FLOW ESTIMATION IN AN UNSTABLE RIVER ILLUSTRATED ON THE RAKAIA RIVER FOR THE PERIOD 1958-1978

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ABSTRACT

The application of improved data checking techniques to the hydrological data for the Rakaia River at the Gorge bridge station is described. Inadequacies in the existing data are demonstrated. Use of computer techniques to display gauging data allowed rating change points to be identified. By grouping together consistent sets of gaugings a single type curve was developed. All ratings are obtained by moving the type curve parallel to the water level axis. In this way, small groups of gaugings can be used to fix the position of a rating.

Where there were no gauging data rating changes were based on differences in the water level hydrograph recession levels. To validate these rating changes the annual flows calculated using them were compared with annual means from one other flow station and seven rainfall stations. High correlations were established with West Coast rainfall stations and a more detailed check of the flow data was made using the Hokitika rainfall record. The accuracy of the flow values calculated using the new ratings is assessed and the 95% confidence limits are shown to vary between ±3% and ±11%. The upper limit is associated with three months of record where there were no gauging data and obvious silting problems in the water level record. As a consequence of the work the long term mean flow value was reduced by 5%.

INTRODUCTION

Several major resource developments taking place in New Zealand require reliable estimates of the flow characteristics of some of the country's biggest rivers. The use of the Rakaia River for irrigation, hydro-electric power generation and recreation is a case in point. The hydrological questions posed by the study of water use alternatives in the Rakaia are typical of those asked elsewhere. This report discusses the steps necessary to produce reliable flow estimates using the Rakaia as a specific application of the methodology developed. Numerical answers specific to the Rakaia are presented elsewhere (Ibbitt, 1979a).

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CATCHMENT DESCRIPTION

Figure 1 shows the catchment of the Rakaia River. The majority of the catchment (2640 km^2) lies above the Gorge Station, while below the Gorge the river drains across a narrow band of the Canterbury Plains to the sea. Both upstream and downstream of the Gorge the river is braided; only within the Gorge is the river confined sufficiently to permit continuous flow monitoring. Additional information may be found in Stephen (1972).

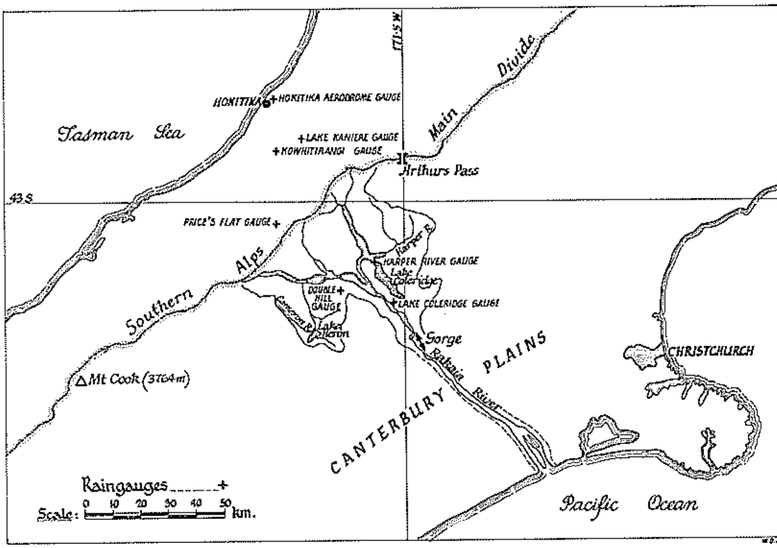

FIG. 1—The Rakaia catchment, South Island, New Zealand.

Upstream of the Gorge the catchment widens towards the main divide of the Southern Alps where small glaciers occur. The precipitation increases dramatically from a mere 864 mm/year at the Lake Coleridge power station to in excess of 5000 mm/year at the divide (Chinn, 1979). The steep rainfall gradient (Fig. 2) shows that nearly half of the mean catchment rainfall occurs in the top fifth of the catchment.

Millions of tonnes of sediment (Thompson and Adams, 1979) pass through the Gorge each year, causing frequent changes of the bed level and hence changes of the stage-discharge rating curve, as well as necessitating regular attention to the water level recorder tower to avoid blockage of the intake pipes.

HISTORY OF DATA RECORDING

Continuous records of water level have been collected at three locations within the Gorge. From 1935 to 1953 charts were collected at a station several kilometres upstream of the Gorge bridge. During this period the few gaugings conducted had the water levels assigned to several different reference levels and in some cases no levels were taken. Although rating curves could probably be constructed using the gaugings and additional information presented in this paper, assigning changes of rating would be difficult, and impossible where there are large gaps in the water level record. About 10% of the water level data for this period is missing. Since flow values derived from the data may well contain large errors, it could be better to simulate the flow of the river from rainfall data and use selected periods of the record to check the results.

