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HYDROLOGY AND STREAM SEDIMENTS
IN A MOUNTAIN CATCHMENT

VOLUME II
(being Volume II of three volumes)

THE STUDIES

CHAPTER 1: The rainfall study.

CHAPTER 2: The stream flow study.

CHAPTER 3: The infiltration rates study.

CHAPTER 4: The study of subsurface discontinuities.

CHAPTER 5: The partial contributing study.

CHAPTER 6: The water yield study.

CHAPTER 7: The vortex tube sediment trap.

CHAPTER 8: The sediment studies

CHAPTER 9: Channel morphology

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FIGURE 1

Location of the Torlesse Stream Catchment
FIGURE 2

Plan of the Torlesse Stream Catchment showing places mentioned in the text.
FIGURE 3

The Torlesse Stream Catchment
Mt Torlesse
Irishman Stream
Vortex tube Sediment trap
Hut
Kowai River
Kowai Scree
CHAPTER 1.

THE RAINFALL STUDY
SUMMARY

Problems of precipitation measurement are briefly reviewed.

Information from one recording rain gauge is presented and compared with limited information from other sites. It is concluded that information from this one site can be used as a reliable index of catchment precipitation.

Information from a 66 year record at nearby Mt. Torlesse station provides an assurance that precipitation values recorded during the study period are representative of the population of possible values. It also shows that while easterly storms are less common than southerly storms, they are more likely to produce floods.
INTRODUCTION

Errors in precipitation measurement account for many of the inaccuracies in rainfall runoff relations and in consequence there is a large literature on the subject of rainfall estimation (for example see Rodda, 1971).

There are two principle objectives in measuring precipitation. The first is to obtain an unbiased estimate of the rain which would have fallen at the site had a gauge not been present. The second is to ensure that a site is representative of the area to which the estimate will be applied.

Many studies have investigated bias caused by the gauge itself and there is a wide range of "improved" designs. For example Kurtyka's (1953) study of rainfall measurement and gauge design lists 1079 references. Two principle sources of bias are wind and topography.

In 1861 Jervons (Hamilton, 1954) attributed discrepancies in measured rainfall to turbulence in the airflow around the gauge. Studies at Rotheram (England) led to the accepted British practice of installing a gauge one foot above ground level and surrounding it by a turf wall on a radius of 5 feet. While this is satisfactory in low vegetation and in land of low relief, it is unsuitable for mountain lands supporting tall vegetation.

Attempts to eliminate bias caused by turbulent air flow around tall gauges have produced shields of the rigid Nipher type or the flexible Alter type. A number of studies have shown that such shields increase gauge catch by reducing eddies around the orifice, and that these increases are more marked with snow than rainfall (see for example Allis et al, 1963). However, only a few studies have attempted to evaluate shield effectiveness for measuring "true" precipitation (for example see Dreaver and Hutchinson, 1974). The main problem appears to be an inability to measure "true" precipitation.

The problems of bias caused by mountain topography have been discussed by a number of authors (for example see Hamilton and Reiman, 1958). The essence of concern is that rainfall estimates for conventional vertical gauges will be in error in steeplands when wind drives rain onto slopes at inclinations
from the vertical. Hamilton (1954) found that when gauges were tilted and oriented normal to slope and aspect, they could accurately sample rainfall actually reaching the ground. Several studies have been made of the character and significance of inclined rainfall in New Zealand (Aldridge (1975), Jackson and Aldridge (1972, 1975) and Finklestein (1972)). The tilted versus horizontal issue can best be resolved by considering the purpose of rainfall measurement. Tilted gauges can be justified in research studies that need "hydrologic" estimates of rainfall. Horizontal gauges should be used for national networks, precipitation maps and comparative purposes (Peck, 1972).

The problem of extending point rainfall data to larger areas is illustrated by Linsley et al (1949), who note that a standard 8 inch gauge provides data from a $8.0 \times 10^{-7}$ mile$^2$ point. Rain gauge networks are therefore intended to record the spatial variability in rainfall and to provide greater confidence in data obtained from such small areas. Although there are guide lines to help establish the density of gauge networks in mountain lands (W.M.O. (1970), Ferguson (1972)), these are modified by a number of considerations.

Three of the more important are:

1. The purpose for which data are needed.
2. The resources available for network establishment, maintenance and data processing.
3. The accuracy which is required of the data.

There is, therefore, no general solution to the problem of network density. If absolute values are needed, then an intensive network should be established (McKay, 1964). Fewer gauges can be used if their data are used as indices of area rainfall. In such cases gauges should be located in areas which contribute most to rainfall (McKay, 1964).

PROCEDURES

A 10.2 cm ($4''$) storage gauge and a 16.0 cm seven day recording syphon gauge were established at 780m on an open terrace above the catchment's outlet. A solar panel was fitted to the recording gauge to prevent freezing in the
syphon chamber (Stratford and Costello, 1974) (Figure 4). Several factors influenced the decision to record precipitation at only one site.

(a) There were insufficient resources to establish a net-work of gauges.
(b) Although precipitation could be expected to increase with altitude, it was thought that such increases would be proportionally more important for light rain and snow events. For rain storms it was thought that a reliable index of catchment rainfall could be obtained from the chosen site.
(c) Rainfall data was needed to better understand stream flow responses. In turn, flow responses were needed to better understand stream sediment behaviour. At the time the study was set up, sediment movement was a principle objective of study. As order of magnitude estimates would have been acceptable, there was little to justify unwarranted accuracy in the estimation of rainfall.
(d) Data from a level orifice gauge would be comparable with that from other gauges in the New Zealand Meteorological Service network.

However, to test the variability in rainfall within the basin, a storage gauge was temporarily located at 1100m (see Figure 5) for the period January - May 1975. In 1976 a network of gauges was set up to provide data for a study of the basin's stream flow contributing areas.

Daily precipitation records from 1909 were available for Mt. Torlesse Station, 10 km east of the study area. These records cover the 24 hour period from about 0900 hours but daily rainfalls for the Torlesse stream catchment are for the 24 hour period from midnight.

The storm frequency analysis of Mt. Torlesse station data was based on a partial duration series.

To supplement the Mt. Torlesse station record, the Christchurch "Press" was searched for information about the direction of the three largest storms in each year. Because early accounts were brief, only three categories of storm direction were used. They are, north-west, south (south and south

Figures 4 & 5 follow
FIGURE 4

Meteorological station Torlesse stream catchment (780m). A solar panel has been fitted to the recording gauge to prevent freezing in the syphon chamber.
FIGURE 5

Location of rain gauges in Torlesse stream catchment.
west) and east (north east to south east).

The 67 years of record from Mt. Torlesse Station introduced the possibility of generating a synthetic rainfall record for the Torlesse stream catchment based on regression analyses of the 1973-76 records from stream and station.

To reduce variability, the data was stratified by storm direction. Only two classes of storm origin were used for these analyses, viz those from the south west (south through west) and those from the north (north through east).

Unless otherwise stated, a storm was arbitrarily taken as any event in which rainfalls exceeded 10 mm in 24 hours.

RESULTS

PRECIPITATION - MT. TORLESSE STATION

The record of annual precipitation for Mt. Torlesse station from 1909 to 1975 is presented in Appendix 2. Figure 6 has been derived from that data and shows a cyclic pattern of annual precipitation about the mean value. Although the period from 1973 was generally wetter than normal, Figure 7 shows that 1973 was a dry year (probability about 90%), and 1975 was a wet year (probability about 3%).

Table 1 has been derived from data held by the New Zealand Meteorological Service and shows that rainfalls, rain days, storms and consecutive days without rain are well distributed throughout the year.

A partial duration series for storms in excess of 20 mm was used to establish return periods for maximum storm precipitation (Figure 8).

STORM DIRECTION - MT. TORLESSE STATION

Table 2 shows that nearly two-thirds of the major storms came from the south or south west and only about one quarter came from the east. However, easters produce an equal number of major events. The probability of a southerly storm being in excess of a five year return period is about 0.1. The probability of an easterly storm exceeding the same return period is about 0.3. Major storms from east and south are both characteristically...
Average annual rainfall Mt. Torlesse Station: 3 yr. moving means.
FIGURE 7

Annual rainfalls Mt. Torlesse Station 1909 - 1975.
% probability that annual rainfall will be exceeded

% probability that annual rainfall will not be exceeded
FIGURE 8

Storm frequency Mt. Torlesse Station 1909 - 1975
<table>
<thead>
<tr>
<th></th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>June</th>
<th>July</th>
<th>Aug</th>
<th>Sept</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean monthly rainfall (mm)</td>
<td>98.4</td>
<td>79.7</td>
<td>76.3</td>
<td>89.0</td>
<td>85.5</td>
<td>71.1</td>
<td>78.9</td>
<td>76.6</td>
<td>80.7</td>
<td>96.9</td>
<td>92.9</td>
<td>102.0</td>
<td>1025</td>
</tr>
<tr>
<td>Standard deviation (mm)</td>
<td>(51.2)</td>
<td>(43.2)</td>
<td>(41.0)</td>
<td>(60.3)</td>
<td>(55.2)</td>
<td>(38.8)</td>
<td>(54.8)</td>
<td>(51.0)</td>
<td>(45.1)</td>
<td>(53.4)</td>
<td>(43.7)</td>
<td>(54.9)</td>
<td>(173)</td>
</tr>
<tr>
<td>No. of storms</td>
<td>2.6</td>
<td>2.2</td>
<td>2.1</td>
<td>2.1</td>
<td>2.1</td>
<td>1.9</td>
<td>1.9</td>
<td>2.1</td>
<td>2.2</td>
<td>2.4</td>
<td>2.7</td>
<td>2.9</td>
<td></td>
</tr>
<tr>
<td>Rain days</td>
<td>10.7</td>
<td>9.0</td>
<td>9.0</td>
<td>9.2</td>
<td>9.8</td>
<td>8.1</td>
<td>8.4</td>
<td>8.3</td>
<td>9.1</td>
<td>10.4</td>
<td>10.3</td>
<td>10.9</td>
<td></td>
</tr>
<tr>
<td>Consecutive days without rain</td>
<td>8.7</td>
<td>8.1</td>
<td>9.1</td>
<td>9.8</td>
<td>9.6</td>
<td>10.8</td>
<td>10.2</td>
<td>11.1</td>
<td>9.6</td>
<td>8.2</td>
<td>8.4</td>
<td>8.2</td>
<td></td>
</tr>
</tbody>
</table>

**TABLE 1**

Mt. Torlesse Station 1909 - 1975

Mean monthly rainfall (mm); mean number of storms per month; (precipitation in excess of 10 mm); mean number of rain days for month; (rainfall in excess of 1 mm); mean number of consecutive days without rain.
<table>
<thead>
<tr>
<th>Storm Size</th>
<th>Number of storms from each quarter</th>
</tr>
</thead>
<tbody>
<tr>
<td>mm</td>
<td>NW</td>
</tr>
<tr>
<td>&lt; 100</td>
<td>20</td>
</tr>
<tr>
<td>100 - 150</td>
<td>0</td>
</tr>
<tr>
<td>&gt; 150</td>
<td>1</td>
</tr>
<tr>
<td>TOTALS</td>
<td>21</td>
</tr>
</tbody>
</table>

**TABLE 2**

Mt. Torlesse Station precipitation 1909 - 1973

Frequency and direction of the 3 largest storms in each year.
of two day duration.

PRECIPITATION - STUDY AREA
The monthly and annual totals shown in Table 3 have been summarised from the daily rainfalls presented in Appendix 1 (Vol. III). Table 4 shows the maximum and mean rainfall amounts for eight durations in the period April 1973 to October 1976.

The mean values were derived from an analysis of 180 rainfall events. As a comparison, maximum values from 24 years of record at Lake Coleridge are shown in Table 5.

RAINFALL VARIATION WITHIN THE STUDY AREA
Table 6 shows accumulated rainfall totals for 3 gauges within the study area for a period of 5 months. The meteorological station storage gauge (780 m) recorded 4% more rainfall than the adjacent recording gauge. The storage gauge at 1100 metres recorded 6% more than the storage gauge (780 m) and 10% more than the recording gauge (780 m).

RAINFALL RELATIONSHIPS BETWEEN MT. TORLESSE STATION AND THE TORLESSE STREAM CATCHMENT
Table 7 shows the results of regression analyses in which Torlesse station rainfall was the independent variable (x) and Torlesse stream rainfall was the dependent variable (y).

While there is little change in the "goodness of fit" between weekly totals and storm totals for southerly events (analyses 3 & 5) there is considerable improvement between weekly totals and storm totals for events from the north (analyses 4 & 6).

If necessary, storm totals for Torlesse stream could be estimated from Torlesse station data using the prediction equations:

\[ y = 42.3 + 1.3(x - 26.7) \] for storms of south to westerly origin \( (r^2 = 0.69) \)

and \[ y = 36.5 + 1.2(x - 36.4) \] for storms originating from a north to easterly direction \( (r^2 = 0.71) \)

Tables 3, 4, 5, 6 & 7 follow
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan</td>
<td>64.9</td>
<td>284.8</td>
<td>147.2</td>
<td>177.0</td>
<td></td>
</tr>
<tr>
<td>Feb</td>
<td>145.6</td>
<td>116.6</td>
<td>208.3</td>
<td>77.9</td>
<td></td>
</tr>
<tr>
<td>Mar</td>
<td>145.9</td>
<td>205.7</td>
<td>68.0</td>
<td>37.9</td>
<td></td>
</tr>
<tr>
<td>April</td>
<td>82.4</td>
<td>294.1</td>
<td>160.4</td>
<td>77.1</td>
<td>120.2</td>
</tr>
<tr>
<td>May</td>
<td>128.7</td>
<td>79.5</td>
<td>111.1</td>
<td>129.3</td>
<td>116.3</td>
</tr>
<tr>
<td>June</td>
<td>64.2</td>
<td>89.7</td>
<td>159.8</td>
<td>93.4</td>
<td></td>
</tr>
<tr>
<td>July</td>
<td>44.0</td>
<td>163.3</td>
<td>103.0</td>
<td>105.2</td>
<td></td>
</tr>
<tr>
<td>Aug</td>
<td>284.1</td>
<td>72.8</td>
<td>184.9</td>
<td>133.8</td>
<td></td>
</tr>
<tr>
<td>Sept</td>
<td>42.5</td>
<td>180.2</td>
<td>126.2</td>
<td>260.5</td>
<td></td>
</tr>
<tr>
<td>Oct</td>
<td>60.6</td>
<td>141.5</td>
<td>139.6</td>
<td>217.7</td>
<td></td>
</tr>
<tr>
<td>Nov</td>
<td>147.1</td>
<td>33.6</td>
<td>119.7</td>
<td>137.7</td>
<td></td>
</tr>
<tr>
<td>Dec</td>
<td>48.1</td>
<td>42.2</td>
<td>73.3</td>
<td>223.3</td>
<td></td>
</tr>
<tr>
<td>An. total</td>
<td>1453</td>
<td>1785</td>
<td>1801</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**TABLE 3**

Monthly and annual precipitation (mm) Torlesse Stream catchment 1973 - 1977
<table>
<thead>
<tr>
<th></th>
<th>0.5 hr</th>
<th>1 hr</th>
<th>2 hr</th>
<th>6 hr</th>
<th>12 hr</th>
<th>24 hr</th>
<th>48 hr</th>
<th>72 hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean*</td>
<td>2.9</td>
<td>4.7</td>
<td>7.3</td>
<td>13.2</td>
<td>17.5</td>
<td>21.1</td>
<td>24.5</td>
<td>26.4</td>
</tr>
<tr>
<td>Max</td>
<td>15.8</td>
<td>20.9</td>
<td>25.9</td>
<td>47.1</td>
<td>76.0</td>
<td>113.4</td>
<td>167.7</td>
<td>177.9</td>
</tr>
</tbody>
</table>

* - derived from an analysis of rainfall events between April 1973 and October 1976.

TABLE 4

Mean* and Maximum rainfall depths (mm)
Torlesse Stream Catchment 1973 - 1976
<table>
<thead>
<tr>
<th>Time</th>
<th>1 hr</th>
<th>2 hr</th>
<th>6 hr</th>
<th>12 hr</th>
<th>24 hr</th>
<th>48 hr</th>
<th>72 hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>11</td>
<td>15</td>
<td>24</td>
<td>43</td>
<td>72*</td>
<td>132</td>
<td>192</td>
</tr>
</tbody>
</table>

* - incomplete record - there is a possibility that a greater value could have occurred.

**TABLE 5**

Maximum rainfall depths (mm) Lake Coleridge 1951 - 1975

Source: N.Z. Meteorological Service

### Rainfall Details

<table>
<thead>
<tr>
<th>Location</th>
<th>Height (m)</th>
<th>Catchment (mm)</th>
<th>Variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lambrecht recording gauge</td>
<td>780</td>
<td>646.5</td>
<td></td>
</tr>
<tr>
<td>Storage gauge</td>
<td>780</td>
<td>673.7</td>
<td>+ 4%</td>
</tr>
<tr>
<td>Storage gauge at Diorite downs</td>
<td>1100</td>
<td>714.0</td>
<td>+ 10%</td>
</tr>
</tbody>
</table>

**TABLE 6**

Rainfalls recorded at 3 sites in the Torlesse Stream Catchment January - May 1975
<table>
<thead>
<tr>
<th>Description of analysis</th>
<th>c</th>
<th>b</th>
<th>r</th>
<th>Equation</th>
<th>Variation explained</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Weekly totals, all data</td>
<td>4.47</td>
<td>1.09</td>
<td>0.78</td>
<td>$y = 29.4 + 1.1(x - 22.8)$</td>
<td>61%</td>
</tr>
<tr>
<td>2. Weekly totals greater than 15 mm</td>
<td>-0.85</td>
<td>1.19</td>
<td>0.71</td>
<td>$y = 44.3 + 1.19(x - 37.8)$</td>
<td>50%</td>
</tr>
<tr>
<td>3. Weekly totals of storms greater than 5mm from South, S.W., or West</td>
<td>6.82</td>
<td>1.36</td>
<td>0.85</td>
<td>$y = 48.2 + 1.36(x - 30.5)$</td>
<td>71%</td>
</tr>
<tr>
<td>4. Weekly totals of storms greater than 5mm from N.W., N., N.E., E.</td>
<td>-0.41</td>
<td>0.62</td>
<td>0.71</td>
<td>$y = 17.3 + 0.62(x - 28.8)$</td>
<td>50%</td>
</tr>
<tr>
<td>5. Storm totals greater than 5mm from South, S.W., or West</td>
<td>6.57</td>
<td>1.34</td>
<td>0.83</td>
<td>$y = 42.3 + 1.34(x - 26.7)$</td>
<td>69%</td>
</tr>
<tr>
<td>6. Storm totals greater than 5mm from N.W., N., N.E., E.</td>
<td>-7.65</td>
<td>1.21</td>
<td>0.84</td>
<td>$y = 36.5 + 1.21(x - 36.4)$</td>
<td>71%</td>
</tr>
</tbody>
</table>

**TABLE 7**

Regression analyses of storm and weekly rainfall between Torlesse Stream ($y$) and Torlesse station ($x$) 1973 - 1976

$y = bx + c$  
$r^2 = \text{corr. coeff.}$
DISCUSSION

The 68 year rainfall record from Mt. Torlesse station allows data from the Torlesse stream catchment to be used with some confidence. First, annual rainfalls in the period 1972 - 1977 have been shown to be representative of the population of possible values. Second, the station record provides valuable information about the relatively uniform distribution of rainfall and storm events throughout the year. Third, the record confirms the locally held view that easterly storms are less common than southerly storms but are more likely to be major flood producing events.

