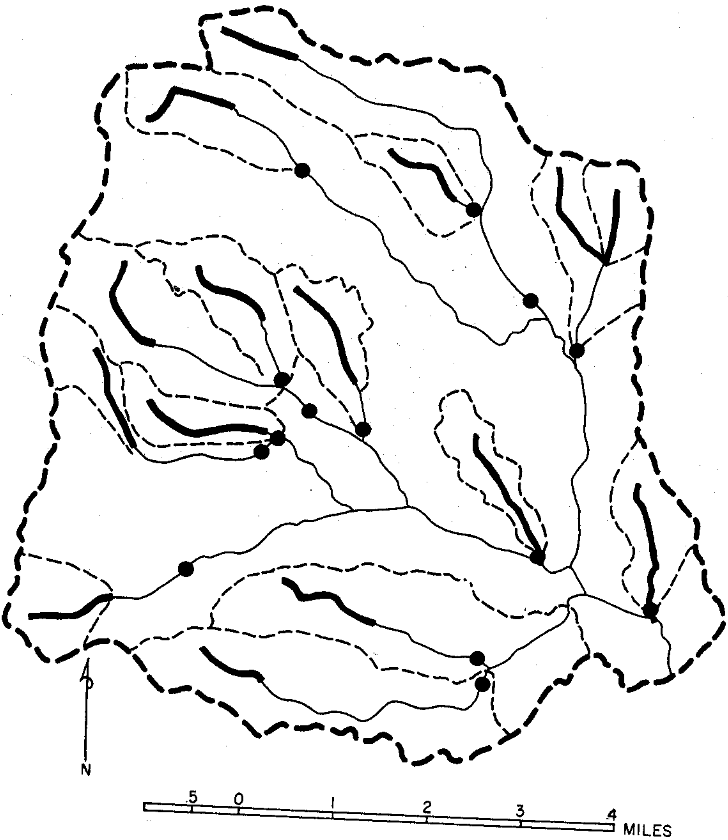

Fig. 8 — Map of the Sleepers River basin showing reaches in which living tree roots cross entire channel (bold lines) and points farthest downstream where debris dams span the channel (dots). Dashed lines denote boundaries or partial boundaries of drainage basins.

or smaller than in reaches under forest, despite differences in drainage area of several square miles. Dams of organic debris still occur in the channel. The second threshold, beyond which the influence of vegetation on channel form is marginal, seems to occur where the drainage area is 4 to 6 square miles. At this threshold, average annual high flows are in the range of 100 to 150 cu.ft, and occasional, but not rare, discharges exceed 200 cu.ft.

These thresholds may serve to separate tentatively small streams, with their distinctive relationships between process and form, from rivers that largely "construct their own geometries" (Langbein, 1964, p. 301). Small streams differ from rivers by having discharges that correspond, at most recurrence intervals, to volumes of flow that are small in relation to the activity of vegetation. These discharges create channels that are, again, small in relation to the geomorphic effect of plants. Thus, simply

Because of scale, channels of small streams are subject to processes that in rivers either do not occur, are almost completely counteracted by discharge, or have a negligible effect on channels hundreds or thousands of feet wide. Two processes peculiar to small streams are the extension of roots and the formation of dams of organic debris across the entire channel. Among the processes that may radically alter the channel of a small stream is the windthrow of streambank trees, especially windthrows may widen the channel by several feet. Material shed from the rootmass of fallen trees may, on the other hand, block the channel and cause channel shifting or the opening of secondary channels. In northern Vermont, a common non-fluvial process that may weaken the banks is the frost-heaving of streambank trees. In small streams, because of small absolute volumes of flow, these changes brought about by non-fluvial processes are not quickly "healed" by fluvial erosion and sedimentation. This is clearly shown by those localities where a local widening of the channel can be traced to a fallen tree whose stage of decay suggests a tree-throw 10 or more years earlier.

Discharges in small streams are, in most years, insufficient to remove much of the debris or obstructions introduced into the channel by vegetation. In reach 1 of Pope Brook, for example, the annual high flows in five years of record have not exceeded 9 cu.ft. As a result, in that reach tree trunks and other large plant remains decay in place. By the time these large debris are removed as comminuted organic detritus, other large solid plant remains will have fallen into the channel and created new disturbance. Small streams also dry up or have low flows insufficient to prevent root growth across the channel. Once established, living tree roots one or more inches in diameter are not easily removed by subsequent high flows of less than 10 or even 20 cu.ft. Roots may also occur in the channel, and thus armor it, as a result of channel shifting towards trees. Thus small streams may have little or no control over the presence of large roots in the channel.

