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INDUCED CHANNEL INSTABILITY AND HYDRAULIC GEOMETRY OF THE MANGAWHARA STREAM, NEW ZEALAND

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ABSTRACT

Approximately 50 percent of the Mangawhara catchment has been converted from forest to pasture in the last 50 years. Streamflow is now more responsive to intense rainfalls and the supply of bedload to the channel has increased as a result of landsliding on the slopes. It has been suggested by Schumm (1971) that increases in bedload and water discharge will be accompanied by increases in channel width, meander wavelength, and width-depth ratio and by a decrease in sinuosity. Changes in gradient and depth may be in either direction. For the Mangawhara all recorded changes are as suggested, while both gradient and depth changes are small and of uncertain direction. Measures of the hydraulic geometry both at-a-station and downstream obey the laws established for rivers elsewhere.

INTRODUCTION

The conversion of native forest to exotic pastures in the steep hill country of New Zealand has frequently been described as the cause of severe erosion on slopes and rapid changes in stream channels (e.g. Campbell, 1945; Grant, 1950). Stable, narrow, sinuous rivers have developed wider and straighter channels as a result of an influx of coarse sediment; and aggradation and an increase in flood peaks has occurred (O'Loughlin, 1969). Similar effects on channels were reported in California when the coarse debris of hydraulic mining was fed in great quantities into the rivers draining from the gold fields of the Sierra Nevada (Gilbert, 1917).

Following the analysis of Schumm (1971) we would expect an increase in bedload and water discharge to be accompanied by changes which may be symbolised as in equation 1.

$$Q^{+}\,Q_s^{+} \simeq b^{+}, d^{\pm}, \lambda^{+}, S^{\pm}, P^{-}, F^{+}. \qquad (1)$$

where:
Q = water discharge
Q_S = bed-material load
b = channel bankfull width
d = channel bankfull depth
λ = meander wavelength
S = channel gradient
P = sinuosity
F = width-depth ratio

The plus and minus exponents indicate increases and decreases.

In this study the term bed-material load is used as a synonym for bedload and is defined as that part of the sediment load of a stream which consists of particle

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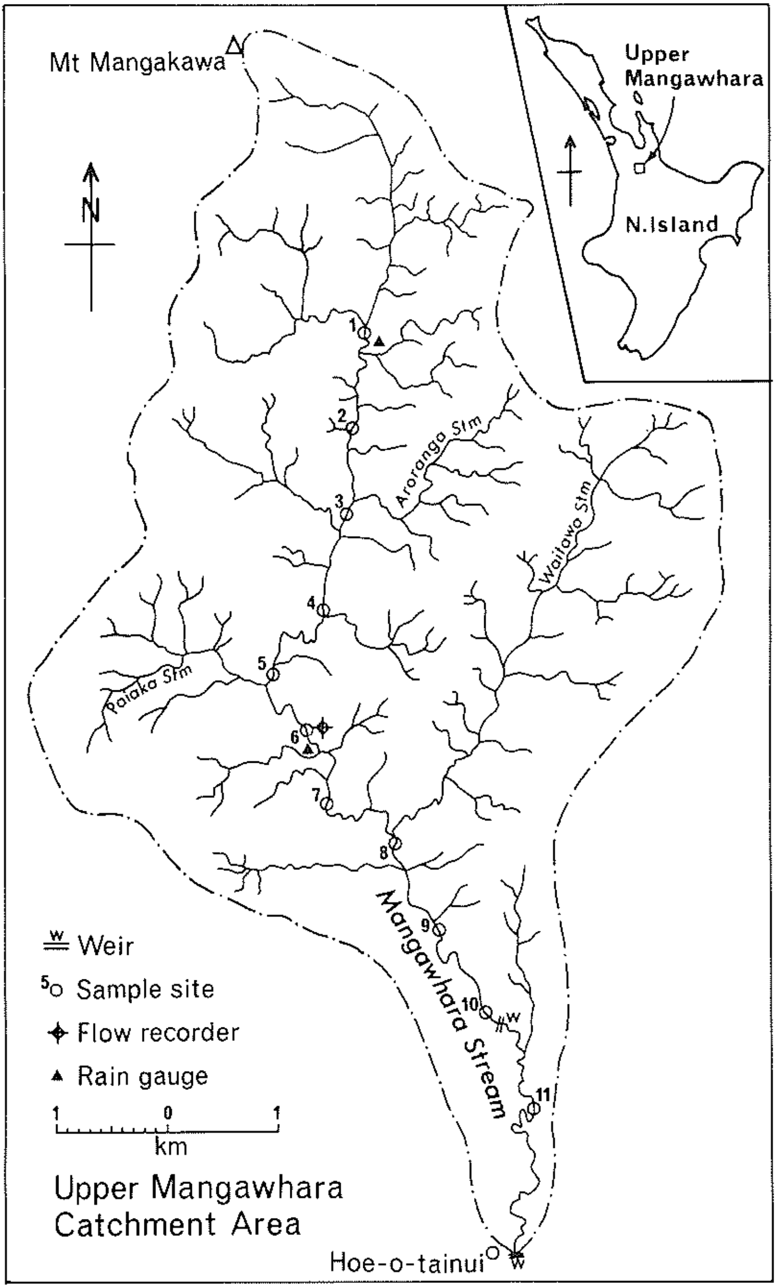