It had been hoped that from this record, it would be possible to derive a synthetic record of flows for the Torlesse stream catchment. However, it is evident from the unexplained variability of the regression analyses, that such a record would have limited value. The regression analyses can, however, be used to estimate the probability (or return period) of particular events.

It is possible that better relationships might be derived as the length of record is increased. However, it is probable that the 10 km and the mountain ridge which separate the two stations will always limit the reliability of such relations.

Although there is only four years of rainfall intensity and duration record for Torlesse stream catchment, results from a 24 year record at Lake Coleridge suggest that the Torlesse information is reliable.

In the studies reported here, catchment rainfall is accepted as that recorded by the one recording gauge at the meteorological site. Limited comparisons with other gauges suggest discrepancies of up to 10%. In the nearby Craigieburn Ranges Rowe (*pers comm.*) found considerable variability in precipitation but failed to show the clear trends of increasing precipitation with altitude shown by Mark (1965) and others. Although it is probable that precipitation does increase with elevation in the Torlesse stream catchment, observation during the study period suggests that these increases are greatest for fogs and mists which have little influence on the basin's rainfall runoff relations. Catchment precipitation is dominated by frontal systems from the south and east. It is little influenced by north westerly snow storms. Because of
the basin's aspect, information from the one recording gauge can be used as a reliable index of catchment precipitation.
CHAPTER 2

THE STREAM FLOW STUDY
SUMMARY

The methods of stream flow measurement and hydrograph analysis are described. Results including variation in flow are presented. Discussion of these results is presented in chapters 5 and 6 (vol. II).
INTRODUCTION
Stream flow represents the integration of hydrological, meteorological and catchment factors that operate in a drainage basin. Because it can be measured at one location it is easier to obtain reliable estimates of a catchment's stream flow than of its precipitation.

Methods of flow measurement have been reviewed by many authors (for example see Church & Kellerhals (1970), Boyer (1964). In most conventional techniques, discharge is estimated as the product of stream velocity and cross sectional area. The measurement of velocity presents more problems than do area measurements, and current meters, floats velocity head loss rods and pitot tubes are used. For most stable channels there is a unique relationship between water level and discharge. Once this relationship has been established, discharge can be estimated from records of water level. If there is no suitable site for a water level recorder, a weir may provide artificial control. A flume may be used where the constraints to weir use cannot be met.

The hydrograph is perhaps the single most valuable piece of hydrologic information, for, by analysis one can infer much about the contributing catchment and its responses to precipitation.

PROCEDURES
Streamflow Measurement
The Torlesse stream leaves its catchment through a well defined opening about 7m wide between large rock outcrops (Figure 9). The site provided an excellent foundation on which to anchor a control section of channel. This control section included the vortex tube sediment trap (see Chapter 8 for details of design). It was intended to incorporate a Parshall flume in this section, but at the design stage it became evident that the costs of a Parshall flume would exceed the costs of the sediment trap. In view of the uncertainties about the efficiency and performance of the sediment trap there seemed little to justify the additional costs of unwarranted accuracy in stream flow measurement. When an attempt to rate an upstream section of stream channel failed, the control section itself was rated by repeated

Figure 9 follows
FIGURE 9

The outlet of the Torlesse stream catchment before the control section was built. Arrows show the rock outcrops to which the control section was later anchored.
current meter gaugings (Figure 10). An eight day water level recorder has provided a continuous record of stage height from May 1973 (Figure 11).

Elsewhere in the Torlesse stream and Kowai river discharge was estimated using current meters (Boyer, 1964) and a velocity head loss rod (Wilm & Storey (1944), Heede (1974)). Current meter gaugings are generally reliable but slow. A velocity head loss rod was used on those occasions when time was more important than accuracy. Low flow gaugings in the pool-riffle system of the Torlesse stream were difficult and unsatisfactory, even with pygmy meters. Chemical dilution gauging (British Standards Institute, 1964) was attempted but abandoned because of unacceptable errors in rates of injection and in the analyses of diluted samples (errors were in the order of 40% to 100%).

Hydrograph Analysis
Each hydrograph was separated into quick flow ("surface runoff") and delayed flow (base-flow). At first this was done by plotting the hydrograph on semi-logarithmic paper (Barnes, 1939). This procedure was later discarded when it was found that separation using a master recession curve (Linsley et al, 1949) was faster, and gave the same results.

Recession Flow
Base flow recession was derived graphically using stream flow periods which were free of rains, snow or snow melt (Bruce & Clarke, 1966). A straight line drawn to envelop points on the right hand side (Figure 14) represents the slowest prevailing base flow recession rate.

Although base flow rates are commonly characterised by a single base flow recession constant ($k$) it is unusual for all base flow recessions to have the same value. Martin (1973) noted that $k$ values tend to lie between 0.5 and 1.0 with a distinct 'bunching' as $k$ approaches unity. Because of this bunching and because they lack physical meaning, Martin suggested that $k$ values are an unsatisfactory method of characterising recession rates of streams. He advocated a concept of a half flow period as a more meaningful and sensitive flow characteristic. The half flow period can be estimated.
FIGURE 10

Stage height and discharge relationship. Torlesse stream control section.
FIGURE 11

Torlesse stream control section and water level recorder.
from the equation:

\[ t_{0.5} = \frac{\log \frac{1}{2}}{\log K} \]

where \( t_{0.5} \) = half flow period

and \( k \) = base flow recession constant (Martin, 1973)

RESULTS

Stage, Discharge Relations (Rating Curve)

Figure 10 shows the rating curve for the Torlesse control section. This rating curve has been used to convert stage height records into flow rates and yields.

Annual Stream Flow

Mean daily stream flows from the Torlesse basins for the period 1973-1977 are presented in Appendix III. Figures 12 and 13 and Table 8 summarise that data.

Flood Flows

Figure 13 shows that flood flows were well distributed throughout the year. Hydrographs of floods in excess of 0.200 \( \text{m}^3\text{sec}^{-1} \) are presented in Appendix IV. The largest recorded flow in the period 1973-1977 was 2.08 \( \text{m}^3\text{sec}^{-1} \).

Figures 12 and 13 show that although streamflow is reasonably well distributed throughout the year the periods of lowest flow tend to be summer and winter.

Low Flows

The lowest recorded flow in the period 1973-1977 was 0.075 \( \text{m}^3\text{sec}^{-1} \). Figure 14 indicates that an average value for the basin's recession constant is in the order of \( k = 0.87 \) but that the slowest base flow recession rate was in the order of \( k = 0.99 \). The half flow periods which correspond with these recession rates are 2.3 days \((k = 0.74)\), 5 days \((k = 0.87)\) and 69 days \((k = 0.99)\).
<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>Jan</td>
<td>55.3</td>
<td>134.3</td>
<td>96.0</td>
<td>144.0</td>
<td></td>
</tr>
<tr>
<td>Feb</td>
<td>70.4*</td>
<td>83.6</td>
<td>115.8</td>
<td>71.6</td>
<td></td>
</tr>
<tr>
<td>Mar</td>
<td>119.7</td>
<td>189.9</td>
<td>68.2</td>
<td>63.3</td>
<td></td>
</tr>
<tr>
<td>Apr</td>
<td>195.9*</td>
<td>113.1</td>
<td>59.8*</td>
<td>66.0</td>
<td></td>
</tr>
<tr>
<td>May</td>
<td>87.3</td>
<td>96.7</td>
<td>137.7</td>
<td>85.6</td>
<td>105.7</td>
</tr>
<tr>
<td>June</td>
<td>85.5</td>
<td>133.3</td>
<td>103.7</td>
<td>81.5</td>
<td></td>
</tr>
<tr>
<td>July</td>
<td>61.9</td>
<td>141.9</td>
<td>92.4</td>
<td>75.8</td>
<td></td>
</tr>
<tr>
<td>Aug</td>
<td>132.9</td>
<td>85.6</td>
<td>100.3*</td>
<td>106.4</td>
<td></td>
</tr>
<tr>
<td>Sept</td>
<td>75.4</td>
<td>146.8</td>
<td>129.3</td>
<td>156.2</td>
<td></td>
</tr>
<tr>
<td>Oct</td>
<td>94.6*</td>
<td>176.0</td>
<td>125.9</td>
<td>295.7</td>
<td></td>
</tr>
<tr>
<td>Nov</td>
<td>92.9</td>
<td>154.2*</td>
<td>128.6</td>
<td>212.1</td>
<td></td>
</tr>
<tr>
<td>Dec</td>
<td>50.8*</td>
<td>77.2</td>
<td>68.9*</td>
<td>169.1*</td>
<td></td>
</tr>
</tbody>
</table>

**TABLE 8**

Monthly streamflow (mm) Torlesse Stream Catchment 1973 - 1977
FIGURE 12

Monthly stream flow (mm)
Torlesse stream catchment 1973 - 1977
FIGURE 13

Annual Hydrographs
Torlesse Stream Catchment 1973 - 1977
FIGURE 14

Relations between discharge and discharge one day later for 11 selected low flow periods Torlesse stream catchment 1973 - 1977.
Discharge m$^3$ sec$^{-1}$

Discharge one day later (m$^3$ sec$^{-1}$)

$K = 0.87$
Variation in Flow

Figure 15 shows flow duration curves for mean daily, mean weekly and mean monthly flow.

During summer months the water level recorder showed a diurnal variation in flow. From about 9 a.m. to 9 p.m. there was frequently a reduction in flow up to 0.01 m³ sec⁻¹ (Figure 16). A reduction such as this is equivalent to about 400 m³ day⁻¹.

DISCUSSION

While the significance of these data will be discussed in subsequent chapters, comment is made here about their reliability.

These data refer only to surface flow. Although the control section cut off wall extends 0.7m into river bed gravels, it does not adjoin the bed rock believed to underlie the structure. Although water discharge through the stream bed is thought to be a very small proportion of total discharge, its rates are unknown. While this uncertainty is not significant to the stream sediment studies, it may contribute to the errors in the water balance study.

The choice of control section design was limited by the need for it to incorporate the vortex tube sediment trap. In consequence it is not an ideal structure for measuring stream discharge. The rating curve (Figure 10) shows the section to be relatively insensitive, particularly at higher flows. In addition, depth measurements are made more difficult by surface waves which develop at flows greater than about 0.30 m depth when flow is near critical, and by standing waves created when the vortex tubes are in use (Figure 17).
FIGURE 15

Flow duration curves
Torlesse stream catchment 1973 - 1976
Percentage of time indicated flow was equalled or exceeded
Diurnal fluctuation in flow for a 7 day summer period Torlesse stream catchment.
FIGURE 17

Flood flows through the Torlesse stream control section. Fluctuations of stage heights in excess of 0.30 m (2.08 m$^3$ sec$^{-1}$) makes it difficult to obtain accurate estimates of discharge.
CHAPTER 3

THE INFILTRATION STUDY
Horton's (1933) concept of surface water runoff requires rainfall rates to exceed infiltration rates. Many studies have compared the influences which factors such as vegetation and land management have on reducing infiltration rates. Such studies have stated or inferred that overland flow rates are increased by more intensive or exploitive land use practices. This is valid only when infiltration rates become less than rainfall rates.

A study of infiltration rates throughout the Torlesse stream catchment confirmed that there are major differences between for example eroded and well vegetated sites. However these differences were found to have little significance to the generation of overland flow for even the lowest infiltration values were found to be in excess of recorded rainfall rates.

This finding is supported by field observations which have failed to confirm the presence of overland flow in this basin, in regions other than saturated riparian lands.
INTRODUCTION

The role of infiltration in the hydrologic cycle was probably first recognised by Horton (1933) who described it as the movement of water through the soil surface.

The rate at which water can enter the soil is dependent on many factors among which may be, litter and plant cover, surface crusting, rainfall energy, slope, soil texture, bulk density, season of the year, soil moisture status and soil structure. Horton recognised maximum and minimum rates of infiltration. Maximum rates occur at the beginning of a storm, and decrease rapidly because of changes in the controlling factors.

Infiltration has been widely studied and it has been a common conclusion that the quantity of living plant material and litter is more significantly correlated with infiltration rates than any other variables. (for example see Meeuwig 1970, Branson et al. 1972). Other studies have shown significant differences between plant communities (Dee et al. 1966), surface conditions (Haupt 1967), season (Gifford 1972), grazing intensities (Rauzi & Hanson 1966), and land improvement (Williams et al. 1972). A general conclusion is that infiltration rates are reduced by more intensive or exploitative forms of land use.

Several New Zealand workers have confirmed this general conclusion. For example, Nordbye & Campbell (1951) found marked reductions in infiltration rates following the conversion of North Island forest lands to pasture. In North Island pumice soils Selby (1970) and Selby & Hosking (1971) found reductions in infiltration rates following conversion from manuka scrub to pasture. Gillingham (1964) studied infiltration rates on three adjacent areas of mountain land at Porters Pass (mid-Canterbury). Although all sites were formerly tall tussock grassland, different grazing treatments had induced contrasting vegetation types. His results suggested that infiltration rates were inversely related to the intensity of land use, but significant differences could not be detected.
Water which is unable to infiltrate moves over the surface as overland flow. This has long been regarded objectionable for two principle reasons. First, overland flow rapidly concentrates in defined channels and causes higher peak discharges in shorter time than water which moves through the soil. Second, high velocity overland flow causes erosion. Because of this, watershed managers have been concerned about the maintenance (or improvement) of catchment cover.

However, while more intensive forms of land use may reduce infiltration rates there will not necessarily be an increase in surface water runoff rates. Horton's overland flow model requires rainfall rates to exceed infiltration rates. In New Zealand, rainfall intensity rates are generally low, and while Horton's excess rainfall concept might apply to the mid-Western United States, it has not been validated in New Zealand mountain lands. It has, however, been accepted as a basic premise of watershed management in this country.

The proposition to be tested in this study was that, regardless of ground cover or degree of depletion, infiltration rates are in excess of all but the most extreme rates of rainfall.

PROCEDURES:

Infiltration measurement

Methods for measuring infiltration rates have been reviewed by Branson et al. (1972), Musgrave & Holtan (1964), Selby (1970), Gillingham (1964), Fitzgerald et al. (1971), many of whom report the concentric ring type of flooding infiltrometer to be a comparatively crude and somewhat unsatisfactory technique. Despite these reservations this method was adopted because it was simple and did not require large amounts of water. Further, this study was more concerned with establishing the lowest rates of infiltration than with evaluating absolute differences within or between plant communities. Under these conditions the technique could be expected to give reasonably
reliable indications of infiltration rates.

The operation of the infiltrometer was similar to that described by Gillingham (1964). A 10 cm internal ring was surrounded by a 15 cm buffer ring and inserted 5-10 cm into the soil. A 2.5 cm head was maintained in both the internal and buffer rings. Infiltration rates were assessed as the rates at which water was released into the internal ring from a graduated Mariotte tube. Recording continued until a constant infiltration rate was attained. This was generally between 15 and 45 minutes. On completion of the first trial, the rings were left in place and a second trial (or wet run) was carried out 18 to 24 hours later.

Study sites were selected in the following manner. G.L. Holgate (pers comm) selected representative sites for detailed botanical study within each of the plant communities mapped by G.D. McSweeney (pers comm). Working from the centre of each botanical site four infiltration areas were chosen using grid co-ordinates and a table of random numbers. The only constraints to selection were that each area had to be within 10 m of Holgate's site and that it had to be possible to insert the double rings with only minimal disruption to the soil. If the constraints did not apply the site was rejected and another was chosen; four sites were rejected for this reason. The coarse scree fields were excluded from study.

Results

Figure 18 shows the location of the 64 test sites. In appendix IV (vol III) results are presented for the mean infiltration rate in the first 10 minutes, the mean infiltration rate, and the 30 minute or 'ultimate' infiltration rate for both dry and wet runs.

Table 9 presents summary information about the 30 minute infiltration rate, and shows that values range from a minimum value of 30 mm.h⁻¹ to a maximum

Figure 18 Table 9 follow
FIGURE 18

Location of infiltration trials in the Torlesse stream catchment.