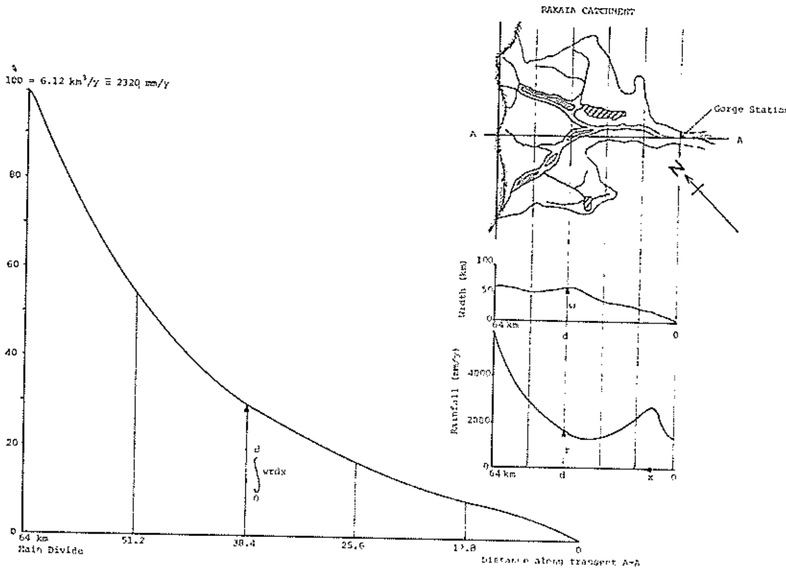

FIG. 2—Approximate cumulative distribution of precipitation across the Rakaia catchment showing the amount occurring downstream of a given location on the transect A-A.

Note: (a) nearly half the catchment precipitation occurs in the top fifth of the catchment.

(b) the 2320 mm/y catchment precipitation compares favourably with the 2340 mm/y catchment runoff considering the approximations in the precipitation analysis.

From December 1957 to the present, a continuous record has been collected just downstream of the Gorge bridge. The water level record is noticeably affected at low flows by the addition of water released from the Lake Coleridge power station while silting has caused differences between the true and recorded water levels to occur. Velocities through the gauging section at the bridge often average 5-6 m/s during periods of high flow and make current meter gaugings difficult and inaccurate, while the shingle bed is unstable and rating changes have been frequent. Unfortunately, few gaugings were carried out in the first six to seven years of the record.

In December 1978 a new station was opened at Fighting Hill, upstream of the Gorge bridge but downstream of the first station. It is expected that this new station will be better than either of its predecessors and that more accurate high stage gaugings will be possible. These gaugings, when related to the level at the Gorge bridge, will also improve the high stage rating for the Gorge bridge station

Upstream from the Gorge are several raingauges with records comparable in length to the water level record at the Gorge bridge. Unfortunately, these rainfall stations are well away from the main divide. The long term station with the highest mean is at Double Hill (Met. No. H31321) but this mean is only 60% of the catchment mean runoff. None of these rainfall stations are, therefore, considered to be representative of catchment mean rainfall. West Coast rainfall stations appear to be better indicators of rain falling in the catchment.

SITUATION AT THE START OF THE INVESTIGATION

The problem was to calculate the flow and flow variation at the Gorge bridge station for the period 1958 to 1978 using the available hydrological data. To produce reliable flow statistics requires all major errors in the water level record to be corrected or at least noted, and all changes of rating to be located and the correct ratings supplied.

The MWD District Hydrology staff had checked and where possible corrected the water level which is kept on a computer file. During the course of this work they noted that for some periods, particularly before 1970, there were distorted records apparently attributable to silting within the recorder tower.

Filed with the water levels were twelve rating curves covering periods from a few months to six years. When gauging data for the site had been loaded it appeared that rating change frequency was directly related to gauging frequency, with a mere 12 gaugings and three ratings during the years 1958-63.

To assess the quality of the ratings, gauged or measured flows were plotted against the flow obtained from the rating curve using the measured water level (the rated flow). Ideally all the gauged values should lie exactly on their appropriate ratings so that when the gauged and rated flows are plotted against one another they should form a single line at 45° to the axes. For the Rakaia gaugings this was not the case (Fig. 3) for many of the differences were well in excess of $\pm 10\%$. Differences of about $\pm 5\%$ could have been expected from measurement errors so a further major source of error is indicated.

ASSESSMENT OF RATING ERRORS

The differences between gauged and rated flows raise the following questions:

1. Is the data spread caused by difficult site conditions leading to inaccurate gaugings?
2. Have some rating changes been missed?
3. Do the ratings have the correct shape?

All three questions are reasonable since the high velocities and mobile nature of the bed would make frequent changes of rating likely. Before assessing the second and third questions, a quantitative answer has to be obtained to the first question in order to know when the scatter in Figure 3 is random and when it arises from some form of systematic error.