FIG.1 – Stream network in the Mangawhara catchment upstream of Hoe-o-Tainui. The sampling points are indicated.

sizes represented significantly in the bed of the stream and hence excludes any silt and clay in the bed material (Einstein, 1950, p. 6, 7). Sinuosity is defined as the ratio of channel length to valley length at the mid-valley line (Schumm, 1968). Meander wavelength is defined as the distance between the axes of the bends in neighbouring meander curves measured along the curved line between them which is concentric with the meander belt axis (Brice, 1964).

Field observations,in the northern Ruahine Ranges have indicated that these trends are valid for channels with very coarse bedload (P. Grant, pers. comm.), but their application to channels in areas yielding finer grained debris to the streams was less certain. The original work by Schumm was related to streams in semi-arid and subhumid regions hence this study in the catchment of the Mangawhara stream has been carried out to determine how the channel of that stream, in a humid climate, responded to changes in landuse within its catchment.

The Mangawhara Valley was chosen as a study area because the history of landuse change there is fairly well known and the geomorphic changes occurring on the slopes during the last ten years and hence affecting the stream channel, have been recorded (Selby, 1967a, b, 1976; Blong, 1971).

THE UPPER MANGAWHARA VALLEY

The Mangawhara Stream rises in a dissected, tephra–mantled greywacke horst block, the Hapuakohe Range, and flows southwards to join the Waikato River. The upper Mangawhara Stream drains an area, north of Hoe–o–Tainui, of 36.2 km² and falls from an altitude of 400 m at the foot of Mount Maungakawa to 41 m at Hoe–o–Tainui bridge in a distance of 12 km, giving an average gradient of 1 in 33 (Fig. 1).

The hillslopes of the upper catchment are steep (usually greater than 20° slope) and straight with little or no basal concavity. The slopes are mantled with colluvium or deeply weathered greywacke and many areas occupied by grassland have been subject to severe landsliding since 1966 (Selby, 1976). The valley floor is occupied by extensive terraces of which the oldest are mantled by Hamilton Ash Beds and hence are regarded as being of middle Pleistocene age, and the youngest were formed in part by two large floods during February 1966, and February 1967, and in part by later floods of lower magnitude (Blong, 1971).