Legend:  
Short tussock grassland  
plots 1, 2, 3, 4, 5, 6, 9, 10, 13, 16

Tall tussock grassland  
plot 8

Manuka scrub  
plots 7, 14

Dracophyllum scrub  
plots 11, 12

Snow totara scrub  
plot 15
<table>
<thead>
<tr>
<th>Community</th>
<th>% of Catchment</th>
<th>Number of Sites in Parentheses</th>
<th>Maximum mm.h⁻¹</th>
<th>Minimum mm.h⁻¹</th>
<th>Mean and Standard Deviation in Parentheses mm.h⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short tussock</td>
<td>20</td>
<td>35 (9)</td>
<td>5,120</td>
<td>120</td>
<td>930 (1,050)</td>
</tr>
<tr>
<td>Tall tussock</td>
<td>8</td>
<td>5 (1)</td>
<td>2,700</td>
<td>30</td>
<td>930 (1,050)</td>
</tr>
<tr>
<td>Dracophyllum scrub</td>
<td>9</td>
<td>4 (1)</td>
<td>820</td>
<td>500</td>
<td>610 (150)</td>
</tr>
<tr>
<td>Manuka and matagouri scrub</td>
<td>3</td>
<td>4 (1)</td>
<td>3,120</td>
<td>210</td>
<td>1,080 (1,390)</td>
</tr>
<tr>
<td>Snow totara</td>
<td>6</td>
<td>4 (1)</td>
<td>5,000</td>
<td>750</td>
<td>2,360 (1,890)</td>
</tr>
<tr>
<td>Bare ground</td>
<td>9</td>
<td>8 (2)</td>
<td>950</td>
<td>80</td>
<td>275 (280)</td>
</tr>
<tr>
<td>Beech forest and herb field</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scree</td>
<td></td>
<td>41</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Bare ground</strong></td>
<td></td>
<td><strong>100</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Bare ground</strong>*</td>
<td><strong>9</strong></td>
<td><strong>12 (3)</strong></td>
<td><strong>420</strong></td>
<td><strong>10</strong></td>
<td><strong>120</strong> (115)</td>
</tr>
</tbody>
</table>

* Wet run results, i.e., 15 to 24 hours after "dry run".
value of 5,000 mm.h\(^{-1}\).

Discussion

Although experience in this study was somewhat more satisfactory than that reported by Gillingham the results show the same marked variability in infiltration rates.

Part of this variation may be due to real differences between sites but part is without doubt due to instrument error. Lateral flow, soil disturbance during emplacement, boundary effects and the smallness of the sampling area, all contribute to instrument error. While sprinkling plots may have overcome some of these problems they would have needed large quantities of water to be carried up to 1,000 metres up steep mountain slopes.

These results are indicative rather than absolute, for flooding rings are known to give higher values than rainfall simulators (Musgrave & Holton (1964)). Nevertheless Gillingham's rainfall simulator study on depleted tall tussock at Porters Pass gave values for ultimate infiltration rates of between 85 mm.h\(^{-1}\) and 105 mm.h\(^{-1}\). His results indicate that the values reported here are reasonable.

Tables 4 and 5 (Chapter 1) showed that the maximum rainfall depths recorded for a 30 minute period were 15.8 mm in the Torlesse catchment and 11.0 mm at Lake Coleridge. These depths are equivalent to intensities of between 20 and 30 mm.h\(^{-1}\). Further west at Cass, it has been estimated that the maximum 30 minute intensity for a twenty year return period would be in the order of 40 mm.h\(^{-1}\). (Greenland & Owens 1967).

Therefore despite the variability and possible inaccuracy of the results they support the contention that rainfall intensity will rarely exceed infiltration capacity. The results suggest that even in a wet condition, infiltration rates exceed extreme rainfall intensities on more than 90% of the sites studied. This finding is supported by field observations which have, to date, failed to confirm the presence of overland flow in this basin.
CHAPTER 4

THE STUDY OF SUB-SURFACE DISCONTINUITIES
SUMMARY

Although there has been a tendency to regard catchments as two dimensional surfaces, this study demonstrates that some soil erosion and some catchment responses to rainfall are determined by sub-surface conditions.

A seismic refraction study is described. This study confirmed that return flow (Dunne & Black, 1970) and some erosion forms are associated with bed rock which is close to the catchment's surface.
INTRODUCTION

There has been a tendency to regard catchments as two dimensional surfaces. This view has been encouraged by that watershed research which has focussed on vegetation influences and given little attention to sub-surface conditions. Although geologists have much data on the hydrologic role of bedrock this has been most often interpreted for its significance to ground water. Only a few studies have attempted to define the role of bedrock in the rainfall runoff process (for example, see Yamamoto (1976), Stephenson (1967), Shields & Sopper (1967, 1969), Burroughs et al (1965), Megahan (1973)).

Water which infiltrates, flows downward until it reaches a zone of reduced hydraulic conductivity. This could be either bedrock or an eluviated soil horizon. Continuing inflow produces saturation above this zone and downslope subsurface flow along the discontinuity.

There are throughout the high country many eroded "scalds" similar to that shown in Figures 21 - 23. Their evolution and existence appear to have been accepted as simply another erosion form. However, during and immediately after rainfall in the Torlesse catchment, water has been observed to flow from these sites. It was possible that at such sites sub-surface conditions caused "ground water" to intersect with the catchment surface. Further, it was possible that this "ground water" was subsurface flow moving over bedrock. Field observations suggested that when sub-surface flow was transformed into surface flow, there was an actual or potential threat to land stability. Observations also suggested that this transformation was important to understanding the basin's hydrologic response to rainfall.

This chapter describes a pilot study, the aim of which was to determine relationships between bedrock, the presence of erosion scalds, and the transformation of soil water into surface flow.

Procedures

Seismic refraction surveys have long been used in oil exploration, but with the development of portable seismographs the technique has been more widely
used. This summary statement of procedures and results is based on the more detailed account presented in Appendix V by R.W. Lewandowski.

Seismic refraction evaluates differences in energy wave velocities that are refracted by bedrock as opposed to those which move more slowly through soil and other surficial deposits.

A knowledge of wave velocities and the distance from their point of origin is used to calculate depth to a refracting surface. There are three basic items of equipment:

(a) a source of seismic energy (in this case a hand operated hammer);
(b) a geophone (or receiving device);
(c) an electronic clock (in this case the instrument had a millisecond digital readout).

Three areas were selected for study. They were selected because water had been observed to flow from them during floods.

40m to 50m transects were laid out across each of the 3 study areas. At one end of each transect the geophone was set, and connected to the clock and hammer as shown in Figures 19 and 20. At regular intervals along the transect the ground was struck with the hammer. At the instant of impact a signal was sent to the clock to begin measuring time. The seismic wave then travelled through the ground and the instant the geophone recorded the arrival of a first wave, the clock stopped.

The information obtained in this manner was used to construct time distance graphs which were then interpreted to estimate profiles of refractor depth and seismic velocities.

Results

Velocity contrasts between surficial deposits and bedrock were generally good. For the surficial deposits velocities were between 200 m sec\(^{-1}\) and 500 m sec\(^{-1}\). Bedrock velocities were between 1000 m sec\(^{-1}\) and 3600 m sec\(^{-1}\). (A few values of between 500 m sec\(^{-1}\) and 1000 m sec\(^{-1}\) were recorded and alternative interpretations of these results are presented in Figures 19 & 20 follow
FIGURE 19

Seismic wave paths.
low velocity surficial deposits $V_1$

high velocity refractor layer $V_2$
FIGURE 20

Equipment used in the seismic survey.
The geophone has been set at the far end of the transect. The travel time of shock waves set up by the hammer are recorded by the electronic clock.
Appendix IV. Velocities recorded at three sites are presented in Appendix V and interpreted in Figures 21 to 23 to indicate the relationship between land surface and bedrock at the three trial areas.

Discussion

The accuracy of seismic refraction surveys is in part dependent on the control available against which results can be tested. In this study, control was limited to a few surface exposures. The problems of a lack of control are illustrated by the two sets of overlapping traverses on the Gingerbread Spur site which did not give coincident refractor profiles (Appendix V). It is probable that such errors can be attributed to variable velocities in the surficial deposits, and to the irregular refractor or bedrock surfaces. However, in this study the magnitude of depth to bedrock along each traverse was more important than the absolute depths below each point on the traverse.

Despite the pilot nature of the study and uncertainties in velocity interpretations, the results confirm that erosion scalds were associated with bedrock close to the surface.

This finding makes it possible to consider the evolution of some erosion features. Figure 25 shows surface and sub-surface conditions similar to those described in Figures 21 - 23. Results from the infiltration study indicate that, regardless of plant cover, almost all rainfall will infiltrate into the upper slope. However, where bedrock intersects with the surface, soil water is transformed into surface flow. Adequate ground cover downslope of the exit point will allow this flow to be safely discharged. However, if the downslope plant cover cannot provide for the safe discharge of the emergent ground water, erosion will occur (Figure 24). Figure 25 is presented to illustrate possible stages in the evolution of an eroded landscape.

Those concerned with soil conservation in mountain lands have considered that vegetation affects the entry of rainfall into the soil. This study suggests that vegetation might have a much more significant role in influencing soil stability at sites where ground water emerges as surface flow.

Figures 21, 22, 23, 24 & 25 follow
FIGURE 21

Relation between surface and sub-surface bedrock
Gingerbread Spur
FIGURE 22

Relation between surface and sub-surface bedrock
Helen Stream face
FIGURE 23

Relation between surface and sub-surface bedrock
Kowai site
FIGURE 24

Erosion down slope of a point of ground water emergence.
FIGURE 25

Possible stages in the evolution of an eroded landscape.
CHAPTER 5

THE PARTIAL CONTRIBUTING AREA STUDY
SUMMARY

Horton's (1933) infiltration model has dominated approaches to runoff generation and become a fundamental premise of watershed management. However, in the last decade it has been increasingly recognised that overland flow is an unsatisfactory model for runoff generation in many humid areas.

The study reported here is the first attempt to apply the concept of partial contributing area (or variable source area) to a New Zealand catchment. It over simplifies the rainfall runoff generation process but establishes that the partial contributing area concept provides for a more satisfactory explanation of the quick flow component of flood hydrographs than does the Hortonian overland flow model.
INTRODUCTION

Since the 1930s the Horton (1933, 1939, 1940) infiltration approach to runoff generation has dominated land-use hydrology and the conversion of rainfall to runoff. It has been incorporated in most standard texts and forms the basis for many contemporary watershed simulation models (for example see Crawford and Linsley, 1966).

However, in recent years it has been increasingly recognised that Horton's concepts are valid in only special circumstances. For example, the results presented in Chapter 3 indicate that in the Torlesse basin, infiltration rates are in excess of all but the most extreme rainfall rates. Hortonian overland flow should thus be confined to exceptional events or very limited impervious areas. Such a conclusion is in line with experience in other humid regions of the world where most infiltration rates have been found to be in excess of rainfall rates.

In such areas it has been suggested that storm runoff can originate from a small but rather consistent part of a catchment. This alternative view of a partial contributing area was first proposed by Hewlett (1961) to explain the "surface" runoff component of a flood hydrograph from catchments in which surface runoff did not occur. In the last 15 years the concept has received a great deal of overseas support and attention.

Overland flow as it is generally known and accepted moves at velocities in the order of 0.05m sec\(^{-1}\) to 0.1m sec\(^{-1}\) (4000m \(\text{day}\)^{-1}). By contrast, water which infiltrates and moves through the soil at 10^{-5} m sec\(^{-1}\) will travel only about 1m day\(^{-1}\) (Hewlett & Nutter, 1970).

The concept of a partial contributing area recognises these differences and ranks the stream channel responses to direct rainfall as more important than has been generally recognised. During a storm, a channel is fed from above by rain and by flow from the adjacent riparian lands. Figure 26 shows a time lapse view to illustrate the expansion of a saturated contributing area during a storm. After the storm, drainage continues and the saturated zone contracts. Eventually, saturated flow is replaced by

Figure 26 follows:
FIGURE 26

A diagrammatic time lapse view of a basin showing expansion of the source area and channel system during a storm (after Hewlett and Nutter, 1970).
slower unsaturated flow. Weyman (1973) found that unsaturated flow was capable of maintaining river flow for months without rainfall. Moreover, it was the decreasing gradient of upslope soil moisture that controlled the area of saturation in subsequent storms.

Although there is now general agreement that storm runoff is generated from relatively small areas of a catchment, there are divergent views as to how water makes its way to a stream channel. For example, in contrast to the saturated through-flow concept developed by Hewlett and Hibbert (1967), Dunne and Black (1970) proposed a concept of return flow, saturated overland flow and direct channel precipitation. Return flow could occur when the ground surface intersects the water table and ground water is forced to emerge as overland flow. Saturated overland flow occurs when water is forced to flow over the surface of the relatively small saturated zone. As a third alternative, Hewlett and Hibbert (1967) have proposed translatory flow in which a pulse of soil water is displaced from the soil by the impact of incoming precipitation. Weyman (1973) proposes yet another process of non-Darcian flow in which water moves rapidly through larger pore spaces, animal burrows and highly permeable subsurface strata (see also Jones, 1971). Freeze (1972) has developed a simulation study that theoretically explains partial area runoff in terms of saturated overland flow and direct channel precipitation.

It is probable that all processes contribute to runoff generation, but the relative importance of each depends on rainfall intensity and duration, and such characteristics as catchment morphology and soils.

Despite divergent views on the processes of flow, there is widespread agreement that in humid regions storm flow can be generated from only part of a catchment. There is also general agreement that this partial contributing area is dynamic in the sense that it may vary throughout a storm and between seasons.

The study reported here is a first attempt to apply the concept to a New Zealand catchment. The proposition to be tested was that the quick flow component of storm hydrographs could be explained in terms of the partial contributing area concept.
Procedures

Twenty nine floods or freshes were selected from the flow records presented in Appendix VI. Floods which had been derived from snow melt were excluded, as were those which originated from long duration storms that produced no quick flow.

Each flood hydrograph was separated into quick flow and delayed flow (Hewlett and Hibbert, 1967) as outlined in Chapter 2. Floods were then grouped into four rainfall classes (Table 10). The hydrologic response of each flood was then calculated by expressing the volume of quick flow as a percentage of the volume of the catchment's flood producing rainfall (Hewlett & Nutter, 1969).

This study adopted the saturated throughflow and direct channel precipitation model of Hewlett and Hibbert (1967) and Freeze (1972). This required some information about water movement rates through soil and scree.

The rates at which water will move through the soils of the catchment are not known. However, as Harvey (1974) had reported values of saturated hydraulic conductivity (k) of $10^{-2}$ cm sec$^{-1}$ to $10^{-5}$ cm sec$^{-1}$ for four variants within the Puketaraki soil set at Dog Range in Central Canterbury, a value of $k = 10^{-3}$ cm sec$^{-1}$ was adopted. For screes and gravel river beds an arbitrary value of $k = 0.1$ cm sec$^{-1}$ was adopted.

The contributing area for storms of less than 25mm and more than 100mm was then estimated, using these assumed k values and the average storm duration. Storm duration was defined as the period from the onset of rain until the end of quick flow. For storms of less than 25mm the average storm duration was 11 hours. During this period rain which soaked into the riverbed and scree deposits was assumed to have moved about 40 metres. Rain which soaked into the soil was assumed to move about 0.5m. For these storms the contributing area was estimated as the perennial stream channel extended 40 metres into scree and gravel deposits and laterally extended into the riparian soils by about 0.5 metres.

For storms in excess of 100mm, storm duration averaged 72 hours. Using the Table 10 follows
TABLE 10

Storm characteristics for 29 floods

Torlesse Stream Catchment
1972 - 1975
<table>
<thead>
<tr>
<th>Date</th>
<th>Precipitation (m.m.)</th>
<th>Peak Discharge (m3/sec)</th>
<th>Quick Flow (m.m.)</th>
<th>Storm Duration (hrs)</th>
<th>Hydrologic Response (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>29.5.73</td>
<td>14.0</td>
<td>0.24</td>
<td>0.22</td>
<td>12</td>
<td>1.6</td>
</tr>
<tr>
<td>4.6.73</td>
<td>21.5</td>
<td>0.24</td>
<td>0.14</td>
<td>10</td>
<td>0.7</td>
</tr>
<tr>
<td>26.6.73</td>
<td>20.3</td>
<td>0.15</td>
<td>0.20</td>
<td>17</td>
<td>1.0</td>
</tr>
<tr>
<td>21.11.73</td>
<td>12.0</td>
<td>0.19</td>
<td>0.11</td>
<td>13</td>
<td>1.0</td>
</tr>
<tr>
<td>16.1.74</td>
<td>24.0</td>
<td>0.18</td>
<td>0.10</td>
<td>16</td>
<td>0.4</td>
</tr>
<tr>
<td>6.8.74</td>
<td>17.0</td>
<td>0.19</td>
<td>0.10</td>
<td>10</td>
<td>0.6</td>
</tr>
<tr>
<td>18.9.74</td>
<td>12.0</td>
<td>0.18</td>
<td>0.05</td>
<td>13</td>
<td>0.4</td>
</tr>
<tr>
<td>19.9.74</td>
<td>18.0</td>
<td>0.22</td>
<td>0.10</td>
<td>17</td>
<td>0.6</td>
</tr>
<tr>
<td>24.2.75</td>
<td>26.0</td>
<td>0.25</td>
<td>0.30</td>
<td>10</td>
<td>1.0</td>
</tr>
<tr>
<td>7.4.75</td>
<td>26.5</td>
<td>0.35</td>
<td>0.30</td>
<td>11</td>
<td>1.1</td>
</tr>
<tr>
<td>19.5.75</td>
<td>15.5</td>
<td>0.39</td>
<td>0.23</td>
<td>11</td>
<td>1.5</td>
</tr>
<tr>
<td>2.11.75</td>
<td>22.5</td>
<td>0.48</td>
<td>0.36</td>
<td>7</td>
<td>1.6</td>
</tr>
<tr>
<td>26.11.75</td>
<td>21.0</td>
<td>0.24</td>
<td>0.10</td>
<td>11</td>
<td>0.5</td>
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<tr>
<td>23.1.76</td>
<td>16.0</td>
<td>0.20</td>
<td>0.06</td>
<td>10</td>
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</tr>
<tr>
<td>23.11.76</td>
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<td>0.26</td>
<td>0.17</td>
<td>8</td>
<td>1.3</td>
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</table>

**Mean and Standard Deviation**

<table>
<thead>
<tr>
<th>Date</th>
<th>Precipitation (m.m.)</th>
<th>Peak Discharge (m3/sec)</th>
<th>Quick Flow (m.m.)</th>
<th>Storm Duration (hrs)</th>
<th>Hydrologic Response (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
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<td>0.17</td>
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<table>
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<th>Peak Discharge (m3/sec)</th>
<th>Quick Flow (m.m.)</th>
<th>Storm Duration (hrs)</th>
<th>Hydrologic Response (%)</th>
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</thead>
<tbody>
<tr>
<td>23.10.73</td>
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<td>0.9</td>
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<td>2.5</td>
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<tr>
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<td>0.3</td>
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<td>0.8</td>
</tr>
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<td>0.5</td>
<td>16</td>
<td>1.5</td>
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<tr>
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<td>0.9</td>
<td>17</td>
<td>2.5</td>
</tr>
<tr>
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<td>0.32</td>
<td>0.7</td>
<td>12</td>
<td>1.9</td>
</tr>
<tr>
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<td>43.0</td>
<td>0.48</td>
<td>0.7</td>
<td>12</td>
<td>1.7</td>
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**Mean and Standard Deviation**

<table>
<thead>
<tr>
<th>Date</th>
<th>Precipitation (m.m.)</th>
<th>Peak Discharge (m3/sec)</th>
<th>Quick Flow (m.m.)</th>
<th>Storm Duration (hrs)</th>
<th>Hydrologic Response (%)</th>
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<tr>
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<th>Date</th>
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<th>Peak Discharge (m3/sec)</th>
<th>Quick Flow (m.m.)</th>
<th>Storm Duration (hrs)</th>
<th>Hydrologic Response (%)</th>
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**Mean and Standard Deviation**

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<th>Quick Flow (m.m.)</th>
<th>Storm Duration (hrs)</th>
<th>Hydrologic Response (%)</th>
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<table>
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<th>Peak Discharge (m3/sec)</th>
<th>Quick Flow (m.m.)</th>
<th>Storm Duration (hrs)</th>
<th>Hydrologic Response (%)</th>
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<td>47</td>
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<td>183</td>
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<td>49.0</td>
<td>78</td>
<td>27.0</td>
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**Mean and Standard Deviation**

<table>
<thead>
<tr>
<th>Date</th>
<th>Precipitation (m.m.)</th>
<th>Peak Discharge (m3/sec)</th>
<th>Quick Flow (m.m.)</th>
<th>Storm Duration (hrs)</th>
<th>Hydrologic Response (%)</th>
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<td>72</td>
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<td>0.70</td>
<td>21.1</td>
<td>25.7</td>
<td>11.9</td>
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</table>
same procedure, the contributing area was assessed as the stream channels extended 250 metres into scree and gravel deposits and 2.5 metres into riparian soils.