Local variations in channel form of small streams can be explained mainly in terms of disturbance or resistance by vegetation. The relationship between channel size and discharge in these streams—as in all streams—is, however, more complex. In heads of valleys, flowing water probably takes a path of least resistance through, around, and under obstructions. The range of dimensions of the channel that results is related, at least indirectly, to the range of discharges. In reach 1 of Pope Brook, for example, widths range from 1.1 to 6.1 feet; the 5-foot difference between these two extremes, rather than one of 10 or 20 feet, indicates that the range of variation in channel size, even under a forest, is rather closely limited by the flow regimen. The mean width of reach 1 (2.8 feet), on the other hand, probably is not the central tendency of width given the flow regimen and geology in this upper reach of Pope Brook. This width may be the average width determined by the degree of activity of forest processes in the Kittredge Hills. The data on widths of stream W-12 show, in addition, that both mean width and the ranges of width can vary with type of vegetation. At most points in time, the channel width of a small stream in sod may represent the balance of a maximum width established by a rare runoff event minus the subsequent encroachment by vegetation. Under forest, on the other hand, channel widths may have been extended beyond those established by infrequent floods by forest processes.

An opportunity to observe the effects of unusually heavy runoff on channels of small streams was afforded by a severe cloudburst that occurred on July 21, 1967, in the Knob Hill area, near Marshfield, Washington County, Vermont. This area is about 13 miles west-southwest of the Sleepers River basin; no rain gauges are located within it. Conservative estimates of runoff based on culvert and slope-area measurements showed that a stream with a drainage area of 1.1 square mile discharged at a peak rate of at least 450 cu.ft, and possibly of as much as 600 cu.ft near its confluence with the Winooski River. Discharge in the same stream where the drainage area is 0.3 square mile was at least 150 cu.ft. In another stream, discharge at a point where the drainage area is 3.3 square miles may have been as high as 1,100 cu.ft.[1] The unusual nature of this runoff may be appreciated by comparing the estimates with the discharge record of Pope Brook and stream W-12 shown in table I. Despite these discharges, the channels in the Knob Hill area were remarkably unaffected, except the channel of the stream draining 1.1 square mile at the point where the discharge may have been as high as 600 cu.ft. In this lower reach, downstream from a reach where the stream normally cascades over exposed bedrock, the channel was widened by 10 or more feet, and locally a new channel 10 to 15 feet wide and 4 to 6 feet deep was formed. Material from these scoured areas formed an alluvial cone containing boulders as much as 3 feet long and 2 feet thick on a meadow and part of highway US 2. Elsewhere along the same stream and the other streams, however, the flood uprooted a tree here and there, created debris dams, and locally caused deep and lateral scour of 1 to 4 feet, but it did not change the basic configuration of the channel, nor did it eliminate the difference in width between a channel under forest and one in sod. On the other hand, in all streams a large amount of sediment, including boulders weighing more than 400 lb., was moved, if only a short distance. The shape of channels in sod was particularly unaffected by the flood, which in most places spread out harmlessly over the grassy floodplain. Apparently if floods have any effect on channels in sod they are of even greater magnitude and lower frequency that the event of July 21, 1967. Under forest, the slightly greater damage (mainly lateral scour of less than 3 feet) seemed to have been caused mainly by eddying and turbulence near trees or snags. Much of the widening of the channel was associated with uprooted trees. Most grassy banks were left intact possibly on account of their relative smoothness rather than higher shear strenght of sod.