The original vegetation in the valley was a forest of mixed broadleaf and podocarp species. Remnants of this forest still occur in the higher parts of the catchment and afford opportunities to compare stream channels within the forest with those in the middle reaches which have drained through grassland since the forest was cleared there in the early 1920s. About 50 percent of the catchment is now in pasture grasses. The main period of forest clearance occurred when a soldier-settlement was established in the period 1925-1930. At this time willow trees were planted along the channel banks and these trees so spread that by 1945 they were almost blocking the stream in some areas and causing frequent overbank flow and deposition of silt. Between 1955 and 1960 local farmers attempted to alleviate this problem by removing the willows and, in a few places, by cutting drains through channel meanders.

Information on the characteristics of the channel in the 1920s and 1930s is available only from descriptions by the older residents. Mr A. Orr (pers. comm.) has described the channel then as having a more regular flow regime than at present, and a more sinuous channel of less width and greater depth. The banks were grassed, gently sloping and stable. More recent information is available from vertical air photographs taken in 1942, 1960 and 1971 and field observations and measurements in 1975. For purposes of study the channel has been divided into 11 reaches, each centred about a sampling point (Fig. 1).

The belief that both water discharge and bed-material load have increased since partial deforestation is derived, in the absence of direct measurements, from infiltration data (Selby, 1967a) and from field observations of the debris supplied by landslides to the channels. This debris is partly silt and clay sized material, but a significant proportion is of gravel and cobble size particles.

CHANNEL CHARACTERSTICS

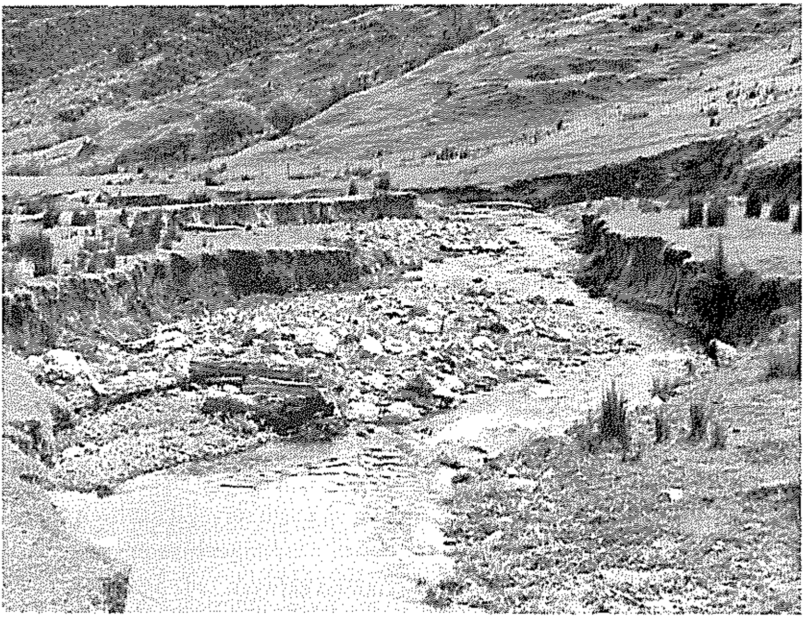
In its upper 3 km the channel is in a forested area with many outcrops of bedrock. The channel here is narrow, being less than 3 m wide during normal flow conditions and stable. At the point of departure of the stream from the forest (site 1 in Fig. 1) the banks are also grassed and stable, but only 100 m below this point the banks become vertical and unstable, and the channel becomes wider and more irregular. These irregular forms occur throughout the valley below site 1 (Fig. 2, a, b, c).

Channel sinuosity (P)

For the purposes of comparison the channel length has been divided into three segments: the upper segment is between study sites 1 and 5, the middle segment between sites 5 and 10, and the lower segment is between site 10 and Hoe–o–Tainui. Using the available airphotos and field survey it has been found that:

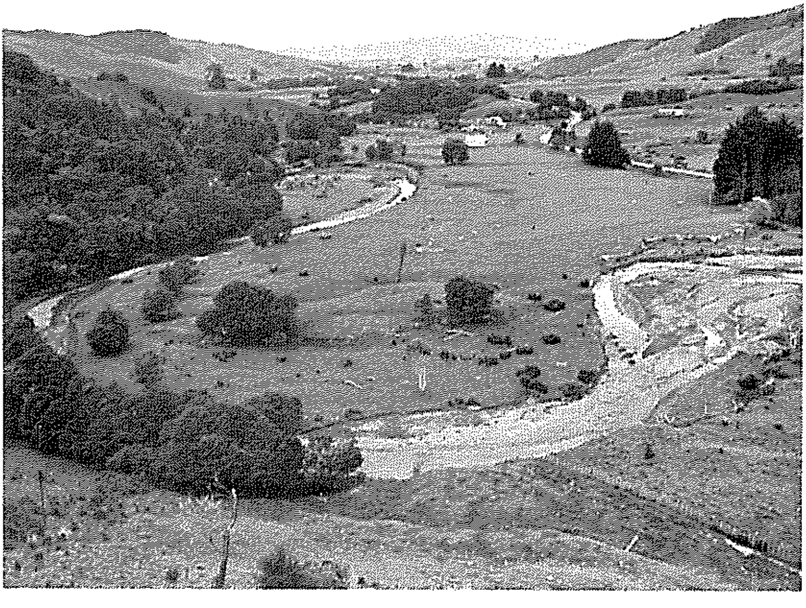
(a) In all segments the sinuosity has decreased between 1942 and 1975.
(b) Changes in sinuousity are great in the upper and lower segments with smaller changes in the middle segment.

FIG.2 — (a) The stable channel at site 1 where the stream emerges from forest.



(b) The channel below site 2 where the banks are being undercut and the channel widened.

(c) Channel widening between sites 5 and 6.
(Photos by M. J. Selby).



(c) The decrease in sinuosity is greatest in the lower segment where the 1975 sinuosity is now almost half that of the 1942 channel.

(d) In the period 1942 to 1960 the channel of the upper and middle segments remained constant, presumbly because it was confined by willow trees.

The data are given in Table 1. As far as can be ascertained from local informants as much as 75 percent of the change in sinuosity may be due to direct human interference wtih the channel, especially by the digging of channels to cut off meander loops. The remainder of the changes are a result of natural processes.

TABLE 1 – Sinuosity of the Mangawhara Stream Channel at given dates

	1942	*1960*	*1975*
Upper segment	1.64	1.56	1.35
Middle segment	1.64	1.57	1.56
Lower segment	2.24	1.65	1.27
Total for all three segments	1.74	1.51	1.42
Channel length of all three segments (km)	16.6	15.2	13.5
Percentage change in channel length from 1942	–	10.7	18.4

Meander wavelength (λ)

Meander wavelength has been determined for each of the eleven reaches (Fig. 1) for 1942, 1960 and 1975. The data are given in Table 2. Between 1942 and 1960 meander wavelength increased in all but three reaches, but from 1960 to 1975 the trend was reversed and wavelength decreased in all reaches but one. The mean values suggest that the overall change has been slight. The decline in wavelength since 1960 is probably a result of human interference in which channel straightening has been a major influence. Increases of wavelength between 1942 and 1960 probably represent the natural trend, and suggest that human interference will have only temporary results unless the channel banks are impounded throughout.

Channel bankfull depth (d)

Channel bankfull depth is a concept which is very difficult to apply in the field. Bankfull discharge may be recognised only for channels with clearly defined banks and hence cannot be applied to many braided reaches nor to streams with one channel incised into a larger, and occasionally active, channel. In the Mangawhara Valley the stream channel impinges on the valley wall in a few places and there are many sites at which a low flow channel lies within a larger channel which is fully occupied by floodwaters at rare, but unrecorded, intervals.