Results

Table 10 shows the mean hydrologic response for storms of less than 25mm to be about 1%. Figure 27 showed the assessed contributing area for these storms. This area represents about 2% of the catchment. For storms between 25mm and 50mm the mean hydrologic response and estimated contributing area were both about 2%.

For storms in excess of 100mm the mean hydrologic response was 21% (Table 15). The estimated contributing area (Figure 28) represents 14% of the catchment.

Discussion

The estimates of hydrologic response show fair agreement with the assumed contributing area and give support to the concept of a partial contributing area. They do not, however, constitute a proof of its existence.

The saturated throughflow and channel precipitation model is known to be an oversimplified approach. Results presented in Chapter 4 demonstrate the existence of return flow and Figure 29 shows non-Darcian flow through scree and terrace deposits. Further, alterations to the assumed value of $k$ make major changes in the size of the contributing area. For example, if the assumed value of $k = 0.1 \text{ cm sec}^{-1}$ for scree deposits was replaced by a value of $1.0 \text{ cm sec}^{-1}$, the channel extension would be increased from 250m to 2500m for a 72 hour storm.

A further complication is that hydraulic conductivity values apply to a porous medium in a saturated condition. Velocities are known to be reduced in unsaturated conditions.

The agreement between hydrologic response and assumed contributing area is best for storms of less than 50mm. For storms in excess of 100mm the agreement between mean values is only fair and for some storms it is extremely poor.

Figures 27, 28 & 29 follow
FIGURE 27

Storm flow hydrograph, hyetograph and estimated contributing area for storms of less than 25 mm precipitation, Torlesse Stream Catchment.
FIGURE 28

Storm flow hydrograph, hyetograph and estimated contributing area for storms of more than 100 mm precipitation, Torlesse Stream Catchment.
FIGURE 29

Non-Darcian flow through terrace gravels.
In a recent study Pearce and McKerchar (1978) re-analysed the data presented here and compared the hydrologic responses with those derived from rainfall runoff records from nine other New Zealand locations. They have suggested that the methods of analysis used in this study underestimate the volume of quick flow because:

(a) No allowance has been made in this study for interception. (Pearce and McKerchar suggest that, because of interception, only 90% of gross precipitation is potentially available for stream flow).

(b) The hydrograph separation method extrapolated a master recession curve back to a point beneath the hydrograph peak, rather than the point of inflection on the recession limb.

The combination of these two factors means that the hydrologic response of storms in excess of 50mm might be 50 - 70% of those calculated by Pearce and McKerchar. They suggest that for storms in excess of 100mm precipitation the contributing area should be in the order of 40% rather than the 20% - 30% estimated here.

Despite these difficulties, results presented here show generally good similarity to those of Pearce and McKerchar, particularly for the larger events.

The variability in hydrologic response of large storms needs further study and it is probable that antecedent conditions are a dominant factor. Field observations further suggest that the antecedent condition of stream bed gravels may have a significant influence on hydrologic response. Groundwater wells installed in the active stream bed in March 1977 have shown that streams can flow over unsaturated gravels. The recharge of this unsaturated zone may be a first demand on water which would otherwise generate quick flow. For example, the low hydrologic response from the storm of 20.1.75 (Table 10) may be due to the first requirement of quick flow to recharge stream bed gravel storage.

Despite the many uncertainties inherent in this study, it does lend support to the concept of a partial contributing area. This concept is a reasonable
explanation of the origin of the "surface runoff" component of the hydrograph in the absence of surface runoff from the catchment. This study also demonstrates the importance of the near channel in the production of storm runoff.
CHAPTER 6

THE WATER YIELD STUDY
In the United States water yield has been one of the most frequently researched topics of land use hydrology. Notwithstanding confusing and conflicting results, water yield has been proposed as an objective for mountain land management in New Zealand.

A catchment water balance model is applied to five periods of Torlesse catchment rainfall and stream flow, to show that 80% - 90% of precipitation is returned as water yield. It is difficult to conceive of any management practice which could significantly affect such yields.

Some North American studies are reviewed and it is found that management influences on water yield have been recorded when 10% - 60% of precipitation is yielded as stream flow.

A pilot study of water yields from three other South Island catchments confirms the view that management for water yield might be more realistic in some drier hill country catchments than in areas similar to the Torlesse stream catchment.
INTRODUCTION

Despite the caution expressed by Holloway (1969) and others, water yield has been advocated as an objective for management of mountain lands (see for example Mark & Rowley 1969, Cuff 1977). The proposition has been that an alteration in the type and/or extent of plant cover will have an effect on the volume of water yielded by the catchment. This proposition derives from much experience in the United States and a few New Zealand studies which have shown that larger native tussocks intercept and supply more water to the soil than does either shorter vegetation or depleted surfaces (Rowley 1970, Mark & Rowley 1969).

Water yield refers to the long term volume of runoff, frequently expressed as annual yield. Low flow refers to the low flow rate during a specific period of time. These terms are frequently used synonymously but they refer to hydrologically distinct characteristics. Techniques which seek to manipulate low flow rates may also involve management for water yield but a clear distinction must be made between the two phenomena.

This discussion refers to water yield.

It is probable that water yield has been the single most frequently researched topic in the last 50 years of small watershed research. From his review of thirty-nine predominantly North American forest treatment studies, Hibbert (1965) concluded that:

1. Reduction of forest cover increases water yield.
2. Establishment of forest cover on sparsely vegetated land decreases water yield.
3. Response to treatment is highly variable and, for the most part, unpredictable.

In contrast to Hibbert's conclusions several Soviet authors have reported increases in water yield with increases in forest cover (Molchanov 1960). Although these conflicting generalisations can be adequately reconciled.
when individual studies are considered in the context of their geographic setting and precipitation form, they serve to illustrate the limitations of generalisations.

This study considers the hydrology of the Torlesse catchment from a water yield point of view. The proposition to be tested was that an a priori case could be established for including water yield as an objective of catchment management.

Procedures

This study is based on a solution to the water balance equation

\[ P = Q + E + \Delta S \]

where
\[ P = \text{precipitation} \]
\[ Q = \text{stream flow} \]
\[ E = \text{evapotranspiration} \]
\[ S = \text{soil moisture} \]

There are many methods of estimating evapotranspiration (Veihmeyer 1964), but a solution based on rewriting the water balance equation \( E = P - Q + \Delta S \), has the advantage of integrating all the spatial variations in evaporation over a catchment without the need to know details of these variations. However, while the concept is simple the need for accurate observations makes it a difficult method to use in most situations. Short term estimates are impossible. Longer term estimates can be made if the term \( \Delta S \) can be eliminated by considering periods between conditions of total soil saturation. In this manner evapotranspiration is treated as a residual in the equation \( E = P - Q \).

The data used in this study are derived from that presented in Appendices I and III (Vol III).

Results

Table 11 shows the values for precipitation, streamflow and the residual

Table 11 follows
<table>
<thead>
<tr>
<th>Period</th>
<th>Precipitation (mm)</th>
<th>Stream flow yield (mm)</th>
<th>&quot;Evapotranspiration&quot;</th>
<th>Estimated annual &quot;Evapotranspiration&quot;</th>
<th>% of Precipitation appearing as water yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>11. 8.73 to 20. 3.74</td>
<td>802</td>
<td>661</td>
<td>141</td>
<td>145</td>
<td>82</td>
</tr>
<tr>
<td>20. 3.74 to 14. 3.75</td>
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<td>1612</td>
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<td>135</td>
<td>92</td>
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<td>4730</td>
<td>602</td>
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<td>89</td>
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<td>3573</td>
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<tr>
<td>26. 6.74 to 30.11.76</td>
<td>4058</td>
<td>3602</td>
<td>456</td>
<td>188</td>
<td>89</td>
</tr>
</tbody>
</table>

Table 11

Precipitation, water yield and estimated evapotranspiration for five periods from Torlesse Stream Catchment.
term "E" for five periods between 1973 and 1976. It shows that between 82% and 92% of precipitation was delivered to the stream as water yield.

Table 12 shows that annual potential evapotranspiration rates at Nursery Hill (Craigieburn Range) are in the order of 250 mm - 350 mm.

**Discussion**

The estimates of "evapotranspiration" include all errors of measurement and calculation. For example, the stream flow terms refers only to surface flow (Chapter 2) and the precipitation data are derived from only one site (Chapter 1). Therefore it is possible that these results may be conservative. Further, results for shorter periods may be less reliable than those for longer periods.

One fundamental assumption in solving the water balance equation is that by taking the period between times of total saturation the soil moisture term can be neglected. However, it is doubtful that the Torlesse basin with its steep slopes, free draining soils and deep scree deposits can ever be "saturated". Errors due to variations in soil moisture are proportionally more important to shorter periods than to longer ones. Because of these uncertainties the derived values of evapotranspiration and water yield should be considered as indices rather than as absolute values.

Nevertheless, the five periods show close agreement and the estimated values of evapotranspiration are realistic when compared against estimated potential evapotranspiration from a similar environment (Table 12). This implies that the estimates that 80% to 90% of precipitation was returned as water yield are also realistic.

This finding raises a first important point. The impact of vegetation management on water yield has been most actively studied in the United States. The environments in which those studies have been made are markedly different from the Torlesse basin. Table 13 has been compiled.
<table>
<thead>
<tr>
<th></th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>April</th>
<th>May</th>
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<td>25</td>
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</table>

F = frozen

**TABLE 12**

Maximum, minimum and mean values for potential evapotranspiration (mm) at Nursery Hill, Craigieburn Range.

TABLE 13

Mean annual precipitation, mean annual stream flow and percentage of precipitation returned as water yield for some United States Experimental Watersheds.
(Source: A.R. Hibbert, 1965).

<table>
<thead>
<tr>
<th>Watershed</th>
<th>Mean Annual Precipitation</th>
<th>Mean Annual Stream Flow</th>
<th>Water Yield Percentage</th>
</tr>
</thead>
<tbody>
<tr>
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(Continues in the next page...)
<table>
<thead>
<tr>
<th>CATCHMENT</th>
<th>Mean Annual Precipitation</th>
<th>Mean Annual Stream Flow</th>
<th>Stream Flow Precipitation %</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>mm</td>
<td>mm</td>
<td>%</td>
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<tr>
<td>Coweeta, North Carolina</td>
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<tr>
<td>13</td>
<td>1829</td>
<td>792</td>
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<td>17</td>
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<td>775</td>
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<td>1285</td>
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<td>1946</td>
<td>1052</td>
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<td>1821</td>
<td>831</td>
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<td>28</td>
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<td>1532</td>
<td>67</td>
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<td>1524</td>
<td>584</td>
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<td>635</td>
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<td>7</td>
<td>1469</td>
<td>788</td>
<td>54</td>
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<td>H.J. Andrews, Oregon</td>
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<td>57</td>
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<tr>
<td>3</td>
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<td>1346</td>
<td>56</td>
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<tr>
<td>San Dimas, California</td>
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<td></td>
<td></td>
</tr>
<tr>
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<td>648</td>
<td>64</td>
<td>10</td>
</tr>
<tr>
<td>Sierra Ancha Arizona</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>North Fork Workman Creek</td>
<td>813</td>
<td>86</td>
<td>11</td>
</tr>
<tr>
<td>South Fork Workman Creek</td>
<td>813</td>
<td>87</td>
<td>11</td>
</tr>
<tr>
<td>Frazer Colorado</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Fool Creek</td>
<td>762</td>
<td>283</td>
<td>37</td>
</tr>
<tr>
<td>Wagon Wheel Gap, Colorado</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>536</td>
<td>157</td>
<td>29</td>
</tr>
<tr>
<td>Coshocton, Ohio</td>
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<tr>
<td>172</td>
<td>970</td>
<td>300</td>
<td>31</td>
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<tr>
<td>Western Tennessee</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Pine Tree Branch</td>
<td>1230</td>
<td>255</td>
<td>21</td>
</tr>
<tr>
<td>Eastern Tennessee</td>
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<tr>
<td>White Hollow</td>
<td>1184</td>
<td>460</td>
<td>39</td>
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Table 13 contd.

<table>
<thead>
<tr>
<th>CATCHMENT</th>
<th>Mean Annual Precipitation</th>
<th>Mean Annual Stream Flow</th>
<th>Stream Flow Precipitation %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central New York</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sage Brook</td>
<td>974</td>
<td>535</td>
<td>55</td>
</tr>
<tr>
<td>Cold Spring Brook</td>
<td>1030</td>
<td>616</td>
<td>60</td>
</tr>
<tr>
<td>Shackham Brook</td>
<td>1030</td>
<td>627</td>
<td>61</td>
</tr>
<tr>
<td>Adirondacks, New York</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sacandaga River</td>
<td>1143</td>
<td>770</td>
<td>67</td>
</tr>
<tr>
<td>South Western Washington</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Naselle River</td>
<td>3300</td>
<td>2690</td>
<td>82</td>
</tr>
</tbody>
</table>
from information presented by Hibbert (1965) and indicates that for 31 United States experimental catchments water yield was only 10% - 60% of catchment precipitation. The notable exception was the Naselle River (Washington) where 80% of precipitation was returned as stream flow. It is also significant that in that basin no change in runoff could be detected in response to logging. In a multiple regression analysis of data from Californian catchments, Anderson (1975) concluded that regions with annual precipitation in the order of 1640mm were those in which water saving management could be most effectively practised. While many New Zealand catchments (including Torlesse) are within such a zone it is important to note that Anderson's analyses estimate annual stream flows to be 980mm or 60% of annual precipitation. One essential difference between the North American experience and that reported here is that some 90% of the precipitation into the Torlesse stream catchment is returned as stream flow.

The opportunities for water yield management were further considered by a pilot study which estimated a water balance for three catchments for which rainfall and runoff records were available (Ministry of Works and Development Filed Data List). Because of the confusing influence of snow on the storage term, only summer rainfall and runoff was considered. (The Jollie catchment in the Southern Alps was originally included but rejected because of uncertainties associated with snow fall). The following yields were obtained:-

Ahuriri (566 km$^2$) 1964 - 1976 96% summer yield
Reynolds (Banks Peninsula) 3.2 km$^2$, 1968 - 1976 42% summer yield
Kaituna (Marlborough) 17.6 km$^2$, 1971 - 1976 52% summer yield

From this pilot study, from the analyses of Torlesse records and from an interpretation of United States experience, it is suggested that management for water yield is less realistic in some mountain catchments than in some drier hill country catchments.
A comparison of the two periods 11 August 1973 to 30 March 1974 and 20 March 1974 to 14 March 1975 shows that although evapotranspiration estimates show close agreement, precipitation in the first period was only about one half of that for the second period. Assuming that these estimates are reliable, they suggest that this catchment's losses from evapotranspiration may be more dependent on evaporation and less dependent on transpiration than in other areas. It is also possible that these losses may be generated from a small portion of the catchment. It is well known that in semi-arid regions major evapotranspiration losses occur from riparian zones where water is freely available (Campbell, 1970; Horton, 1974). It is conceivable that in the free draining soils and gravels of the Torlesse basin the major evapotranspiration losses occur only from damper riparian sites.

The results from this study make it difficult to conceive of any management which could significantly affect water yield from this catchment. This conclusion is at odds with that of Mark and Rowley (1969). It should be noted however that Mark and Rowley based their conclusion on evidence obtained at a point on their catchment's surface. They then assumed that it was valid to infer catchment responses from behaviour at that point. In view of the known complexity of hydrologic processes which operate between a point on a catchment and its stream outlet (Sharp et al, 1959), the validity of Mark and Rowley's conclusion can be called to question. That tall plants can intercept fog and light rain and thereby provide additional water to the soil is not in question. It is the fate of that water about which there is uncertainty. For example, it is possible that surplus water at a point may be transpired by downslope plants as the water makes its way to the stream channel.