If infrequent floods have little or no effect on channels, at least where the slopes are of the order of 0.06 feet/feet or less, then more moderate discharges are even less important in determining the dimensions of small streams (see Leopold and others, 1964, pp. 83-84). If this is true, then small streams again differ from rivers, the channels of which may be formed mainly by flows at or near the bankfull stage, that is by flows that occur about once a year (Leopold and others, 1964, pp. 81-83). The relationship between discharge and channel dimensions of small streams is not yet well understood, particularly in an area like northern Vermont where the alternation of severe freezes and thaws during several months every year probably has some effect on fluvial land-forms. However, the probable influence of vegetation on these dimensions can be illustrated with a hypothetical example. Consider a basin of one square mile underlain by till. Average annual high flows range from 3 to 15 cu. ft, depending on the location along the stream. Without vegetation, channel widths range from 1 to 8 feet, depending on distance from the divide and the local texture of the sediment. Mean width for the whole channel is 3 feet, not an unreasonable dimension in clayey-sandy till. With forest occupying the valley floor, non-fluvial processes begin to dam the channel or wrench material from the banks. Roots grow across the channel, and in forest clearings sod encroaches on the channel left dry by low or no flow. As a result, widths subsequently range from 0.8 to 15 feet, and the new mean width is 6 feet. In the Sleepers River basin, the channel dimensions of streams W-12 and W-16 lend particular support to such a hypothesis.

The control that vegetation exerts over the channels of small streams apparently influences, indirectly, the occurrence of bankfull and overbank flow in these streams, thus further complicating the relationship between discharge and channel form. This was suggested by observations made in the Sleepers River basin during the period of maximum snowmelt runoff of 1967. On April 2-3, 1967, most streams draining less

---

(1) We are indebted to Messrs. D.J. Calkins and M.L. Johnson, USDA-ARS, Danville, Vermont, for these estimates of runoff.

than one square mile had overtopped their banks, though not in all reaches. Overbank flow was common in narrow reaches in sod. The flow in one tributary, in the reach where the drainage area is 0.8 square mile, was over the banks or at the bankfull stage for a total of at least 14 days between April 2 and 30, 1967. The only visible effect of this long-lasting high flow on the reach, which is flanked by sod and dense alder thickets, was the deposition of a band of sediment about one foot wide and ½ inch thick along the edge of the channel. Part of this high flow was diverted over a low divide into a boggy meadow that drains into another stream. In contrast, in April 1967 the Sleepers River in the reach where the drainage area is about 44 square miles was at all times at least 2 feet below the tops of its banks. Thus in small streams the bankfull discharge may occur more frequently than in rivers, the frequency of overbank flow varies depending upon the local configuration of the channel as influenced by vegetation, and the duration of bankfull or overbank discharge may be longer.

In a downstream direction, the transition from small stream "passively" circumventing obstructions put in its way by vegetation to a stream or river more "actively" forming its channel probably occurs where the discharge is such that logs and blowdown mounds can be floated or washed away at least on an annual basis, and where roots cannot cross the channel. As noted earlier, in the Sleepers River basin this transition seems to occur where the drainage area exceeds 4 to 6 square miles, and average annual high flows are in the range of 100 to 150 cu.ft. As discharge increases and the channel widens and deepens, the influence of vegetation on channel form probably decreases regardless of the ability of most discharges to remove obstructions. Presumably this occurs because the channel becomes too wide to be dammed by debris or to be spanned by fallen trees. High banks also hold tree trunks off the water, at least near the banks, at most stages of discharge. Bank scour and the formation of an irregular channel are thus less likely than farther upstream.

In headwater reaches, the vegetation influences channel form and, locally, the position of the stream. The vegetation, however, probably has little or no influence on the location of heads of valleys. Pope Brook and its tributary *1a*, for example, rise parallel to the strike of bedrock (see Hall, 1959, plate 1), possibly along a joint. Other headwater tributaries of Pope Brook may, on the other hand, occupy chutes caused by unusually heavy runoff (see Hack and Goodlett, 1960, pp. 43-47). These tributaries are mainly those that rise on the summit of the Kittredge Hills, and whose course is normal to the slope of the Hills. Where the slope is of the order of 25 to 30 degrees because of resistant bedrock, energy relationships and adjustments of channel to process are, as suggested by the dimensions of the chutes in the Kittredge Hills (see section on topography), considerably different from those that apply to reach 1 of Pope Brook or to rivers. The relationship between process and channel form and location on the upper slopes of the Kittredge Hills is further complicated by active rockfall and blowdown that commonly displace one or more cubic yards of material.

Summary

1. In the Sleepers River basin of northern Vermont, channel width does not increase, in a downstream direction, where the drainage area is less than 0.2-0.8 square mile. Encroachment and disturbance by vegetation apparently eliminate the geomorphic effect that downstream increases in discharge may have on the uppermost reaches.