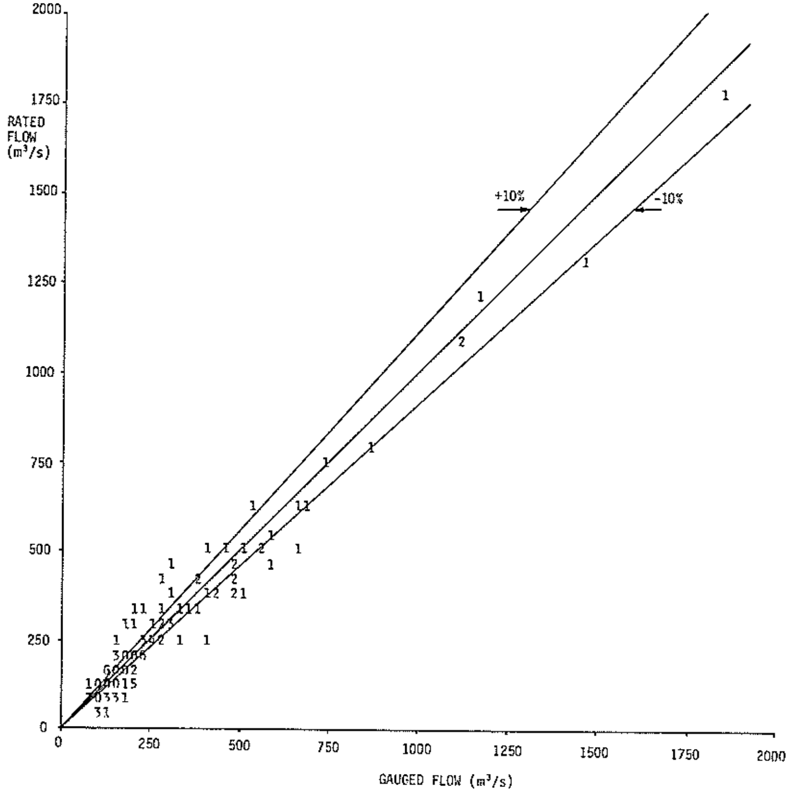

FIG. 3—Rated flow versus gauged flow at the beginning of the investigation (264 gaugings covering the period 25/Feb/58 to 27/Dec/78 have been plotted. The figures used to plot symbols indicate the number of values to be plotted in a given position. A zero represents 10 or more values).

A computer program by Thompson and Wrigley (1974) was used to assist in answering the first question. The program plots, in chronological order, the difference between water level measured at the time of each gauging and the water level calculated from the rating curve using the corresponding measured flow. This difference represents how much the bed level of the river has risen or fallen relative to the bed level at the time the rating was established.

During August 1967 the river was gauged over a large range of flows and it was possible to construct a rating such that the corresponding calculated bed level at each gaug'ng was within ±50 mm of a constant (Fig. 4). Variations up to ±50 mm are believed to represent the size of unavoidable errors in good quality field work, though differences much in excess of this value can arise at high stages. However, a systematic difference in excess of 50 mm occurs after August 1967, and it seems that the quality of the gauging data is high enough to allow more accurate ratings to be constructed. This could not have been demonstrated had there not been an intense period of gauging. There were a number of periods of intensive gauging from 1964 to 1978 and August 1967 was the best of these.

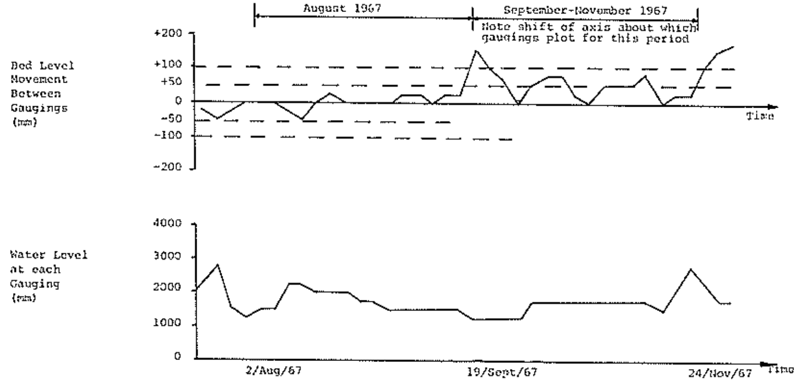

FIG. 4—Apparent bed level movements between gaugings.

For periods such as 19 September to 24 November 1967 the differences show a systematic move away from their zero line and examination of the stage levels at which the gaugings were conducted shows that the differences are unrelated to the stage magnitude (e.g., big positive differences are not consistently associated with either high or or low stage values). This implies that a rating change occurred around 19 September 1967 but that the shape of the rating was not altered, only its position relative to the origin of the water level measurements. Had the rating changed shape, then values in the region of the greatest change of shape would have been expected to show the largest differences.

When gauging are infrequent (less than one per month) gaugings belonging to different ratings may be used to produce a single rating. Distortion of the resulting rating would probably be worst at lower stages where a greater number of gaugings would belong to different ratings. The shapes of the ratings in use at the start of this investigation (Fig. 5) support this deduction.

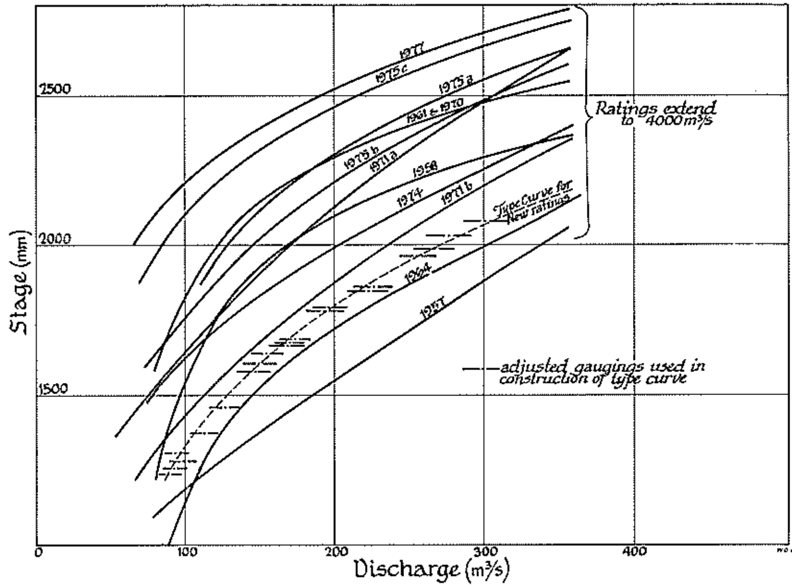

FIG. 5—Comparison of the rating curves at the start of the investigation with the shape of the revised ratings.