These results also illustrate the fundamental but often neglected proposition that water yield is largely dependent on precipitation 'The changing volume of water which (rivers) carry is accountable first of all by variations in precipitation...' (Molchanov, 1960). Even if it were possible to modify
water yield by vegetation management, variations in rainfall (Chapter 1) would mask these affects.

This study has failed to confirm the proposition that water yield is a realistic objective for land management in this basin.
CHAPTER 7

THE VORTEX TUBE SEDIMENT TRAP
SUMMARY

Methods of bed load measurement are reviewed. The Torlesse vortex tube sediment trap is described and its performance is reviewed.

The device is more successful in small and moderate sized storms, in which it gave reliable information about sediment yields and transport rates.
INTRODUCTION

Each year the world's rivers deliver $15 \times 10^9 - 20 \times 10^9$ tonnes of sediment to the oceans and in so doing play an important part in landscape evolution (Holeman (1968), Sundborg (1973)). But societies, like landscapes, are also dynamic and in response to changing needs build structures on or close to rivers for power generation, communications, flood control, water abstraction, etc. Sediment tends to be recognised only when it becomes a problem, for example by impairing the effectiveness of a structure. Alternatively the demand for river sediments for construction and development may exceed their supply. In both cases information is needed about yield and supply rates of river sediments.

Prior to 1925 there were only a few isolated sediment measurements anywhere in the world. It is only within the last few decades that procedures for sediment measurement have been seriously considered. In lowland rivers, total sediment yields have been assessed either by direct measurement, by sampling, by estimating equations, or by correlation with suspended sediment measurements. (Total sediment yield is usually regarded as bed load yield plus suspended load yield.)

**Direct Measurement**

The simplest method of estimating sediment yields and mean transport rates is to trap material in a dam and periodically resurvey the change in volume of stored detritus, making allowances for variable trap efficiency. In this manner Thomson *(pers comm)* has estimated the rate of sediment accumulation in Lake Roxbrough (Central Otago) at 330 tonnes per square kilometer of catchment. However, because surveys are limited to dam sites, and cannot provide information about relations between solid and fluid flows, a variety of alternative methods have been developed for the direct measurement of sediments.

**Sampling**

Instruments which provide a continuous record of bed load transport rates are permanently located and can provide information for only that site. Studies which seek information from various sections of one or more rivers use a
basket, pan or pressure difference sampling device. Bed load sampling is fraught with problems and much effort has been directed to improving sampler design and performance (see for example Inter-agency Committee, 1964).

In the United States suspended sediments form the bulk of sediment yield. With sponsorship from several federal agencies a variety of suspended sediment samplers have been developed. The USDH48 depth integrating sampler is one such device (Federal Inter-agency Committee, 1948). In Europe, greater attention has been paid to bed load measurement and a variety of pans, baskets, trays and boxes have been developed. The Swiss Federal Authority Sampler (1939) is an example of one such device.

The ideal bed load sampler makes secure contact with the bed and recovers an unbiased sample of bed sediment discharge. A first major problem is that the instrument can alter flow conditions in the sample zone and so bias the estimate of discharge. A second problem can be that as the sampler is lowered into the stream it passes first through a surface zone of higher velocity and moves into a zone of lower velocity near the stream bed. As the down stream force is reduced, the sampler may tend to move up stream and dive into the bed. The sediment it scoops up may not be in motion. A third problem is that alluvial stream beds are dynamic and irregular with consequent temporal and spatial variations in the rates of bed load movement. Short period sampling introduces uncertainty as to the representativeness of the sample. Long period sampling produces large quantities of sediment and the possibility that flow conditions alter during the sample period.

An Inter-agency subcommittee on sedimentation (1964) concluded that basket or box samplers are best suited for coarse gravel measurements in mountain streams. However, as these may have hydraulic efficiencies of 30% - 50% (Nanson, 1974) the information they provide should be used with care. Pan type samplers, for example the Poliakov sampler, are best suited to relatively smooth sand bed rivers with relatively low rates of bed load discharge (Da Chuna, 1968).

Although there are a variety of pressure-difference samplers, the Helley-Smith (1971) bed load sampler appears to offer promise as a versatile
instrument suited to a wide range of flow and sediment conditions.

In small catchments, sediment yields have been sampled at permanent installations using multislot divisors (Geib, 1933), splitters (Brown et al., 1970), the Coshocton wheel (Parsons, 1955), or sharp-edged slot samplers (Barnes & Fraevet, 1954). Leopold & Emmett (1976) have described an ambitious programme to assess bed load sediments from a large catchment (180 square miles, 470 square kilometres), using a 48 foot (14.6m) gated slot across the river bed. This slot was fitted with an endless belt to remove sediment to a sump on the river bank.

In addition to the procedures and techniques reviewed here there have been attempts to develop devices using acoustic, nuclear and tracing principles (Gregory & Walling, 1973). Although all methods have been found to be more or less satisfactory for a particular place and set of flow conditions, there is still:

"no single apparatus or procedure, whether theoretical or empirical which has been universally accepted as completely adequate for the determination of bed load discharge". (Hubbell, 1964)

Estimating Equations

The general approach of estimating equations has been to assume that the stream transports a capacity sediment load and that this is related to bed shear stress. If the size of the bed material, the bed shear stress, and the critical shear stress required to initiate movement are known, then a rate of bed load transport can be calculated. Unfortunately, results from various formulae are often drastically different. In consequence, formulae should be regarded as guides for planning and design. Those who need to use bed load formulae for estimating sediment yields in lowland rivers can refer to a number of critical reviews. (See for example American Society Civil Engineers,(1971), Graf (1971), Herbertson (1969), Shepherd (1963) and White et al. (1973)). A limitation to the use of these formulae for New Zealand lowland gravel rivers is that a majority have been developed for sand and silt bed systems. Bagnold (1966) is the only author who has attempted to describe a bed load transport equation without recourse to experimentally derived coefficients. His approach was to show bed load transport as a function of the rate of stream power expenditure.
Correlation with Suspended Sediments

Estimates of suspended sediments are in general more reliable than estimates of bed load, and easier to obtain. If a sediment rating curve can be established (flow rate vs sediment concentrations) information about total suspended sediment yields can be derived from information about stream flows. To estimate total sediments it is often assumed that bed load is a fixed percentage of suspended load. Although this may vary from 2% to 20% (Gregory & Walling, 1973), a figure of 10% is frequently adopted (Maddock & Borland, 1951).

Vortex Tube Sediment Traps

Vortex tubes have been used for many years to eject unwanted sand and silt from irrigation canals and ditches in several parts of the world. In the United States their use was pioneered by Parshall (1933) and Rowher et al (1933) and their hydraulic behaviour has been tested by Robinson (1962). Their use for measuring bed load transport rates in a cobble-bottomed stream in Oregon has been described by Klingerman and Milhous (1970).

Figure 30 shows a vortex tube trap which is simply a tube open along the top and placed in the bed of a controlled section of stream channel at an angle to the direction of flow. Movement of water across the opening sets up a vortex pattern within the tube. The vortex has a component along the tube towards the downstream end, which can be opened to allow discharge into a work-pit area adjacent to the stream. Sediment moving on the stream bed drops or is drawn into the tube and is trapped. It is carried to the downstream outlet and discharged into the work-pit whenever the gate is opened.

Although vortex tube traps are confined to one site they have a number of advantages. They provide continuous records and avoid problems of sampling; they are simple of design and construction and have no moving parts; and they provide information about relations between solid and fluid flows.

By emptying the trap at regular intervals during a storm, a rate measurement can be obtained. This represents a significant advance on methods, which either sample (in lieu of a total measurement) or simply measure total yield for a storm.

Figure 30 follows
FIGURE 30

A vortex tube sediment trap
Design and Construction of the Torlesse Trap

The Torlesse Stream leaves its catchment through a well defined opening approximately 7 m wide between a large rock outcrop and a steep bank (Figure 9, Chapter 2). The outcrop provided an excellent foundation on which to anchor the control structure. At the time the trap was designed there was little hydraulic, hydrological or sediment information available for the Torlesse Stream catchment. The control structure was therefore designed to relate as closely as possible to the upstream and downstream channel. A longitudinal slope of approximately 1:15 persisted for a distance of 200 m upstream and for low to medium flows the stream had a width of less than 4 m.

To determine a suitable flume width, stage-discharge curves for four stream cross sections near the flume site were estimated by assuming a Manning's $n$ of 0.055. These curves are plotted in Figure 31, which shows that for a 3 m-wide section there should be little difference between the stage-discharge relationship of the control section and that of the adjacent channel for flows up to $6 \text{m}^3\text{sec}^{-1}$.

Velocities through the section would be largely controlled by the upstream flow conditions, viz a steep rough channel. To compensate in part for the large drop in roughness, the control section was designed to have a slope of 1:220, the value obtained by use of the Manning equation. A section length of 8 m was adopted.

As a safety feature, the true right-hand wall of the section was built 0.91 m high, with its top edge 0.2 m lower than the left-hand wall. At very high flows (approximately $9 \text{m}^3\text{sec}^{-1}$) this would act as a side spillway and prevent flooding of the work area behind the left wall. A slope of 1:40 was incorporated across the section to improve the measurement of low flows by confining them to the left-hand wall. (Subsequent experience showed that because of upstream sediment aggradation the side spillway could overflow at about $2.5 \text{m}^3\text{sec}^{-1}$.)

Results from Klingerman and Milhous's (1970) experience were not to hand at the design stage, so the vortex tubes were designed following Robinson's (1962) criteria. These are set out in Table 14.

Figure 31, Table 14 follow
FIGURE 31

Relations between stage height and discharge for control section and upstream channel.
Height of side spillway

- 21 m downstream
- 18 m upstream
- 33 m upstream
- 63 m upstream
- 3 m control section
<table>
<thead>
<tr>
<th>Robinson's criteria</th>
<th>Torlesse trap</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Width of tube opening - between 15 and 30 cm</td>
<td>27 cm</td>
</tr>
<tr>
<td>(2) Tube angle - 45° to flow</td>
<td>45°</td>
</tr>
<tr>
<td>(3) Tube length less than 4.5 m</td>
<td>4.24 m</td>
</tr>
<tr>
<td>(4) Tube length/width of opening should not exceed 20</td>
<td>15.7</td>
</tr>
</tbody>
</table>

TABLE 14

Vortex tube design criteria
Robinson suggested (i) that the shape of the tube was not particularly important provided that material entering the tube is not allowed to escape back into the channel, (ii) that constant-section channels are as effective as tapered ones, and (iii) that the elevation of the upstream and downstream lips can be the same.

To ease construction, a length of 0.3m diameter steel pipe with the top removed to give an 0.27m opening was selected to form the tube. This opening was thought large enough to trap the larger sizes of bed load, and the tube shape would inhibit any tendency for trapped material to be returned to the flow.

Laboratory Testing

To test the performance of the proposed vortex tube, a 0.6m wide section was built and tested in the Fluid Mechanics Laboratory at the University of Canterbury. A floor 8m long and 0.6m wide was placed in a 1.1m wide flume. The vortex tube was set into this floor at 45° to the flow direction and 5m from the upstream end (Figure 32).

Two tube shapes were tested. The first was the 0.3m diameter semi-circular shape described above. The second had a square cross-section with 0.25m sides. The upstream and downstream lips were at the same level and flush with the floor. The tubes extended through the side wall of the structure and could be either blocked off or allowed to discharge into the flume. Discharges were measured using one of the laboratory's calibrated pits, and flow depths were determined with point gauges.

Sediment was introduced approximately 3m upstream of the vortex tube by hand pouring from a weighing tray. This formed a small bar across the flow which was subsequently eroded over periods of up to 15 minutes. During this time the behaviour of the tubes could be observed and, when all the sediment had moved through the flume, their trapping efficiency determined.

A variety of sediment sizes was tested under a wide range of flows. Table 15 shows some typical results. They are from a series of tests using the semi-circular tube to recover three size ranges of material. For each test in

Figure 32, Table 15 follow
Laboratory model of vortex tube. Sediment introduced by hand can be seen moving along the floor of the model towards the vortex tube at the bottom of the photograph.
<table>
<thead>
<tr>
<th>Sediment size (mm)</th>
<th>Water velocity m sec(^{-1})</th>
<th>Water depth (m)</th>
<th>Froude No.</th>
<th>Prototype discharge m(^3) sec(^{-1})</th>
<th>Percentage retained</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;9.5</td>
<td>0.91</td>
<td>0.10</td>
<td>0.92</td>
<td>0.278</td>
<td>98.5</td>
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<tr>
<td>&lt;9.5</td>
<td>1.04</td>
<td>0.18</td>
<td>0.78</td>
<td>0.555</td>
<td>23.4</td>
</tr>
<tr>
<td>&lt;9.5</td>
<td>1.13</td>
<td>0.25</td>
<td>0.72</td>
<td>0.834</td>
<td>3.7</td>
</tr>
<tr>
<td>9.5 - 19.0</td>
<td>1.07</td>
<td>0.18</td>
<td>0.81</td>
<td>0.555</td>
<td>98.5</td>
</tr>
<tr>
<td>9.5 - 19.0</td>
<td>1.13</td>
<td>0.25</td>
<td>0.72</td>
<td>0.834</td>
<td>96.9</td>
</tr>
<tr>
<td>9.5 - 19.0</td>
<td>1.19</td>
<td>0.32</td>
<td>0.67</td>
<td>1.110</td>
<td>25.6</td>
</tr>
<tr>
<td>19.0 - 38.0</td>
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<td>0.24</td>
<td>0.76</td>
<td>0.834</td>
<td>100.0</td>
</tr>
<tr>
<td>19.0 - 38.0</td>
<td>1.22</td>
<td>0.31</td>
<td>0.71</td>
<td>1.110</td>
<td>89.0</td>
</tr>
</tbody>
</table>

**TABLE 15**

Laboratory tests with semi-circular vortex tube.
Table 15 the tube outlet was closed and a 9.1kg sample was introduced upstream.

The results indicate that trapping efficiencies of 90 per cent and above can be obtained. The efficiency is reduced markedly for the finer sizes, particularly at the higher discharges. Part of the loss can be attributed to material passing right over the tube. However, the larger portion is caused by the strong induced vortex in the tube, which was observed to throw trapped material back into the main flow downstream of the trap. Tests with the square-section tube showed greater trapping efficiencies, with material being able to remain in the corners where the vortex flow is not so effective.

With the tube outlets open, very much higher efficiencies were obtained for the finer materials. In this case the sediment was sluiced from the tube as rapidly as it was deposited, giving little time for any to be ejected by the vortex flow. Sluicing through the outlet was not as effective with the square tube.

Three main points emerged from the laboratory tests:

1. When the trap is functioning, tube outlets should be open and the sediment removed continuously.

2. The trap should consist of two parallel tubes so that sediment which escapes from the first tube of semi-circular section may become trapped in the second, which should be of square section.

3. A design based on Robinson's criteria would be satisfactory, at least for the tested range of flows, viz up to 1.10m$^3$sec$^{-1}$.

Accordingly, two tubes 0.5m apart were incorporated into the control structure. They protruded through the left-hand wall and discharged into a concrete-floored work pit. A vertically sliding plate (miner's gate) was provided at the end of each tube. This gate has the advantage, essential in determining sediment rates, of being easily and quickly opened or shut regardless of the water and sediment flow.

Facilities designed adjacent to the structure included the work pit, a
monorail and hoist, extensive wingwalls upstream to ensure that the structure would not be bypassed, and a protective apron downstream to prevent scour or undermining. The structure is shown in Figure 33. The vortex tubes can be seen discharging into the work pit in Figure 34.

The structure was built by staff of the Tussock Grasslands and Mountain Lands Institute from January to May 1972. The 60 tonnes of concrete used in the reinforced control section was mixed on site using screened gravels from the river bed (Figure 35).

**Operating Procedures**

At streamflows up to approximately $0.10\text{m}^3\text{sec}^{-1}$ the entire flow is diverted through the first vortex tube. With increasing flows the intensity of the vortex is increased and the proportion of diverted streamflow is reduced. The vortex has always been strong enough to carry the bed load associated with the particular flow from the stream through the wall of the control section and into the work pit.

The vortex tubes discharge into a steel-mesh basket lined with an hydraulic filter cloth which will retain all sediment sizes down to fine sands. Each time the basket is filled it is removed, using the monorail and hoist, and weighed (Figure 36). Material not retained for size analysis is then moved down the monorail and returned to the stream below the control structure.

For transport rates up to 2000kg/hour all the sediment can be trapped, weighed and returned to the stream. The tube gate is open while the basket is being filled (5-20 minutes), and is closed while the basket is removed for weighing (2-3 minutes). During this latter time some material may be lost from the tube by being thrown back into the flow, but at low flows this is certainly a minimal amount.

Rates in excess of 2000kg/hour can only be handled by a programme of sampling in time. For these higher flow rates it is desirable to keep the tube gate open at all times. To achieve this, a sluice way is fitted beneath the outlet of the vortex tube (Figure 37). The sluice way carries the water and

Figures 33, 34, 35, 36 & 37 follow
FIGURE 33

The Torlesse Stream vortex tube sediment trap and control section.
FIGURE 34

Vortex tube discharging into work pit.
FIGURE 35

FIGURE 36

Sediment weighing
A sluice is filled under the vortex tube to by-pass the work-pit when sediment transport rates exceed 2000kg h$^{-1}$. This is periodically removed and sediment transport rates for short periods is recorded.
gravel across the work pit and discharges it into the stream channel. To make a measurement the outlet is closed, at time zero, the sluice is removed and replaced by the basket, the gate is opened and the sediment collected for a measured time. Typically the gate would be closed for 20-30 seconds and the basket would fill in 1-3 minutes.

Because the bed load transport appears to be an unsteady phenomenon, the periods between samples must be kept to a minimum. With two or three men working it is possible to sample every 10 to 20 minutes for periods up to 30 or 40 hours (Figure 38).

Suspended Sediment Estimation

Suspended sediments were estimated using a DH48 suspended sediment sampler and standard methods of sediment determination (Inter-agency Committee, 1964).