2. Along one stream, variability in channel width reaches a maximum where the drainage area is about 2 square miles. This maximum variability may be the result of disturbance by vegetation in a channel generally less than 15 feet wide, combined with annual high flows in the range of 70 to 140 cu.ft.

3. Along the stream described under 2) above, relatively uniform widths occur where the drainage area is about 6 square miles and peak discharges occasionally exceed 200 cu.ft.

4. A complete record of width of a stream draining 0.8 square mile shows that the channel is wide under forest and narrow in sod, regardless of the distance from the basin divide.

5. The mean width of a reach under forest, where the drainage area is 0.3 to 1.1 square mile, is about the same as the mean width of another stream in a reach in sod where the drainage area is about 2.8 square miles. In turn, the mean width of this reach in sod is about 5 feet less than the mean width of the same stream farther upstream, where the drainage area is 1.3 square mile and the valley floor is forested.

6. The width-depth ratios of streams in sod is generally smaller than those of channel under forest, which suggests that sod behaves more like cohesive sediment than bank material consolidated by tree roots. It is possible, however, that differences in channel form under different types of vegetation are caused mainly by relative disturbance of the above-ground part of vegetation, rather than by differences in shear strength resulting from different root systems.

7. Mapping disclosed that living roots of trees cross the entire channels of streams to points with drainage areas of 0.8 to 1.2 square mile. Dams of organic debris that span the entire channel apparently do not occur beyond points with drainage areas exceeding 4 square miles.

8. There are apparently two "thresholds" along small streams of the Sleepers River basin. They occur roughly where the drainage area is 0.2-0.8 square mile and 4 to 6 square miles. Upstream from the first threshold, annual peak discharges are generally of less than 20 cu.ft. Channel form, size, and location are greatly influenced by non-fluvial processes such as tree blowdown, damming by debris, and extension of roots. Flow is commonly underground. Mean width in such reaches probably represents a balance between the width established by rare runoff events plus or minus the subsequent encroachment or disturbance by vegetation. With drainage areas exceeding 0.2-0.8 square mile channel width increases, but both mean width and ranges of width vary greatly according to the type of vegetation lining the stream. With drainage areas exceeding 4 to 6 square miles, annual high flows greater than 200 cu.ft, and mean width of more than 15 feet, the influence of vegetation on channel form becomes marginal.

9. In headwater reaches, especially where the drainage area is less than one square mile, forest processes—that is non-fluvial processes—possibly double or triple the channel dimensions that would occur with the same discharge regimen in the same geologic setting. In small streams, the vegetation appears not only to change the roughness of the channel and the shear strength of the sediment, but also actively to determine the mean and extreme channel dimensions.

REFERENCES

Brooks, A.S., 1967, Environmental factors influencing the distribution of stream insects in the Sleepers River, Danville, Vermont: unpub. M.S. thesis, Univ. of Vermont, 79 p.

Hack, J.T. and Goodlett, J.C., 1960, Geomorphology and forest ecology of a mountain region in the central Appalachians: *U.S. Geol. Survey Prof. Paper 347*, 66 p.

Hall, L.M., 1959, The geology of the St. Johnsbury quadrangle, Vermont and New Hampshire: *Vermont Development Commission*, Bull. no. 13, 105 p.

Holtan, H.N. and Whelan, D.E., 1965, National summaries and analysis of experimental watershed data: *IASH, Symposium of Budapest*, Representative and Experimental Areas, V. 2, pp. 351-360.

Langbein, W.B., 1964, Geometry of river channels: *Jour. Hydr. Div.* (*HY2*), *Am. Soc. Civ. Eng. Proc.*, V. 90, pp. 301-312.

LEOPOLD, L.B., WOLMAN, M.G., and MILLER, J.P., 1964, Fluvial processes in geomorphology: San Francisco and London, W.H. Freeman & Co., 522 p.
SCHUMM, S.A., 1960, The shape of alluvial channels in relation to sediment type: *U.S. Geol. Survey Prof. Paper 352-B*, p.p 17-30.
U.S. Agricultural Research Service, 1963, Hydrologic data for experimental agricultural watersheds in the United States 1956-59: *USDA Misc.*, Pub. no. 945.
—, 1965, Hydrologic data for experimental agricultural watersheds in the United States 1960-61: *USDA Misc.*, Pub. no. 994.