CORRECTION OF RATINGS

The plot of "bed levels" from 1958 to 1978 was divided into groups, the criterion for inclusion in a group being that the bed level should vary randomly about an axis parallel to the line of zero movement, with the amplitude of oscillations not exceeding ±100 mm (Fig. 4). The size of the groups varied from 1 to 17 gaugings, with six groups having 10 or more gaugings. The approximate range of flows was from 86 m^3/s to 350 m^3/s, the mean flow being about 200 m^3/s. The large groups of gaugings were then plotted and tentative rating curves drawn. Some groups were unusable for this purpose owing to the limited range of values in the group. The ratings drawn were approximately parallel over the range of values 86 to 350 m^3/s. Adopting Manning's equation

$$q = \frac{A\ r^{\frac{2}{3}}\ s^{\frac{1}{2}}}{n} \qquad (1)$$

in which s is the bed slope, n is Manning's coefficient and q is the discharge through a section of area A and hydraulic radius r, and assuming that the channel has a wide parabolic cross-section then

$$q \propto d^{2.167} \qquad (2)$$

where d is the depth (MWD, 1978a; Appendix 1). Now when sites are established every effort is made to set the origin for water level measurements close to the mean bed level. To test the validity of assuming that all the ratings for the Rakaia are parallel over the range 86 to 350 m^3/s, consider the following four pairs of water levels and discharges taken from the first rating, the shape of which was based on the August 1967 gaugings and the position of which was fixed using the 1958 gaugings.

d (m)	q (m^3/s)
0.860	86
1.260	154
1.465	208
1.737	300

Substituting the 3rd pair of values into equation 2 gives

$$q = 91d^{2.167} \quad (3)$$

Substituting the 1st, 2nd and 4th values for d into equation 3 gives flows of 66 m^3/s, 150 m^3/s and 301 m^3/s respectively. The differences between the calculated and rated flows are −23%, −3% and 0% respectively, the low predicted flow for the minimum point on the rating perhaps indicating a narrow low flow channel through the control section.

This close agreement with equation 2 justifies the assumption that the discharge depends only upon the depth and so the rating curves can be expected to be parallel. Hence there should only be a single shape of curve and it should be moved parallel to the stage axis to fit all gaugings. A flow value near the middle of the range of gauged flows used to construct each tentative rating was selected and the corresponding stage value was subtracted from all the gaugings used to construct the rating. When all the gaugings from all the tentative ratings were adjusted in this way and were plotted together, a single type curve was drawn through them that was very similar in shape to the tentative ratings (Fig. 5). The type curve was then compared with all the groups of unadjusted gaugings to fix the position of the rating for each group. Using the new ratings, fresh plots of bed movement were constructed. Any movements in excess of ±100 mm were then examined. The following reasons are proposed for the movements:

a. The shape of some ratings (e.g., 1957 and 1971a, see Fig. 5) were markedly different from the shape of the type curve and their associated gaugings could be expected to come from more than one distinct rating.
b. Some gaugings, notably at high flows, were likely to contain large errors because of the difficulties of conducting high flow gaugings at this station.
c. Some erroneous gaugings were present, the ones at low flows perhaps resulting from rapid changes of water level during the gauging owing to Lake Coleridge Power Station releases.

Checking of individual gaugings identified under (b) and (c) coupled with (a) led to some minor adjustments in the position of the rating curves and, more significantly, to the introduction of some further ratings changes.

Up to this time the dates of rating changes had been approximately derived by reference to the dates of the gaugings. Frequently, gaugings were many weeks apart, so the stage hydrograph was examined to fix likely events to which rating changes could be related. In some cases no satisfactory event could be found. When this occurred individual gaugings near the apparent change were checked for magnitude and error. Satisfactory dates for all rating changes were obtained. The plot of measured flows against those calculated from the rating curve (Fig. 6) shows that the scatter of the data from the 264 gaugings in Figure 3 has been greatly reduced for flows below 1000 m^3/s. Above 1000 m^3/s gauged flows are believed to be over-estimated owing to the difficulties in carrying out each gauging.