TABLE 2 – Meander wavelength of the Mangawhara Stream Channel given as the mean value for each reach

Reach No.	*Mean meander wavelength (m)*		
	1942	*1960*	*1975*
1	78.8	93.7	–
2	128.5	148.7	–
3	109.5	134.1	–
4	162.0	130.6	161.0
5	151.1	135.3	129.6
6	158.0	177.8	174.9
7	176.8	165.6	156.6
8	281.2	315.1	236.1
9	243.7	261.8	201.1
10	450.0	476.7	469.1
11	196.3	242.4	234.6
Mean of reaches 4-11	251.9	268.4	249.7

In neither of these circumstances is it possible to clearly define a bankfull situation. The attempt by Dury *et al.* (1963) to define bankfull stage by a fixed flood recurrence interval of 1.58 years affords little help. In the observation period only once did the recorded stage approximate bankfull as seen in the field and the recurrence interval for this flood, as determined from daily rainfall data was 2.6 years, although, because of the intensity of the rain, it is possible that the return period was even longer.

Even if bankfull discharge could be determined with confidence at the present, the depth of the channel at this discharge at times in the past is not known. Changes in channel bankfull depth have therefore to be inferred from present trends and discrete items of historical evidence.

Three cross-sections, one each at sites 2, 6 and 10, were surveyed at intervals during a period of 7 months (13.3.75 to 16.10.75). Field observations were made in all reaches. The increases in channel depth range from nil at site 1, through 0.5 m at site 6, and 2 m at site 11. Site 10 was affected by a weir and showed an anomalous accumulation of bed material; this accumulation may have been partly responsible for the incision at site 11 below the weir.

A 7 month record is far too short to indicate long term trends and may merely reflect the short term effect of a single flood. A trend towards deepening is not supported by observations of local residents.

Channel bankfull width (b)

Channel bankfull width determination in the field is faced with the same problems as those associated with definition of bankfull depth. Because of recent bank undercutting, however, channel banks in the Mangawhara Valley are mostly nearly vertical and the width between these vertical banks has been taken as indicating bankfull width. In order to obtain an indiction of the direction of change in channel widths pegs were placed on the banks at two sites in each of the sample reaches. One set of pegs was set in a straight part of a reach where minimum bank erosion was probable, and the other on the outside of a meander bend where maximum rates of erosion might be expected. Spot values of changes in channel width were therefore obtained for 22 sites. The measurements were taken in March 1974 and September 1975, an interval of 19 months. The total bank erosion at each site for the period is indicated in Fig. 3. Most of the changes occurred on the outside of meander bends but a general widening appears to be taking place everywhere in the channel below site 1. In reach 7 widening was slight because here the channel is still partly controlled by trees along the banks, and by gabions which prevent channel migration and potential undercutting of a road.

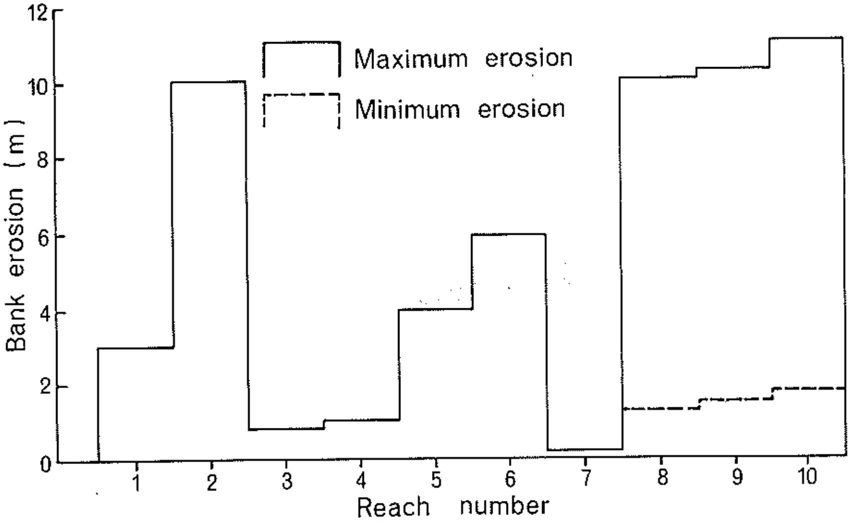


FIG.3 — Total bank erosion, at points in each sample reach, between March 1974 and September 1975.