DISCUSSION

The vortex tube trap has proved to be a most satisfactory, if physically demanding, method of estimating bed load movement from this catchment. However, two observations are relevant to others contemplating this method. The first concerns the operating range of the trap. From his investigations of the performance of vortex tubes, Robinson (1962) suggested that the Froude number of flow over the tubes should be in the order of 0.8. However, he also noted that the Froude number had little effect on trapping efficiency at stage heights of less than 1.5 times the width of tube opening. This suggested that the Torlesse trap might be effective up to stage heights of 0.4m. During floods of April 1974 and April 1978, (recurrence interval between 1:5 - 1:20 years) trap efficiencies were observed to be markedly impaired at stage heights greater than 0.30m. It is evident, therefore, that the vortex tube trap can provide valuable information about sediment movement in more frequent events but is less useful in the larger lower-frequency floods.

The second observation concerns the rate at which sediment can be discharged through the vortex tubes. From experience during the study period, sediment Figure 38 follows
FIGURE 38

Night work at the sediment trap.
rates in excess of about \(200\text{kg/min}^{-1}\) either cannot be handled in the work pit or discharged through the vortex tubes. Within the trap's operating range such rates were found only rarely and for very brief periods. However, it will be shown later that the sediment yield from the Torlesse stream is controlled by its supply and that "capacity" loads have not been recorded. From Figure 47 (Chapter 8) it can be inferred that with "capacity" load the trap would be unable to function at flows in excess of about \(0.12\text{m}\) depth. This would suggest that if sediment was freely available to the Torlesse stream, this trap would have been able to monitor sediments from only about \(10\% - 20\%\) of all flood events.

Within the operating range, trapping efficiency is believed to be in excess of \(98\%\). As the semi-circular upstream tube was able to discharge most sediments, the square downstream tube was seldom used. It did, however, provide a valuable guide to the structure's trapping efficiency.
CHAPTER 8

THE SEDIMENT STUDIES
SUMMARY

In the last few decades much information has been presented about sediment transport in flumes and lowland rivers but comparatively little is known about sediments in mountain streams. Because there are obvious differences in stream energy and sediment supply, mountain streams can be expected to behave differently to lowland streams.

Results and experience from mountain streams are reviewed and found to be sometimes confusing and in conflict. Results from 5 years of study in the Torlesse stream catchment are presented as a contribution to a better understanding of mountain stream sediment behaviour.

Although the Torlesse stream catchment is commonly described as 'severely eroded', sediment yields have been found to be amongst the lowest reported values. Suspended sediments are estimated to contribute less than 10% to annual sediment yield. Bed load sediment yields are found to vary greatly between storms and are also found to be more dependent on a supply of sediment than on the transport capacity of stream flow. A downstream 'wave-like' movement of sediments is described.

Conventional bed load prediction equations are found to overestimate sediment yields by up to several orders of magnitude. Bagnold's (1966) concept of stream power and the proportion of stream power utilised in bed load transport is found to show close agreement with measured values.
In the last few decades much information has been provided about stream sediments in lowland rivers. Most of this work has been carried out in silt and sand bed flumes and lowland rivers. In the same period little attention has been paid to mountain streams, where, because of obvious differences in stream energy and sediment supply the pattern of behaviour can be expected to be different.

Mountain Rivers

Results from the comparatively few studies of sediment in mountain streams are sometimes confusing and in conflict. Table 16 presents mean annual sediment rates as estimated from reservoir surveys in a range of New Zealand catchments. These results suggest that the models of Langbein & Schumm (1958) and Fournier (1960) in which sediment yield is regarded as a function of climate are inadequate for New Zealand's steep and mountain lands. Likewise the models of Strakov (1967) (sediment as a function of relief) and Corbell (1964) (sediment as a function of climate and relief) are equally inadequate. Although much information is concealed in the results presented in Table 16 they do provide a valuable first step toward the regionalisation of sediment yields.

From the studies reported by Leaf (1966), it can be assumed that annual sediments yields will vary perhaps an order of magnitude or more about these mean values. Variation in sediment production within any one season can also be expected as a reflection of variations in both stream flow and sediment supply. For example Nanson (1974) and Sundborg (1956) working in Canada and Sweden both found that sediment concentrations increased dramatically with seasonal peak discharge but that concentrations per unit discharge declined after the peak of seasonal snow melt. This decline was attributed to a reduction in sediment supply. Studies by Takei et al. (1975) and Hayward & Sutherland (1974) have also shown variations in bed load sediment supply rate and suggest that these variations may be more

Table 16 follows
<table>
<thead>
<tr>
<th>Location</th>
<th>Yield m$^3$ km$^{-2}$ yr$^{-1}$</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frazer, Central Otago</td>
<td>30</td>
<td>1</td>
</tr>
<tr>
<td>Opuho</td>
<td>70</td>
<td>1</td>
</tr>
<tr>
<td>Opiki</td>
<td>80</td>
<td>1</td>
</tr>
<tr>
<td>Tangawai</td>
<td>220</td>
<td>1</td>
</tr>
<tr>
<td>Otaki</td>
<td>1000</td>
<td>1</td>
</tr>
<tr>
<td>Mangahao</td>
<td>1600</td>
<td>1</td>
</tr>
<tr>
<td>Tuki Tuki river, Folgers Lake</td>
<td>1500</td>
<td>1</td>
</tr>
<tr>
<td>Lake Tutira</td>
<td>1700</td>
<td>1</td>
</tr>
<tr>
<td>Waipoa</td>
<td>1600</td>
<td>1</td>
</tr>
<tr>
<td>South Eastern Ruahines</td>
<td>1000 - 5000</td>
<td>2</td>
</tr>
<tr>
<td>North Westland</td>
<td>55</td>
<td>3</td>
</tr>
<tr>
<td>Nelson</td>
<td>5</td>
<td>3</td>
</tr>
</tbody>
</table>

1. presented by Mosley 1977 (Table 8)  
2. Mosley 1977  
3. O'Loughlin et al., personal communication

TABLE 16

Annual sediment yields for some New Zealand mountain catchments
dependent on sediment supply than on stream flow. Milhous & Klingeman (1971) found that bed load transport per unit water discharge increased after peak flow. They attributed this increase to a break down in bed armour which allowed sediments to be supplied from the stream bed.

Many studies of suspended sediments on lowland rivers have shown a hysteresis loop of concentration associated with rising and falling stage. However Nanson's (1974) results suggest that a series of sub-parallel rating curves may more accurately describe this relationship for mountain streams. He concluded that variations in this relationship were due to variations in sediment supply.

Although sediment estimating equations have been used to assess annual yields and transport rates, a majority of these have been developed from laboratory flume data. Field verification has generally been limited to sand and silt bed rivers. Kellerhalls (1972) reported that in steep gravel-bed rivers in Canada, published formulae give inconsistent and widely divergent results. Hayward & Sutherland (1974) showed that even the "most appropriate" formulae overestimated sediment yield by up to two orders of magnitude.

The relative proportions of bed load and suspended load in total stream sediments are much more variable than for lowland rivers. For example Jarocki (1957 quoted by Gregory & Walling 1973) estimates that bed load accounts for 70% of the total sediment from alpine streams. Kellerhalls (1972) and Leaf (1966) both confirm that bed load makes a significant contribution to total sediments in the mountain levels of Alberta and Colorado. On the other hand the studies of MacPherson (1971) and Nanson (1974) show contrary results. At Bragg Creek (Alberta) MacPherson found that bed load accounted for less than 1% of total annual sediment yield. An analysis of Nanson's data for Bridge Creek Alberta, confirms this finding. Klingeman & Milhous (1970) showed that for Oak Creek (Oregon) the proportion of bed load in total stream sediments varied with flood magnitude. At flood discharges corresponding to the mean annual flood, about 25% of sediment yield
was transported as bed load. For discharges with a return period of about once-in-20-years 40+% of sediment was transported as bed load. While it may be possible to explain such widely divergent results in terms of catchment size, glacial history, lithology flood magnitude etc. they serve for the moment to illustrate the variability which is associated with mountain stream sediments.

PROCEDURES

Procedures for measuring suspended and bed load sediments have been outlined in Chapter 7.

RESULTS. A. SUSPENDED SEDIMENTS.

Suspended sediments were found to be transported for only brief periods during some storm events. This response in the Torlesse stream was in marked contrast to the adjacent Kowai River which drains a 10 km$^2$ catchment (above the Torlesse confluence) and in which suspended sediments were transported continuously throughout each storm event.

Table 17 summarises suspended sediment yields from five storm events for which reliable information is available. Suspended sediment sampling was discontinued in 1975 when it was found that suspended sediments were only a minor fraction of total annual sediment yield but their determination required a disproportionate amount of time and effort.

Discussion

Suspended sediments were observed to move through the sediment trap in 'clouds' or 'waves'. These 'clouds' were characteristically of one to three hour duration. In most storm events there were prolonged periods during which suspended sediment was not transported and the water was clear enough to observe bed load movement.

Field observations showed that the passage of each cloud of suspended sedi-

Table 17 follows
## TABLE 17

Suspended sediment yields for seven storms, Torlesse stream catchment.

<table>
<thead>
<tr>
<th>Date</th>
<th>Time</th>
<th>Concentration</th>
<th>Flow $m^3sec^{-1}$</th>
<th>Yield kg</th>
<th>Storm yield</th>
<th>Bed load yield for same period</th>
<th>Bed load yield for storm</th>
<th>Total sediment yield</th>
<th>S.S. as % of total sediments</th>
<th>S.S. as % of total storm sediment</th>
<th>Stage</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.8.73.</td>
<td>0700</td>
<td>225</td>
<td>0.270</td>
<td>655</td>
<td>84</td>
<td>739</td>
<td>89</td>
<td>Rising</td>
<td>1677</td>
<td>15000</td>
<td>16700</td>
</tr>
<tr>
<td></td>
<td>1800</td>
<td>114</td>
<td>0.350</td>
<td>287</td>
<td>67</td>
<td>354</td>
<td>81</td>
<td>Rising</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2330</td>
<td>276</td>
<td>0.370</td>
<td>735</td>
<td>107</td>
<td>842</td>
<td>87</td>
<td>Peak</td>
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<tr>
<td></td>
<td>0130</td>
<td></td>
<td></td>
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<td></td>
<td></td>
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<td></td>
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<td></td>
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<td>0.240</td>
<td>53</td>
<td>10</td>
<td>75</td>
<td>128</td>
<td>Rising</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1600</td>
<td></td>
<td></td>
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<td>29.8.73.</td>
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<td>0.400</td>
<td>132</td>
<td>74</td>
<td>206</td>
<td>64</td>
<td>Rising</td>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0530</td>
<td></td>
<td></td>
<td>1677</td>
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<td>0515</td>
<td>3542</td>
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<td>1147</td>
<td>478</td>
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<td>70</td>
<td>Rising</td>
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<tr>
<td></td>
<td>0715</td>
<td></td>
<td></td>
<td>1677</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>1400</td>
<td>1500</td>
<td>365</td>
<td>0.700</td>
<td>919</td>
<td>3800</td>
<td>4719</td>
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<td>1800</td>
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<td>1688</td>
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<td>50</td>
<td>122</td>
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<td>Peak</td>
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<td></td>
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</tr>
<tr>
<td></td>
<td>1900</td>
<td></td>
<td></td>
<td>123</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>2100</td>
<td></td>
<td>24</td>
<td>0.470</td>
<td>41</td>
<td>20</td>
<td>61</td>
<td>67</td>
<td>Falling</td>
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<tr>
<td>29.1.75.</td>
<td>0900</td>
<td>620</td>
<td>0.600</td>
<td>4017</td>
<td>936</td>
<td>4953</td>
<td>81</td>
<td>Peak</td>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1200</td>
<td></td>
<td></td>
<td>4017</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Totals for 5 storms</td>
<td></td>
<td></td>
<td></td>
<td>8640</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
ment was related to a sudden influx of sediment into the stream channel; for example in the case of a bank collapse.

Table 17 shows that when suspended sediments are being transported they may account for up to 90% of sediment yield. However, because suspended sediments are transported for only a small proportion of total storm time they account for much less of total storm sediment yield. Table 17 also shows that the percentage of total sediments, that is suspended sediment, is greatest in small events. It will be shown later that these small events contribute little to total annual sediment yield. These results support the findings of Leaf (1966) and Kellerhalls (1972) that suspended sediment is a relatively minor component of total sediments in some mountain streams.

The time distribution of suspended sediment was similar to those reported by O'Loughlin et al. (pers. comm.) in that the highest concentrations occurred on the rising limb. Field observations suggest that fine material perched on stream banks was entrained on the rising stage. On a falling stage such sediments were generally unavailable to the stream.

RESULTS: B. BED LOAD SEDIMENT YIELDS.

Results

Bed load sediment yields and transport rates from 81 storm events between 1972 and 1977 are shown in Appendix VI. Results for sediment yield are summarised in Figure 39 and Table 18. The total yield of sediment amounts to 564 tonnes. The average annual sediment yield was 115 tonnes or 30 tonnes per square kilometer of catchment.

Figure 43 shows that a majority of this sediment was delivered in only a few events, for example it can be shown that 10 storms produced 90% of the 5 year total. As these storms took place over a total of 17 days it is evident that 90% of the sediments were delivered in 1% of total time. Figure 39 follows
FIGURE 39

Table 18 shows sediment yields from the 81 recorded storms distributed between 12 storm classes.

DISCUSSION

Sediment Yields

Reliable bed load data are sparse and it is therefore possible that these results, like those presented by Leopold & Emmett (1976), have greater value than analyses or interpretations which may be possible at the time of writing.

The estimated specific sediment yield of 30 tonnes per square kilometer of catchment is approximately 12 m³ km⁻² yr⁻¹ (density 2.5 g cm⁻³). This indicates that erosion rates in the Torlesse catchment are amongst the lowest-reported values (see Table 16). If this result is taken for its face value it is indeed surprising. Figure 9 (Vol I) and detailed surveys by Saunders et al. (pers comm) suggest that over 50% of this catchment is in a 'severely eroded' condition. However, a re-examination of the eroded areas shows that the coarse scree and block fields are much more stable than their depleted condition might at first suggest.

This contemporary rate of erosion can be compared with a long-term or natural erosion rate. A paleo-range was reconstructed by the simple but subjective method of extrapolating the present day contours along the probable trends of the range. The volume of material removed from the paleo-catchment to create the present catchment was distributed over an assumed 2.5 million year period of landscape evolution. Although very crude, this method indicates a long-term erosion rate in the order of 400 cubic metres per square kilometer of catchment per year. This suggests that erosion rates measured between 1972 and 1977 might be at least an order of magnitude less than long-term or natural rates of erosion.

Although the study period was reasonably representative of both weather and climate it did not include an 'extreme' event. In April 1978, a storm of
<table>
<thead>
<tr>
<th>peak flow class.</th>
<th>sediment yield</th>
<th>No. of storms</th>
<th>min</th>
<th>max</th>
<th>mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>m^3/sec. (depth m)</td>
<td>tonnes</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.150 - 0.200 (0.10m)</td>
<td>0.058 0.025 0.005</td>
<td>0</td>
<td>0.107 0.04 0.03</td>
<td>14</td>
<td>0</td>
</tr>
<tr>
<td>0.201 - 0.250 (0.115m)</td>
<td>0.015 0.032 0.014</td>
<td>0</td>
<td>0.075 0.002 0.034</td>
<td>12</td>
<td>0</td>
</tr>
<tr>
<td>0.251 - 0.300 (0.13m)</td>
<td>0.042 0.136 0</td>
<td>0</td>
<td>0.050</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>0.301 - 0.400 (0.15m)</td>
<td>0.01 0.078 0.015 1.20</td>
<td>0</td>
<td>1.0 0.54 0.405 17.6</td>
<td>19</td>
<td>0</td>
</tr>
<tr>
<td>0.401 - 0.500 (0.165m)</td>
<td>29.6 1.26 0.04 4.0</td>
<td>0</td>
<td>2.5 2.5 15.0</td>
<td>13</td>
<td>0</td>
</tr>
<tr>
<td>0.501 - 0.600 (0.18m)</td>
<td>6.0 10.6 0.095 0.50</td>
<td>0</td>
<td>27.8 8.28</td>
<td>6</td>
<td>0.095 27.8</td>
</tr>
<tr>
<td>0.601 - 0.800 (0.20m)</td>
<td>0.05 3.5 1.0</td>
<td>0.05 73.6</td>
<td>5</td>
<td>0.05 73.6 15.64</td>
<td></td>
</tr>
<tr>
<td>1.00 - 1.10 (0.23m)</td>
<td>27.0</td>
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<tr>
<td>1.21 - 1.30 (0.245m)</td>
<td>50.0 0.9 91.2</td>
<td>0.065</td>
<td></td>
<td>4</td>
<td>.065 91.2 35.5</td>
</tr>
<tr>
<td>1.41 - 1.50 (0.26m)</td>
<td>5.0</td>
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</tr>
<tr>
<td>1.75 (0.28m)</td>
<td>1.57</td>
<td></td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>2.8 (0.35m)</td>
<td>72.0</td>
<td></td>
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<td>1</td>
</tr>
</tbody>
</table>
return period in excess of 20 years delivered about 800 tonnes of sediment in 70 hours. Although this event is not included in the data presented here, it is mentioned to indicate the significance of low frequency events.

Wolman & Miller (1960) have suggested that most of the work of moving sediment from a drainage basin is done by frequent flows of moderate magnitude. However, as they caution, this proposition is valid only when applied stress exceeds a critical or threshold value. Therefore while their proposition may be valid for sediment movement in silt and sand bed rivers, several authors have pointed out that it cannot be applied to mountain land erosion (Selby 1976, Rapp & Strömquist 1976, Renwick 1977) or mountain stream sediment yields (O'Loughlin pers. comm). The findings of this study support these views.

If the study period 1972–1977 is extended to include the event of April 1978, specific sediment yields increase from 30 tonnes km$^{-2}$ yr$^{-1}$ to about 60 tonnes km$^{-2}$ yr$^{-1}$. Although it is a matter of some speculation, it is possible that if the study could be extended for a much longer period to include several low frequency events, contemporary erosion rates might be found to be of the same order as long-term or natural rates of erosion.

Be that as it may, these results question the validity of the generally accepted view that contemporary erosion has increased stream sediment yields in this mountain catchment.