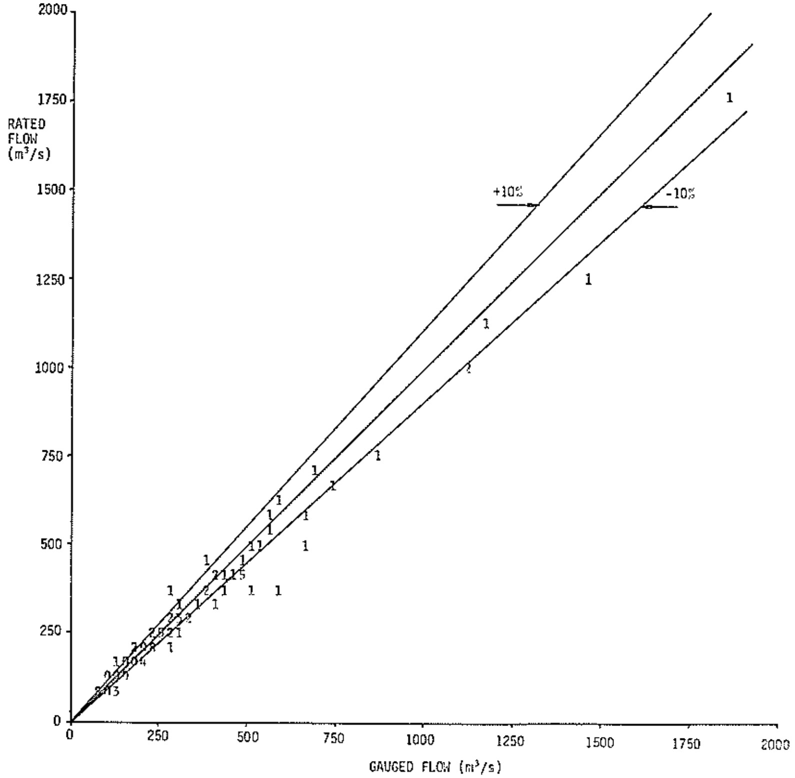

FIG. 6—Rated flow versus gauged flow after revision of ratings (264 gaugings covering the period 25/Feb/58 to 27/Dec/78 have been plotted. The figures used as plot symbols indicate the number of values to be plotted in a given position. A zero represents 10 or more values).

ASSIGNMENT OF RATINGS TO PERIODS WITH FEW OR NO GAUGINGS

For the years 1958 to 1963 there were few or no gauging data. By plotting on the stage hydrograph the dates of rating changes and the levels corresponding to the minimum flow of each accepted rating, a picture was built up of how the river changed ratings during the period when gaugings were available. In particular the July to August water level frequently approached that of the minimum level for the rating (Fig 7). The ratings for the early part of the record seldom showed this characteristic and rating changes were much less frequent during this period. This seemed an unlikely situation.

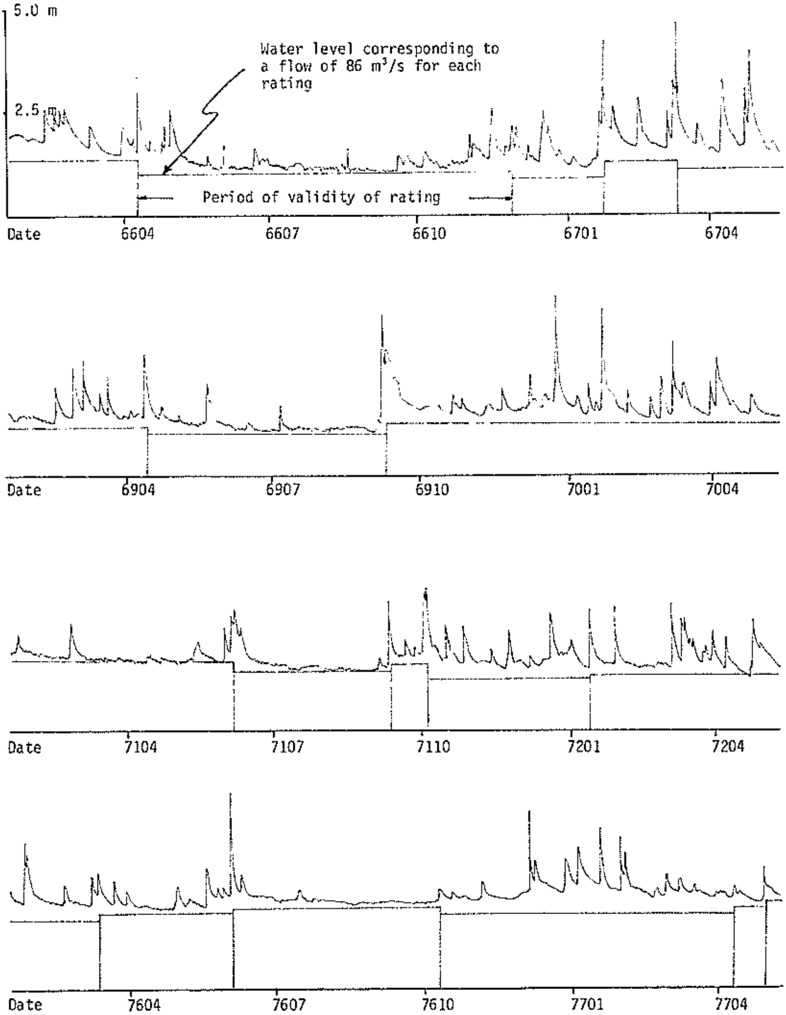

FIG. 7—Water level hydrograph.

The 12 early gaugings (from 1958 to 1963) were rigorously checked and where there was no reason for doubting their accuracy they were used to position the type curve. Floods which appeared to cause significant change in recession level were then identified. The type curve was then positioned by assessing the apparent change in level from the previous rating. Caution has to be exercised when dating rating changes in this manner, since although spring floods often produce rating changes, the change can not always be deduced from a comparison of winter and summer recession levels as the latter may be influenced by snowmelt.

For periods where no gaugings were available, rating changes were made only where there was clear evidence on the stage hydrograph of a change in recession level. Fortunately, this technique can be checked since selecting ratings in this manner can be continued to include one which has some gaugings to justify it. By comparing the two estimates, the differences between them can be assessed and adjustments can be made to minimise this difference.

SELECTION OF A STATION WITH A COMPARATIVE RECORD

The work reported on so far has described how rating curves and rating changes were established from available gauging data. When few gaugings had been conducted, 1958-1963, there was a strong chance that some rating changes would have been missed.