Channel gradient (S)

As indicated in the discussion of channel depth, there has been an overall cutting down in the lowest reach (11) and no cutting down in the upper reach (1) in the 7 months of observation. Judging from the maximum possible incision below the flood plain of 1942, of about 3 m, there has been a slight steepening of the stream channel which may be still continuing. This increase seems to have mostly occurred since the willow trees were removed in the late 1950s. This inferred trend, however, is opposed to that suggested by the local inhabitants.

Width-depth ratio (F)

In the absence of quantitative data for past channel depths it is not possible to determine the values of F in the past. The substantial recorded increases in width, however, indicate that the value of F is increasing at present.

Bedload (Q_S)

There are no data on bedload in the past and few available for the present. All that can be safely said is that the active erosion of the banks and the considerable influx of colluvium into the channel, from the widespread mass movements on the slopes in the storms of 1966 and 1967, suggest that bedload has increased significantly since 1966. Before about 1960 the channel was mostly confined by trees and overbank deposition of silts was common. The bed at that time was apparently armoured by large boulders in many reaches and movement of gravel was regarded by local inhabitants as being a rare occurrence. After the 1966 storm, however, a concrete ford in the middle reaches was several times buried by coarse gravel and this fact alone suggests that there has been a marked increase in bedload in recent years.

DISCUSSION OF CHANNEL CHANGES

An increase in bedload seems to be clearly associated with storms which have caused severe landsliding on the grassed slopes of the catchment. Landsliding in the forest area has been comparatively slight and is not known to have contributed material to the channel. Lower infiltration rates into soils under pasture than under forest (Selby, 1967a) imply increased runoff to stream channels. Concomitant changes which seem well established are; an increase in channel width, an increase in meander wavelength where channels are not modified by direct human interference, an increase in width–depth ratio and a decrease in channel sinuosity. These changes are all in the direction indicated by equation 1. It is not clear in what manner gradient and depth should change. In his discussion of equation 1 Schumm (1971, p.5–3) suggests that width–depth ratio is predominantly influenced by type of load. An increase in width may therefore be associated with either a constant depth or a decrease in depth. Channel gradient will probably increase because sinuosity decreases. Data from the Mangawhara is inadequate to throw light on changes in the values of d and S.

HYDRAULIC GEOMETRY OF THE UPPER MANGAWHARA STREAM

Empirical and theoretical studies have shown that relationships exist in natural channels between the measures of channel form and the processes operating in the channel – this is the assumption implicit in the work described above. Work by Leopold and Maddock (1953), Wolman (1955) and Leopold and Miller (1956) established that mean velocity ($\bar{v}$), mean depth ($\bar{d}$) and mean width ($\bar{w}$) of the flowing water are related to mean discharge (Q) in power functions of the form:

$$\bar{w} = aQ^b\, ; \bar{d} = cQ^f\, ; \bar{v} = kQ^m;$$

where a, c, k, b, f, m are constants.

As cross sectional area $A = \bar{w}.\bar{d}$, and $\bar{w}.\bar{d}.\bar{v}. = Q$

$$\text{then } aQ^b \,.\, cQ^f \,.\, kQ^m = Q$$

$$\text{thus } a.c.k. = 1.0 \text{ and } b + f + m = 1.0.$$

Studies by numerous workers have established that these relationships expressed as the hydraulic geometry of stream channels, are affected by climate, vegetation cover and therefore landuse. Few data are available on the hydraulic geometry of New Zealand rivers and it is not known, in quantitative form, how the geometric properties of rivers have changed in response to the changes in vegetation which have been common in many catchments in the last 100 years. These characteristics for the Mangawhara stream are therefore recorded here in the hope that resurveys in future may contribute to an understanding of channel changes.