Variability of bed load sediments

While Figure 39 shows that the largest sediment yields are associated with highest peak flows, it also shows a number of notable exceptions. For example, storms on 8 September 1976 and 11 October 1976 both produced peak flows of 1.3 m$^3$ sec$^{-1}$. However, sediment yields were 91,000 kg for the first storm and only 65 kg for the second. Results such as these give a new perspective to the movement of sediment from this catchment.

Figure 39 gives the impression of a periodicity of sediment movement which
is only partially dependent on flood magnitude. Table J8 shows that there is great variability in sediment yield from floods of comparable peak discharge. While part of this variation can be explained in terms of hydrograph shape and duration of flood flows, a more important explanation involves the availability of sediment.

During the study it became clear that sediment yields were strongly influenced by the amount of sediment held in storage in the stream channel. (In turn, this was influenced by the stability of a restricted area of upper catchment riparian land). In 1974 the programme was extended to monitor changes in the storage of channel sediments.

Although streams such as the Torlesse have been generally described as mountain torrents, this description is inappropriate (see Chapter 9 Vol I). The Torlesse stream channel is a sequence of pools and ripples. Sediment has been found to be stored within the pools and subsequently released by flood flows. A series of cross sections was established throughout the channel to monitor changes in the volume of detritus held in storage. Figure 40 indicates the changes which took place in a pool 75 m upstream from the sediment trap. Three features should be noted about Figure 40.

Changes in storage are expressed as changes in the cross sectional area with respect to a mean bed level. Values below the mean bed line represent scouring and levels above represent aggradation. An alternative view would be to consider everything above the lowest recorded levels as sediment held in storage.

Changes in cross sectional area can be rapid. The general pattern was that pools would scour on a rising stage and refill on a falling stage. However, many changes went unrecorded during a storm because of the difficulties of monitoring sediment yields and channel conditions at the same time. While Figure 40 underestimates the frequency of channel change it does indicate periodic increases in the volumes of stored sediments. These were found to be coincident with variability in recorded yields at the trap.

Figure 40 follows
Changes in cross-sectional area, pool 2A Torlesse stream channel 1974 - 1976
A clearer pattern emerges when changes at all cross sections are plotted on the long profile of the Torlesse stream. Figure 41 shows the measured and inferred changes which took place over a 30 hour period in April 1975. This figure gives support to field observations of sediment moving wave-like down the stream channel. In this storm the bulk of the 'wave' did not reach the sediment trap and the recorded yield of 1500 kg was low for a peak discharge of 1.90 m$^3$ sec$^{-1}$.

A gravel wave was observed to move through the Torlesse stream channel in two events between December 1976 and March 1977. This wave travelled 3.5 km in 20-24 hours, say 0.15 km h$^{-1}$.

In the five year study period there was a total of about 650 hours of sediment transport time. This is an average of about 10 hours per month. Based on a travel rate of 0.15 km h$^{-1}$ the average residence time for gravel once deposited in the Torlesse stream channel would appear to be 1 - 3 months.

Experience during the study period suggests that it is both the presence (or absence) and location of these sediment 'waves' which is the main determinant of storm sediment yield.

In presenting results from the Hirudani experimental catchment, Japan, Ashida et al. (1975) show variations in stream bed levels similar to those described here. Although those authors do not present results to show variability in sediment yields, it would be reasonable to conclude that such variability does exist.

While Figure 39 and Table 18 show a wide range in sediment yield from floods of comparable peak discharge the mean values show an orderly progression with peak flow rate. The line which can be fitted by eye through these mean values represents the average behaviour of the Torlesse stream channel (Figure 42). Using the terminology of Blench (1957) this relationship can be considered as a first approximation of regime for the Torlesse stream. Figures 41, 42 follow.
FIGURE 41

Changes in cross-sectional areas, Torlesse stream catchment.

30 April - 1 May 1975
Sediment transport rate = 2–4 kg/min.

Sediment transport rate = 1 kg/min.

Sediment transport rate = 0 kg/min.

Distance from furthest sediment source (km)
FIGURE 42

Torlesse stream catchment range of sediment yields (minimum, mean, maximum) and peak flows 1972 - 1977 (logarithmic scales).
stream catchment. If further study can confirm this relationship and extend it to higher flow rates and sediment yields then future long-term sediment yields could be predicted from information about flood frequency.

For a particular storm, sediment yield will be determined by the amount of sediment held in storage. When stream bed levels exceed mean bed level, yields will be high and the stream will be in a condition of oversupply. Conversely, the stream will be undersupplied when bed levels are below mean bed level.

**Sediment size**

The smallest bed load particles retained in the trap were coarse sands. These were observed in all flows capable of transporting bed load. The largest particles to be ejected by the vortex tubes were in the order of 0.4m (long axis) and of 20 kg mass. At flow depths in excess of 0.30 m (2.0 m$^3$ sec$^{-1}$) boulders in excess of 0.5 m and 40 kg mass were observed to roll or slide over the vortex tubes.

Figure 44 has been selected from data presented in Appendix VII to illustrate the variability in particle size distribution throughout a storm. Because only a limited number of samples were retained for size analysis, Figure 44 and the data presented in Appendix VII probably under-state the variation in the proportions of bed load sediments during storm events.

Observations of bed load movement through the sediment trap confirm these significant changes in the size distribution of sediments. While the reasons for these changes need further study it is probable that they reflect changes in the upper catchment and channel. For example the collapse of a stream bank may cause an influx of sediment to the stream channel. The preferential movement of the finer fraction results in a shift in size distributions of sediment retained at the trap. Coarser sediments may be stored or detained in pools and subjected to a degree of sorting. The subsequent release of these coarse gravels from a pool (or

Figures 43, 44 follow
FIGURE 43

Sediment yields Torlesse stream catchment 1972 - 1977
Number of storms

Percentage of storms

Percentage of yield 1972-1977

100

80

60

40

20

Number of storms

1  4  6  8  14  17  20  43  86

10  20  30  40  50  60  70  80  90  100
FIGURE 44

Variability in distribution of particle sizes during one storm.
pools) may result in substantially coarser material being discharged through the trap.

Some trends in sediment size distributions which are common to the figures in Appendix VII are shown in Figure 44. The highest proportions of coarse material are found about or immediately following peak flow. This is also the period when bed load transport rates show their most rapid rates of increase. (see Appendix VI). As the flow rate decreases, stream power and sediment transport rates decrease, and the stream loses competence to transport coarser material. Figure 44 shows that the proportion of fine sediments increases. A storm by storm comparison of data presented in Appendices VI and VII shows that this increase in the proportion of finer sediments is associated with a rapid decrease in the rate of sediment transport.

Measured Yields vs Those Derived from Estimating Equations

Figure 45 shows the distribution of bed load transport rates (kg min\(^{-1}\)) through the 3 m wide sediment trap for a range of flow depths. Upper and lower envelope curves and a line of best fit are also shown. The upper and lower curves are fitted by eye.

Figure 46 compares bed load transport rates estimated by five prediction equations with measured rates. Figure 47 shows the range of possible transport rates depending on the value used for slope in the estimating equation. In each case the lower estimates are based on the slope of the water profile through the pool (0.025). The upper estimates represent transport rate when the pool-riffle features are 'drowned' by water and sediment and the water surface slope approximates valley slope (0.067). For both measured and computed transport rates particle sizes were, \(d_{50} : 0.015\) m, \(d_{90} : 0.050\) m.

Many authors have urged caution in the use of bed load prediction equations. These results confirm Kellerhall's (1972) view that conventional estimating equations are inappropriate for estimating sediment yields from mountain Figures 45, 46, 47 follow
Sediment transport rates at the vortex tube sediment trap. Upper and lower envelope curves filled by eye. The line of best fit for depths between 0.12 m and 0.28 m $\gamma = 481900.5$ where $D =$ depth of flow (m) and $\gamma =$ sediment transport rate (kg min$^{-1}$).
FIGURE 46

Bed load sediments recorded at the Torlesse stream sediment trap vs those estimated by some conventional estimating equations.
FIGURE 47

Bed load transport rates estimated by some conventional equations. Estimates for each equation are within the slope ranges 0.025 and 0.067.
catchments.

Shield's formula has been found to over-estimate yields in a wide range of flume and field conditions (White 1973). In this study the estimates from Shield's formula were consistently three orders of magnitude higher than the measured values. The best agreement came from Engelund & Hansen's formula (quoted by White et al., 1973), which gave estimates in the same order of magnitude as the measured values. However, as this formula was developed in a laboratory flume using sand sized particles, this agreement should be regarded as fortuitous.

It was noted earlier that most estimating equations assume that a capacity load is transported and that this is related to bed shear stress. These assumptions are not valid for the Torlesse stream and therefore the use of such estimating equations is inappropriate for this or similar mountain catchments.

**Measured Yields vs Stream Power**

Bagnold (1966) is the only author to describe theoretically bed load transport without recourse to experimentally derived coefficients. In Bagnold's approach the rate of bed load transport should be a function of stream power. Stream power is the product of mean flow velocity and bed shear stress. That is, stream power is the product of water density, velocity, depth and slope. When sediment is freely available, Bagnold has suggested that at low values of stream power transport rate increases rapidly with increases in stream power. However, at higher values of stream power further increases in bed load transport are a direct and linear function of stream power. This hypothesis was tentatively confirmed by Leopold & Emmett (1976) using measured bed load data for the East Fork River, Wyoming.

In a further study, Emmett (1976) reported that at lower values of stream power a river loses competence to transport the coarser bed particles and the channel bed becomes armoured. This limits the availability of smaller material.
The highest recorded rates for sediment transport in the Torlesse stream are shown in Figure 45. It is assumed that these rates represent periods when sediment was freely available. These upper values tend to confirm Bagnold's view that, in this case, transport rates increase rapidly with increases in flow depth up to about 0.15 m. Thereafter, increases appear to be directly proportional to increases in depth. The upper limit values shown in Figure 48 have been derived from a line fitted by eye through the upper values shown in Figure 45.

In Figure 48 comparisons are made between stream power calculated for a range of flow depths for the Torlesse stream through the 3 m wide control section, the upper values of recorded bed load transport rates, and the mean values of transport rates within the depth range 0.15 m - 0.28 m. The median of gravel sizes ranged from 0.015m - 0.030m. The proportion of stream power utilised in sediment transport (E = efficiency) when sediment was assumed to be freely available was found to be within the range of 5% - 7%. This finding is in remarkable agreement with the estimates of Leopold & Emmett (1976) who suggested efficiency values of 8% for d50, 0.010m and 5% for d50, 0.050 m.

The proportion of stream power expended in bed load transport in "average" conditions (i.e. on the line of best fit) was found to be less than 1% (0.6% - 0.8%).

These estimates of stream efficiency have been made from data obtained over a limited range of flow depths and in consequence they should not be generalised. They do indicate however that stream power and stream efficiency can provide more reliable estimates of bed load in at least this mountain stream than can conventional estimating equations.

Figure 48 follows
FIGURE 48

Measured bed load transport rates and calculated stream power.
LEGEND

\( \zeta \) = Stream efficiency
\( \varepsilon \) = proportion of power utilized in sediment transport
\( \Omega' \) = Total "stream power" Torlesse Stream
\( = \rho \times 600 \) \( \text{OS kg min}^{-1} \)
where \( \rho \) = density of fluid = 1000 \( \text{kg m}^{-3} \)

\( Q' \) = discharge \( \text{m}^3 \text{sec}^{-1} \)

\( S \) = slope = 0.046
CHAPTER 9

THE CHARACTER AND SIGNIFICANCE OF THE MORPHOLOGY OF

THE TORLESSE STREAM CHANNEL
Although river channels exhibit widely differing form, it has been suggested that there is a continuum or uninterrupted range of patterns, (Leopold & Wolman 1957). A review of channel literature shows that shallows and deeps (pools and riffles) are a feature of all channels but that they may become a dominant feature in mountain stream channels.

Longitudinal and cross section profile surveys were made of the Torlesse stream channels. During these surveys, channel forms were classified on largely subjective criteria. The survey and classification showed a 'major' pattern of riffle steps or boulder steps which separated regions of lower velocity stream flow. The riffle steps usually included a 'minor' pattern of boulder steps which separated pools. It is suggested that the 'major' pattern is determined by low frequency events with return periods in the order of 50 - 100 years. The 'minor' pattern is determined by more frequent events with return periods of <1 - 5 years. Although the channels are generally well ordered, they include some disordered segments. These are believed to be in the process of adjustment towards a more ordered state. The concept of dynamic equilibrium may be more appropriate to the Torlesse stream channel than the appearance of the catchment might at first indicate. Relations between step height and length are found to be consistent and vary with grade.

A comparison is made of stream energy through one pool to illustrate the significance of the pool riffle morphology in dissipating 95% of the stream's capacity to do work. It is suggested that this energy dissipating role is relatively unimpaired as long as flow through the pool remains subcritical. Results from a laboratory study are noted to support the field observation that when gravels fill pools there is a sharp increase in the stream's capacity to do work.

The significance of these findings to channel management is briefly discussed.
INTRODUCTION

Over the last century there has been a rapid growth in the number and value of structures built on, over or adjacent to rivers. From a river engineer's point of view the problem is that rivers generally refuse to remain in one position. It has therefore become necessary to know something about a river patterns, and their likely responses to change.

The literature on the reasons for river patterns shows a diversity of hypotheses which are comparable only to the diversity of channel pattern itself (Schumm & Khan 1972). Some authors (for example Simons & Richardson 1962, 1971 Callender 1969) give emphasis to an understanding of channel hydraulics. Others give emphasis to geologic and geomorphic understanding (see for example Schumm 1971, 1977). Schumm 1972 has compiled a selection of some of the more significant contributions to our understanding of channel morphology and behaviour.

There are a number of systems for channel classification but Leopold & Wolman 1957 noted that although braided and meandering patterns are strikingly different, they actually represent extremes of an uninterrupted range of channel patterns. They presented the concept of a continuum of channel patterns and suggested that the hydraulic processes operating within channels may be more comparable than differences in their patterns would at first suggest.

Schumm & Khan (1972) developed this concept of a continuum and showed that when a channel is at or close to a threshold of change, a relatively small increase in sediment load could cause the river to adopt a different form (Fig. 49).

A majority of the literature on channel form refers to the straight, meandering and braided channels shown in Fig. 49. These channels characteristically have gradients of up to about 0.02. For channels steeper than this there is less information.

Figure 49 follows
Relation between sediment load and flume slope showing increased rates of sediment transport at thresholds of channel pattern change.

From Schumm & Khan, 1972.
Leopold & Wolman (1957) noted that shallows and deeps are a fundamental characteristic of almost all natural rivers. Because the shallows have a riffle surface, Leopold et al. (1964) proposed the term pool-riffle.

In some mountain areas, the pool-riffle pattern becomes the dominant channel form. (See, for example, the descriptions of Heede (1972), Harr (1976) and Kellerhalls (1966). In other investigations this channel form has not been mentioned. (See, for example, the studies of O'Loughlin (1969).) Leopold et al. (1964) suggested that a pool-riffle morphology depends to some degree on the heterogeneity of bed material size. Pools tend to form behind coarser bed materials or boulders. In some instances pools may also form behind logs which have become embedded in a channel (Heede, 1972).

Mountain channels are characterised by steep gradients, but the pool-riffle morphology modifies this grade. Water moves more slowly through the deeper pool segments and rapidly through the shallower riffle segments. A sequence of pools is thus a sequence of hydraulic jumps and is thereby one mechanism for dissipating the potential energy of stream flow.

It is known that a submerged hydraulic jump is a less effective energy dissipater than a free jump (Govinda & Rajaratnam, 1963). Therefore it can be assumed that in a pool riffle channel, submergence of the pools (for example by flood flows) will increase velocity and stream energy. This increase in the capacity of the stream to do work will have a potential affect on stream channel stability.

To a casual observer the Torlesse stream channel appears to contain sections of pools and riffles that have been formed by the alignment of boulders and larger sediments across the stream channel. Other reaches appear to have little order with sediments strewn in apparent random fashion.

The objective of this study was to describe the morphology of the Torlesse stream channel and to consider its significance to stream energy.
PROCEDURES

Channel Description

The channel description was based on stadia theodolite surveys and descriptions of channel morphology at each survey point.

Longitudinal and cross section profile surveys were made of the channels of the Kowai River and Torlesse stream in March/April 1974 (see appendix 10). These were stadia theodolite surveys in which bearings were related to grid north. A geodometer and second theodolite were used to establish ground control and tie this to the nearest bench mark some 30 km distant. The Torlesse stream channel was surveyed for a distance of 1.450 km upstream of the sediment trap. The Irishman stream was also surveyed 0.645 km upstream from its confluence with the main channel. The survey was closed in a loop joining the two branches. The accuracy of this survey is estimated at ± 0.05 m for reduced levels and 0.5 m for distances.

A first survey was made in March/April 1974. A resurvey was made in May 1975 to check the reliability of the 1974 survey and to determine if two major storms in the intervening 12 months had modified the channels.

The description of the morphology of the channel at each survey point is based on a classification of riffle zones. Three types of riffle zone were defined and used as a basis for the channel description. They were, boulder steps, riffle steps and rock steps.

1. Boulder steps consist of a group of boulders arranged in a straight or curved line across the channel (Fig. 50).
2. Riffle steps are a collection of larger than average sized sediments which steepen the channel profile (Fig. 51).
3. Rock steps are found where the channel is confined between bedrock outcrops. In these regions channel morphology is controlled by geologic rather than hydraulic conditions (Fig. 52).

Figures 50, 51, 52 follow
FIGURE 50

Boulder steps.
This channel form also includes broken boulder steps and boulder/rock steps.
**FIGURE 51**

Riffle steps.
FIGURE 52

Rock steps.
Although clear cut examples of these step types are frequently found, there are many variations in their form. Figs. 50 - 51 show the subdivisions of the step types which were used as an aid to field identification. (This classification was itself the subject of study and evolved from several trials and 'practice' surveys.)