Besides missed rating changes, other errors in the flows were probable. During the original preparation of the water level record occasions were noted when the intake pipe to the recorder well was completely or partially blocked by river sediment. Erroneous levels on these occasions when converted to flows cause additional errors in flow estimates.

To check for errors in the flow from missed rating changes or silting requires comparison of the flows with data that exhibit the same general temporal variation. Rainfall representative of catchment mean rainfall fulfils this requirement as would flows from an upstream station unaffected by silting problems.

The only flow stations with records of comparable length to that at the Gorge are on the Harper River where it is diverted into Lake Coleridge and at Lake Heron (Fig. 1). The Harper is a tributary of the Rakaia and drains the northern part of the catchment. It does not drain any of the main divide where most of the catchment precipitation occurs. Linear regression of the mean annual discharges for the two stations shows that the Harper record explains only 28% of the variation in the Rakaia flow. Lake Heron collects water from a small area in the south of the catchment. Difficulties with rating the lake outlet coupled with uncertainty of how much of the flow of the Cameron River enters the lake in time of flood make the record of little value for checking Rakaia flows.

The rainfall gauges in the catchment with records covering the period 1958-1978 are all well away from the main divide. For the gauge nearest the main divide, Double Hill, a value that is only 60% of the runoff at the Gorge is recorded. Consequently a water balance for the catchment could not be computed using the gauges within the catchment.

The catchment receives most of its rainfall from the northwest. Northwest rainstorms often go unrecorded in the area where the present long-term raingauges are located. Therefore, records for three sites on the West Coast were examined—Hokitika Aerodrome (F20793) and further inland at Kowhitirangi (F21901) and at Lake Kaniere (F21812).

For the Hokitika Aerodrome record it was necessary to substitute values from the Hokitika South station for the years 1958 to 1961, after adjustment to the Aerodrome normals. Hokitika South was closed in favour of Hokitika Aerodrome in 1965. From the station history it appears that maintenance of the Aerodrome station seriously deteriorated in 1965-66 and that in October 1967 the station was moved because of airport building. Since then "exposure and upkeep have been excellent". The Meteorological Office have not issued any adjustments to the 1941-70 rainfall normals for the station and it is concluded that the 1967 move has not significantly affected the record. The Hokitika gauge generally receives less rain than gauges inland, but there are, however exceptions. For a 12 month period starting in late 1961 and extending into 1962 rainfall on the Coast was 3% above normal while inland it was 10% below. This suggested that the inland sites at Lake Kaniere and Kowhitirangi would be better indicators of rainfall in the

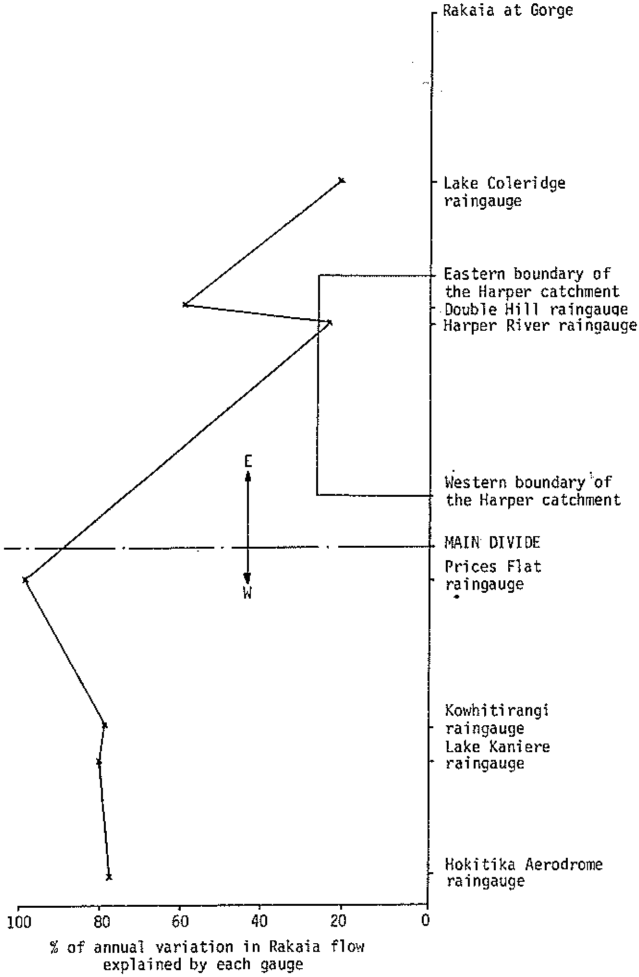

FIG. 8—Percentage variation of annual Rakaia flows explained by various gauges.

headwaters of the Rakaia. Unfortunately the Kowhitirangi gauge was moved a substantial amount in 1964 and eight months of record are missing between June 1964 and February 1965. The history for the Lake Kaniere station is also chequered with poor exposure being reported until 1969, followed by changes of location in 1969 and 1972.

In order to select the best stations for use in a detailed water balance comparison with the Rakaia flows, each station's annual total was regressed against the annual flow in the Rakaia at the Gorge. The results (Fig. 8) illustrate the dominance of north-westerly conditions on the Rakaia flows. The amount of variation explained by the West Coast stations is considerably higher than for the stations east of the Main Divide, with the gauge at Prices Flat in the upper Hokitika explaining 98% of the annual variation in the Rakaia flows. Unfortunately the record from this station covers only a part of the Rakaia record and so is unusable for checking for systematic errors in the whole Rakaia record.