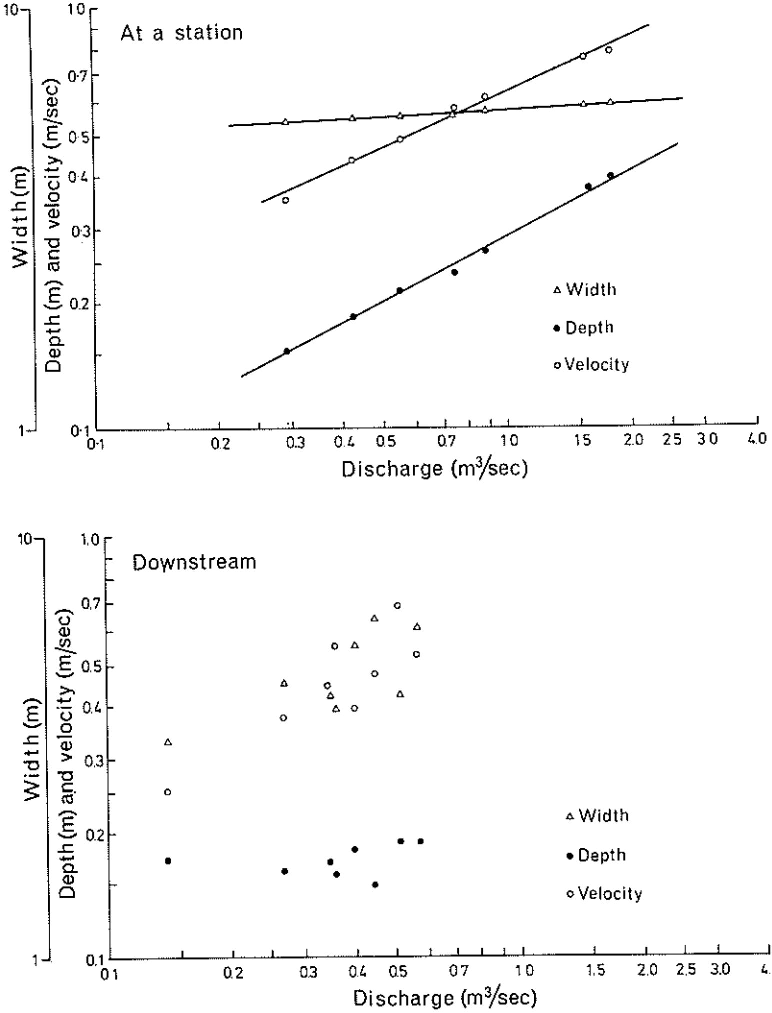


FIG.4 – Relation of width, depth and velocity to discharge at-a-station (top), and downstream (below), for the Mangawhara Stream.

Hydraulic geometry at–a–station

For at–a–station studies site 6 was chosen as being a reach with a stable channel and banks. An automatic, Foxboro pressure bulb, weekly water level recorder was installed at the site and a stage–discharge rating curve was established. Water velocities below 1 m/s were measured with a Pygmy current meter and those over 1 m/s with an Ott current meter. Methods of data collection and evaluation followed those of Toebes (1963).

Following the method of Leopold and Maddock (1953) values for water width, depth and velocity have been plotted against discharge on log paper (Fig. 4). The slope of the straight lines through the plotted points is the value of the exponents $b, f,$ and m. At site 6 the values determined are:

$$b = 0.05, f = 0.52, m = 0.43; \text{ and } b + f + m = 1.0.$$

Knighton (1975) has determined the mean values and the frequency distribution for values of b, f and m from data for 206 cross-sections given by Leopold and Maddock (1953), Wolman (1955), Leopold and Wolman (1957), Fahnestock (1963) and Leopold, Wolman and Miller (1964). When the values for the Mangawhara Stream are compared with these it can be seen that the hydraulic geometry of the Mangawhara at site 6 closely resembles that of the streams observed elsewhere (Table 3).