The actual field classification was made by the staff-man during the channel survey. (In less obvious conditions there was consultation between staff-man and surveyor). Survey points were made every 1 m - 5 m along the stream channel. Each factor that affected the surface water profile was recorded at these sites (e.g. waterfalls, steps, bends) and detailed diagrams and notes of bed features were made. The boundaries between channel features were frequently indistinct and different observers could identify different features. In well ordered reaches boundaries were clear and discernable to several observers. In less ordered reaches boundaries were less clear. During the trials to evolve the system of classification it was found that although different observers often failed to record coincident boundaries, the overall patterns described by independent assessments were comparable, when averaged over several lengths of channel.

Results

The long profile survey showed that the Torlesse stream channel consisted of a series of steeper and flatter reaches. The overall channel grade was controlled by rock steps (massive sandstone and siltstone which out-crop and confine the channel). In some reaches larger boulders up to 2 m diameter appear to have a similar grade control function.

Between these structural controls two patterns were identified which are tentatively described as 'major' and 'minor'. The 'minor' patterns were found within the 'major' and were most commonly boulder steps. The 'major' patterns were most commonly riffle steps, or rock steps. Fig. 54 is a Figure 53 follows
Mean step height to step length relations (metres) for segments of Torlesse stream channel
schematic presentation to show the manner in which the 'major' pattern modifies channel grade, and the 'minor' pattern modifies the grade of the 'major' pattern. This 'major' and 'minor' pattern was found in the lower channel below the Forks. The upper channels were characterised by a series of minor patterns (boulder steps). Table 19 summarises step height to step length relations for the surveyed reaches of the Torlesse stream channel. Figure 54 shows distance, height relations for the 'minor' pattern throughout the Torlesse stream channel. The consistency of relations between step height and distance between steps is shown in Figures 55 and 56.

The upper Torlesse channel above the Forks includes large boulders of up to 2 m diameter and two segments of rock step. The channel gradient is very steep (0.12 - 0.16), but the well ordered boulder and rock steps have created a stable channel. Throughout the study period there was no major source of sediment to this reach. Channel morphology is assumed to be determined by major floods of return period in excess of 50 years. Channel side slopes are stable since flow rarely escapes from the ordered channel.

The Irishman stream from Rainbow gully down to Beech Falls shows a wide variation in slope and channel form. There are no rock steps or large boulder steps. The channel is composed of angular rock fragments (from Rainbow gully) and exhibits little order. The gradient is very steep (0.15) and is modified only by unstable small rock steps. These break down in freshets and minor floods and the channel adopts a debris-flow form.

The channel of the Irishman stream from Beech Falls to the Forks is on or near bed rock. The channel is ordered and consists of a 'major' pattern of boulder steps (up to 1 m diameter) and rock steps. A minor pattern is superimposed on the major pattern. In storms in 1974 and 1975 at least four 'minor' boulder steps were observed to break down and reform within a few metres.

The lower Torlesse channel between the Forks and the control section shows
### TABLE 19

A summary of morphologic features of Torlesse stream channel.

<table>
<thead>
<tr>
<th>Tributary</th>
<th>Reach Code</th>
<th>Mean step Length (wavelength) (m)</th>
<th>Mean step Height (amplitude) (m)</th>
<th>Mean Slope (low flow)</th>
<th>BED WIDTHS (m)</th>
<th>ACTIVE Channel</th>
<th>Total Avail. Bed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main True Right</td>
<td>S → V</td>
<td>3.5</td>
<td>0.56</td>
<td>0.160</td>
<td>0.8 → 3.5</td>
<td>5 → 16</td>
<td></td>
</tr>
<tr>
<td>Branch - Torlesse Stream</td>
<td>X → I</td>
<td>3.0</td>
<td>0.38</td>
<td>0.123</td>
<td>0.6 → 2.5</td>
<td>10 → 30</td>
<td></td>
</tr>
<tr>
<td>True left</td>
<td>Q¹ → N¹</td>
<td>1.8</td>
<td>0.27</td>
<td>0.151</td>
<td>0.5 → 1.5</td>
<td>15 → 35</td>
<td></td>
</tr>
<tr>
<td>Irishman's Creek</td>
<td>N → I</td>
<td>4.0</td>
<td>0.44</td>
<td>0.108</td>
<td>0.5 → 3.0</td>
<td>8 → 15</td>
<td></td>
</tr>
<tr>
<td>Main Torlesse Stream (below Forks)</td>
<td>H¹ → F</td>
<td>10.2</td>
<td>15.9</td>
<td>0.69</td>
<td>1.06</td>
<td>1.2 → 2.5</td>
<td>20 → 50</td>
</tr>
<tr>
<td>(below Forks)</td>
<td>D → A</td>
<td>10.3</td>
<td>14.8</td>
<td>0.59</td>
<td>0.84</td>
<td>1.5 → 3.5</td>
<td>15 → 30</td>
</tr>
</tbody>
</table>
FIGURE 54

Pool riffle morphology of Torlesse stream channel
FIGURE 55

Relations between step height and distance between steps, Torlesse stream catchment (semi-logarithmic plot).
$y = a \cdot bx$

$r^2 = 0.65$

Mean step length (m)

Mean step height (m)

LEGEND

- Upper Torlesse Strm.
- Slug Creek
- Irishman Strm.
- Lower Torlesse Strm. (minor pattern)
- Lower Torlesse Strm. (major pattern)
The following sections have been deleted from these linear regressions:

- Lower Torlesse CB (wide divide of channel, disordered reach)
- DC (wide divide channel)
- Upper Torlesse YY1 (bed with 2 x - 3 x greater than)
- YZ (remainder of Upper Torlesse stream channel)

FIGURE 56

Relations between step height and slope, Torlesse stream catchment
a full range of structures in both 'major' and 'minor' patterns. The 'major' pattern is determined by rock steps and riffle steps of boulders of up to 2 m diameter. The 'minor' pattern of boulder steps is contained within the 'major' pattern. Between 1974 and 1977 several minor steps were observed to break down and release sediment to flood flows. The largest boulders in these steps moved only a metre or so downstream to become the basic elements about which new boulder steps formed.

Discussion

It is important to appreciate that this classification of channel features was chosen to describe a pattern which was observable in the stream channel. If the river had been regarded as only a physical system, and if sites for wholly objective measurement were selected in random fashion, it is doubtful that the results presented here could be substantiated. Schumm 1972 pointed out that to regard the river as a contemporary physical system is to ignore its history. The character of any channel or section of channel is a product of both its physical properties, and its history. This method of description requires the observer to have an a priori understanding of channel behaviour in order that sites might be classified as outlined here.

Boulder steps were generally found on slopes greater than 0.05, where a straight or curved line of boulders extended across the stream channel. The lip of this line forms a small waterfall which discharges into a downstream pool.

Riffle steps were found on slopes of less than 0.05. Whereas the boulder steps separate distinct pools, the riffle steps separate reaches of lower velocity water and may contain boulder steps.

Between the first survey in 1974 and the resurvey in 1975 there were two floods with return periods in the order of 2 - 5 years. The resurvey showed that whereas the main channel structures were unaltered, the over-
all pattern was more clearly defined. That is the channel had become
more ordered.

From this finding and from other observations made during the study period
it is suggested that the 'major' pattern is determined by large magnitude
low frequency floods with return periods in the order of 50 - 100 years.
The 'minor' pattern (boulder steps) is gradually superimposed on the 'major'
pattern by more frequent events (return periods of perhaps < 1 - 5 years).
The "disordered" sections of stream channel are thought to be part of the
'minor' pattern which is in a process of readjustment. It is suggested
that the Torlesse channel will always include segments of channel which
are adjusting to changes in flow and sediment conditions. However,
overall the stability of the channel was found to be determined by
"permanent" features such as rock steps and large boulders.

The channel is therefore regarded as a sluice for eroded debris which
moves downstream to the Kowai River.

Mackin (1948) described a graded stream as one:

"in which, over a period of years, slope is delicately adjusted
to provide, with available discharge and with prevailing channel
characteristics, just the velocity required for the transportation
of load from the drainage basin ...

Its diagnostic characteristic is that any change in any of the
controlling factors will cause a displacement of the equilibrium
in a direction that will tend to absorb the effect of the change".

In what he believed to be a more valid approach to "steady state" Hack
(1960) proposed the concept of "dynamic equilibrium" in which:

"... within an erosional system all elements of the topography
are mutually adjusted so that they are down wasting at the same
rate. The forms and processes are in a steady state of balance ...
(thus) ... an alluvial fan would be in dynamic equilibrium
if the debris shed from the mountain behind it were deposited on
the fan at exactly the same rate as it was removed by erosion
from the surface of the fan itself".

In Hack's view, dynamic equilibrium allows for a landscape to evolve from
one form to another.
The application of the graded river and dynamic equilibrium concepts to a high energy environment like the Torlesse system is open to geomorphic debate. However it is clear from the description of the Torlesse stream channel and its behaviour over the study period that they are more appropriate to this system than may be at first assumed from casual observations of the depleted appearance of the catchment, and the 'boulder strewn' stream channel.

During floods there were observable differences in flow conditions between well ordered and poorly ordered segments of channel. In an attempt to better describe these, a pygmy current meter was used to determine point velocities through pool riffle segments of stream channel. These measurements were found to be reliable at low flows in well ordered pools. At low flows in poorly ordered reaches, and at higher flows when sediment was being transported through well ordered reaches, the results were unreliable and sometimes confusing. Velocities at higher flows were estimated using a velocity head rod. Fig. 57a shows velocities and Froude numbers through a riffle and pool at a low flow of 0.350 m$^3$ sec$^{-1}$. (Four to six velocity estimates were made by pygmy meter at each section within the riffle and pool). These estimates were made 0.04 m above the bed. Fig. 57b shows velocities and Froude numbers through the same pool riffle when the flow rate was 0.800 m$^3$ sec$^{-1}$.

Fig. 57 illustrates some interesting features of the energy status of water flowing through this riffle and pool. At point A (the lip of the upstream boulder step) stream energy is the sum of both potential and kinetic energy. At point B (outlet of the pool) stream energy is kinetic energy. Between these two points energy is dissipated by the friction of turbulent mixing in the pool. That which is not dissipated in heat is available to do work.

Fig. 57 shows that at the lower flow rate the energy available at point A was 1,500 joules but the energy available at point B was only 100 joules. That is, there was a 95% loss of energy due to turbulent mixing in the Figure 57 follows
FIGURE 57

Energy estimates in a pool and riffle in both low flow and minor flood flow.
Stream energy = kinetic energy
\[ E = \frac{mv^2}{2} \]

Low flow
When \( Q = 0.350 \text{ m}^3\text{sec}^{-1} \),
\( V = 0.78 \text{ m sec}^{-1} \)
\( D = 0.18 \text{ m} \)
\( F = 0.6 \)

Then \( E = 106 \text{ joules} \)

Low flood
When \( Q = 0.350 \text{ m}^3\text{sec}^{-1} \),
\( V = 1.6 \text{ m sec}^{-1} \)
\( D = 0.12 \text{ m} \)
\( Z = 0.30 \text{ m} \)
\( F = 1.5 \)

Then \( E = 1,480 \text{ joules} \)

Energy dissipation in pool = 93%

Minor flood flow
When \( Q = 0.800 \text{ m}^3\text{sec}^{-1} \),
\( V = 1.40 \text{ m sec}^{-1} \)
\( D = 0.25 \text{ m} \)
\( F = 0.9 \)

Then \( E = 784 \text{ joules} \)

Minor flood flow
When \( Q = 0.800 \text{ m}^3\text{sec}^{-1} \),
\( V = 4.40 \text{ m sec}^{-1} \)
\( D = 0.20 \text{ m} \)
\( Z = 0.35 \text{ m} \)
\( F = 3.1 \)

Then \( E = 10,490 \text{ joules} \)

Energy dissipation in pool = 93%

Legend:
- \( Q \) = flow
- \( V \) = velocity
- \( D \) = depth
- \( z \) = height above pool surface
- \( m \) = mass
- \( g \) = gravitational constant
- \( E \) = total stream energy
- \( F \) = Froude number
\[ F = \frac{v}{\sqrt{gD}} \]
pool. At a higher flow, energy available at point A was 10,500 joules but the energy available at point B was 800 joules. The loss due to turbulent mixing was again 95%. Although the relative effectiveness of the pool in dissipating energy was unimpaired it is important to note that there was a 7 fold increase in the absolute amount of energy available for sediment transport and other work at point B.

The Froude number estimates indicate that at 0.300 m$^3$sec$^{-1}$, stream flow through the upstream riffle is shooting, or supercritical. However at the pool outlet flow is streaming or subcritical. Although this pattern is maintained at 0.800 m$^3$sec$^{-1}$ the Froude number estimate of 0.9 at the downstream end of the pool suggests that flow through the pool is approaching supercritical. It is thought that a relatively small increase in discharge under these conditions would result in shooting turbulent flow through both riffle and pool.

The data in Figs. 57 are presented as a tentative illustration of the significance of the pool riffle morphology in dissipating stream energy. A number of factors limit their reliability.

Although several low flow and higher flow estimates were made these are the only two which can be compared. There are many difficulties associated with field measurements at higher flows. During storms it was not possible to service the sediment trap, survey the pool riffle morphology and monitor stream flows at the same time. Although a number of velocity and depth estimates were made at higher flows, all but those presented in Fig. 57 could not be compared with prestorm conditions because of significant alterations to the pool and riffle zone. Further, it is difficult to obtain reliable estimates of velocity using a velocity head rod in flood flows. The flood flow estimates therefore include errors which are unknown but presumed to be large.

Despite these and other limitations this example indicates the importance of the pool riffle morphology as one mechanism of stream energy dissipation.
The 0.30 m boulder step illustrated in Fig. 57 a and b is a substantial channel feature. Most other steps are less substantial and their pools are submerged by either higher stream flow rates or sediment waves.

Observations during storms indicated that although minor pools would become submerged by higher flow rates their effectiveness in dissipating stream energy was more seriously impaired when they were filled with gravel. Because of the difficulties of field measurement, this observation was tested in a laboratory flume (see Appendix II). Fig. 58 has been extracted from data presented in Appendix II and shows that in a laboratory pool-riffle model, mean velocity through the test reach increased with increasing discharge. However when the pools were filled with gravel to simulate a gravel wave which would prevent turbulent mixing in the pools, there was up to a four fold increase in mean velocity.

As kinetic energy increases with the square of the velocity, the significance of these velocity increases is more apparent in Fig. 59 in which the kinetic energy of stream flow is plotted for flows of the same discharge with and without gravel filling the pools. Fig. 59 shows up to a 20 fold increase in the capacity of the stream to do work because gravel has filled the pools.

This laboratory study gives support to the field observations which suggest that the effectiveness of a pool riffle morphology to dissipate stream energy is markedly impaired when gravels fill pools and prevent energy dissipation by turbulent mixing. It further aids in our understanding of why it is that this normally stable channel can, in major storms events, transport large quantities of sediment through it, in comparatively short periods of time.

These findings have considerable significance to stream channel management but this will only be briefly noted here.

Figure 55 and 56 shows that in the absence of artificial structures stream
Figure 58

Mean velocities through a laboratory model of a pool riffle channel.

(Ref. Appendix II vol III)
FIGURE 59

Kinetic energy of stream flow in a laboratory model of a pool riffle channel.
(Ref. Appendix II vol III)
flows and channel debris interact to form a discernable and repeatable channel pattern. Any modification to the channel (such as check dam construction, log jams etc.) can be expected to set up new hydraulic conditions which may induce a new channel pattern. For example a debris dam is a major channel structure and if not sited with respect to the existing channel pattern it may set up downstream adjustments which negate the benefits of the structure.

A comparison of the upper Irishman stream and the upper Torlesse stream (true right) suggests that afforestation of the Irishman channel would be more significant in terms of inducing channel and riparian land stability than would comparable treatment of the upper Torlesse channel. Because the upper Torlesse channel contains a diversity of sediment sizes it has formed an ordered and stable channel. In contrast the Irishman stream channel includes few large roughness elements, is poorly ordered and unstable. Perhaps the greatest influence of afforestation in such a catchment would be the formation of steps by logs which fell across the channel. Where these were effective in reducing flow energy, there would be greater stability of both channel and adjacent riparian land.

It has been found that stream energies increase sharply when gravels fill pools and thereby eliminate the opportunity for energy dissipation by turbulent mixing in pools. This finding has significance for those management practices which aim to prevent, or may cause, slope deposits to collapse into a stream channel. In chapter 8 it was shown that a sudden influx of sediment moves downstream as a 'wave'. As this 'wave' moves through each segment of stream channel, flow energies may increase sharply. When the stream is raised out of its normal channel and has access to unconsolidated riparian lands or riparian deposits a proportion of this increased energy is expended in the entrainment and transport of additional riparian sediments. Land management for soil conservation gives emphasis to the retention of soil and slope deposits on site. One important reason in some mountain catchments for this practice can now be stated as the maintenance of stream channel stability. This will in turn, aid in the stability of the slopes subtending the channel.
REFERENCES
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American Society of Civil Engineers (Committee on Sedimentation), 1971: Sediment transportation mechanics (H.) sediment discharge formulas. *Journal of Hydraulics Division, Proceedings American Society of Civil Engineers HY4*: 523-567.


Ashida, K., Takahashi, T., Sawada, T., 1974: Runoff process sediment yield and transport in a mountain watershed. Kyoto University Disaster Prevention Research Institute, Annual report No.17B. (In Japanese)


Holgate, G.L. (personal communication): Plant frequencies within representative sites in the Torlesse Stream catchment.


Horton, R.E., 1933: The role of infiltration in the hydrologic cycle. Transactions American Geophysical Union 14: 446-460.


Jarocki, W., 1957: A study of sediment (Bodanie Rumowski). Wyda wriicthwo Morskie, Poland. (Quoted by Gregory & Walling, 1973)


Maddock, T., Borland, W.M., 1951: Sedimentation studies for the planning of reservoirs by the Bureau of Reclamation Transactions 4th Congress on large dams, New Delhi 4. 103-118.


McSweeney, G.D., personal communication: Plant communities of the Torlesse Stream catchment.


Swiss Federal Authority, 1939: Untersuchungen in der natur Uber Bettbildung Geschiebe-und Schwebest-offUhrung mitterlung des Antes fur wasser wirtschaft 33 Berne. (Quoted by Da Chuna, 1968)