In view of the station histories for the Lake Kaniere and Kowhitirangi gauges, the supplemented and adjusted Hokitika Aerodrome record was selected for further comparison with the Rakaia flows.

RESIDUAL MASS ANALYSIS OF HOKITIKA RAINFALL AND RAKAIA FLOWS

The analysis follows that described in MWD (1978b). First annual cycles were removed from the monthly series of flow and rainfall by taking 12 month moving means. Each of these values then had its record mean for the period 1958-1978 deducted, and this difference was expresed as a proportion of the record mean. When suitably weighted, the difference between the rainfall and flow results represents the departure of the 12 month moving mean evaporation from its record mean. The importance of this difference is that, because its annual cycle has been removed, its variation about its mean is small (Finkelstein, 1973). Accumulation of these differences highlights trends which show in the data as a series of increasing or decreasing values. While trends in the rainfall or flow values lasting several years may arise because of a series of wet or dry years, little variation in their accumulated difference is expected, and where significant trends are detected at least one of the following causes is likely:

1. The chosen index of catchment mean rainfall is not representative.
2. Prolonged droughts have reduced the water available for evaporation and invalidated the assumption that annual evaporation does not vary.
3. There are errors in the rainfall or flow record. Such errors may range from large and of short duration to small and of long duration. While the former type of error should have been detected by routine data checking, the latter type of error can be cumulatively significant and is easily detected by this calculation.

When this analysis was applied to the Rakaia flows and Hokitika rainfall the following points were noted.

Significant trends occurred in the 1960-63 period. Only four gaugings cover this period, two in early 1960, one in 1961, and one in late 1963.

It was, therefore, highly probable some rating changes had been missed. Examination of the recession levels of the stage hydrographs confirmed this suspicion. Some additional ratings were introduced, the type curve position being determined by using the apparent changes in recession level to relate rating movement to ratings in 1959 and 1964 whose positions depended on gauging data. Rerunning the residual mass analysis confirmed the changes when allowance was made for the previously mentioned unusual rainfall situation in late 1961-62.

Significant trends occurred in 1967-68. Since the ratings for this period had been confirmed by gauging data, other sources of inconsistency were investigated. The known deterioration in raingauge exposure at Hokitika Aerodrome in 1967 is believed responsible for most of the early inconsistency, while after October 1967 errors in the water level record caused by the partial blockage of the recorder well intake pipe are the most likely. These were known to have been bad in early 1968 and would cause the flows to be overestimated resulting in an underestimation of the evaporation. This agrees with what was observed (Fig. 9): the error arising from the 1967-68 inconsistencies can be estimated as equivalent to between two and five months of mean evaporation. For an annual evaporation of 800 mm these figures correspond to between 130 and 330 mm for the year.

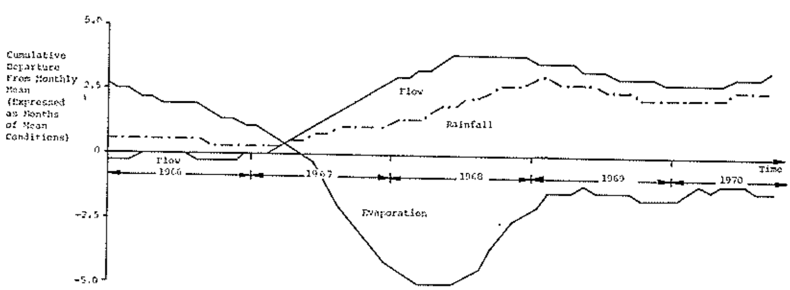

FIG. 9—Cumulative departures from the monthly means expressed as a proportion of the long term monthly mean.

Since probably one-fourth of this error results from the raingauge undercatching, the effects of the blockage of the intake pipe probably represents an error of between 100 and 250 mm in the annual runoff for 1968, corresponding to an overestimate of the annual flow by 4%-10%. Corrections have not been made to this period owing to the large amount of work involved. Since no other major departures occurred, the other less serious periods of silting that had been noted appear to have an insignificant effect upon the long term flow pattern.

ACCURACY OF FLOW ESTIMATES

In the estimation of flows from water level and rating curve there are three major sources of error:

a. random errors in the water level measurement;

b. semi-systematic errors arising from imperfections in the shape of the rating curve; and
c. systematic errors arising from failure to detect changes of rating.

The first source of error is probably the least significant provided a recorder of reasonable precision is used to record water levels. The errors are random and when averaged over a period of time they tend to cancel out. An estimate of their size can be obtained from the precision of the recorder. For the early Rakaia data 0.5 mm of chart movement corresponded to 12 mm of actual water level movement. Using this as the 95% confidence interval on water level measurements it converts to an error in an instantaneous flow estimate of ±1.5%. For a fuller explanation see Ibbitt (1975).

The second source of error can be treated as the estimation of the standard error of estimate for a non-linear regression analysis between water levels and their corresponding measured flow. Ibbitt (1975) deals in detail with this source of error. For the Rakaia all of the 227 gaugings in the flow range 86 m^3/s-350 m^3/s during the period of record contribute some information to the shape of the type curve. Since the 95%* confidence limits on an individual gauging can be expressed as ±100 mm, corresponding flow estimates derived from the type curve vary from ±12 m^3/s at a flow of 86 m^3/s to ±54 m^3/s for a flow of 350 m^3/s. In terms of proportional errors the 95% flow limits are approximately constant at ±15% for the range of flows 86 m^3/s-350 m^3/s. No significant improvement in these limits is likely using present techniques at this site.