TABLE 3 — Values for at-a-station variables

Exponent	*Mangawhara Stream*	*Streams in U.S.A., mean for 206 cross sections (Knighton, 1975)*
b	0.05	0.16
f	0.52	0.43
m	0.43	0.42

Hydraulic geometry downstream

Measurements of $\overline{w}$, $\overline{d}$, $\overline{v}$ and therefore Q were made at sites 2 to 9, inclusive, during a period of normal summer flow. The data are plotted in Fig. 4; the values of b, f and m derived from a least-squares fit line, sum to 0.96 and thus correspond well with the theoretical expression. When these values are compared (Table 4) with those derived from other rivers, however, it will be seen that the Mangawhara Stream is different in that, although the value of b is close to the expected, f is far smaller and m is much larger than normal. This implies that the depth of water remains nearly constant as discharge increases, while velocity increases markedly with increasing discharge. In the rivers studied by Leopold and co-workers velocity tended to remain nearly constant as discharge increased.

The reasons for this discrepancy are not entirely clear but the most obvious possibility is that of downstream reduction in loss of energy by bed friction in the Mangawhara Stream. It has been determined by study of the particle size of channel bed sediments that there is a diminution in grain size downstream. The

TABLE 4 – Values for downstream variables for the Mangawhara Stream and various channels in the United States of America

Location	*b*	*f*	*m*
Midwestern U.S.A. (Leopold & Maddock, 1953)	0.5	0.4	0.1
Brandywine Creek, Pennsylvania (Wolman, 1955)	0.42	0.45	0.05
Appalachian Streams (Brush, 1961)	0.55	0.36	0.09
Mangawhara Stream (1975)	0.53	0.02	0.41

TABLE 5 – Channel bed particle characteristics for the Mangawhara Stream.

Notes: (1) Full data are given in Bennett (1975). Methods are those of Folk and Ward (1957).
(2) 64 mm diameter represents the boundary between pebbles and cobbles; >30 mm has been taken as representing a larger than small gravel fraction.

Site	*Mean size (mm)*	*Percentage of particles (by weight) exceeding 64 mm diameter*	*Sorting* $\sigma_I(\emptyset)$	*Roundness of >30 mm fraction*
1	27.7	40.41	2.95	3.12
2	45.5	47.12	2.52	2.82
3	53.5	60.30	2.55	3.50
4	27.7	29.33	2.04	3.01
5	21.4	17.50	2.03	3.01
6	23.7	18.27	2.02	3.00
7	32.2	30.08	2.02	3.21
8	43.0	53.96	2.11	3.70
9	27.5	27.71	1.96	3.62
10	16.0	16.58	1.80	3.58
11	14.5	1.71	1.61	3.63

general trend is partly obscured by the influx of tributaries which bring a supply of larger and more angular particles and this particularly accounts for the increases in mean size at sites 2, 3, 7 and 8 (Table 5). Particle sorting and particle roundness also increase downstream and these factors, combined with reduced particle size, may be associated in reducing channel bed roughness and hence losses of energy by bed friction. By contrast, it has been noted by Brush (1961) that downstream changes in bedload characteristics are not constant or systematic for many Appalachian streams.

The marked increase in width downstream in a small channel is unusual when compared with overseas data, for vegetation often prevents a small channel from widening downstream, although it has little effect on large channels. The increase in width in the Mangawhara is probably a reflection of the present channel instability and widening.

DISCUSSION OF HYDRAULIC GEOMETRY

Understanding of the controls upon the hydraulic geometry of streams is important because present and future changes in basin processes, instigated by modifications of climate or of basin characteristics, have implications for the size and shape of river channels. Changes in the characteristics of runoff resulting from changes in landuse are well known for many areas of New Zealand, but accurate measurements of their effect upon channel form are limited. If losses of land and production are to be avoided more attention must be paid to effects of changes in vegetation upon runoff and sediment yield, and hence upon channel forms.

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