The standard error of estimate for instantaneous flow values computed from a rating based on the type curve, will be approximately:

$$\frac{15}{\sqrt{227}} \% \simeq 1\%$$

This form or error is semi-systematic; as long as the flow does not change greatly the error in each instantaneous flow estimate can be expected to have the same sign. Only when the flow changes sufficiently will shape errors in different parts of the rating compensate for one another in the calculation of a flow over a finite period of time, e.g., one month.

The third source of the error is the most systematic in that if a rating change is missed a whole series of instantaneous flow estimates will either be under or overestimated. Only in the calculation of mean flows for many years of record will errors of this type compensate (Ibbitt, 1979b). Since the magnitude of an error is related to gauging frequency a single figure cannot be applied to the whole record. Instead the period 1958-78 was subdivided into periods with and without frequent gaugings. For the periods 1 April to 1 February 1968 and 1 April 1969 to 1 January 1979 the mean time between gaugings was 23 days with a standard deviation of the mean of 1.5 days. Assuming the mean times between gaugings are normally distributed there is a less than 5% chance of the

* Of the 227 gaugings in the flow range 86 m^3/s-350 m^3/s, 9 actually plot outside the ±100 mm limits, i.e., 4% of the values (see Ibbitt 1979a). This confirms that ±100 mm. are realistic 95% confidence limits.

mean period exceeding 23 + 1.65 × 1.5 = 25.5 days. Using 25.5 days and a rating change frequency of once per 120 days with the graphs in Ibbitt (1979b) gives 5% chance that flow errors will exceed ±2%. Table 1 summarises the data for all the periods.

Period	95% Confidence Interval on Flows Over Periods Up to 1 Year
17 Dec 57 to 1 Apr 64	greater than ±20%
1 Apr 64 to 1 Feb 65	±2%
1 Feb 68 to 1 Apr 69	greater than ±20%
1 Apr 69 to 1 Jan 79	±2%

TABLE 1—95% confidence intervals for instantaneous flow errors arising solely from missed rating changes.

Table 1 is based solely on frequency of gaugings. Had flow errors greater than 20% occurred for more than a few months during the periods 17 Dec 1957 to 1 April 1964 or 1 Feb 1968 to 1 April 1969 they would have been detected in the comparison with the rainfall data. This is because a 20% flow error for a period greater than five months would be equivalent to an accumulated flow error of at least one month's mean flow. Since the annual runoff for the Rakaia is approximately three times the annual evaporation, an evaporation departure of more than three units would have occurred (departures of more than three units are only expected on average for 5% of the length of a record according to MWD (1978b)). For the period 17 Dec 1957 to 1 April 1964 evaporation departures seldom exceed ±1 month (see Ibbitt 1979a) if the period 1 July 1967 to 1 July 1962 is discounted on account of the known anomalous rainfall distribution. If variation in the cumulative departures for 17 Dec 1957 to 1 April 1964 is attributed to errors arising from missed rating curves, and if, on average, a rating lasts for four months (Ibbitt 1979b) the corresponding consistent flow error is about 8% (four months with an 8% flow error = a flow departure of 0.32 months = an evaporation departure of 3 × 0.32 months because runoff ≃ 3 × evaporation). Thus the 95% confidence limit used in the calculation of the overall 95% confidence limit has been taken as 8%.

By assuming independence between the different types of error the overall 95% confidence limits can be calculated as:

$$\sqrt{1.5^2 + 1^2 + x^2 + s^2}\ \% \qquad (4)$$

where x is the error arising from missed rating changes and s is the error arising from silting problems. The value of x is either 2 or 8 while the value of s has been taken as 7% for 1968 and 0 otherwise. The final results are presented in Table 2.

Since the values in Table 2 are for instantaneous flows some reduction in the error at the 95% confidence interval can be expected in the calculation of daily and monthly flows. The actual amount can be derived by deleting the water level error but because of the form of expression (4) this will not reduce the final 95% confidence interval by more than 0.5%.

Period	Probable % Error at 95% Confidence Interval From: Water Level	Rating Shape	Missed Ratings (x)	Silting (s)	Final 95% Confidence Interval %
17 Dec 57 to 1 Apr 64	1.5	1.0	8.0	0.0	8
1 Apr 64 to 1 Dec 67	1.5	1.0	2.0	0.0	3
1 Dec 67 to 1 Feb 68	1.5	1.0	2.0	7.0	8
1 Feb 68 to 1 May 68	1.5	1.0	8.0	7.0	11
1 May 68 to 1 Apr 69	1.5	1.0	8.0	0.0	8
1 Apr 69 to 1 Jan 79	1.5	1.0	2.0	0.0	3

TABLE 2—95% confidence intervals for each source of error in an instantaneous flow estimate.

WATER LEVEL DATA AFFECTED BY SILTING

From the start of data collection at the Gorge bridge, silting of the recorder tower has been a problem. Fine sediment enters the recording well intake pipes, and may block or partially block the intake pipe or fill the well to such a level that the recorder float is unable to record low water levels because it comes to rest on the silt.

Coarse sediment that cannot enter the intake pipe may cover the inlets to the intake pipe, with partial or complete blockage. Since the blockage is external to the intake pipe it may be cleared by the river naturally eroding bed material and may not be detectable by field inspection because it is not occurring when the site is visited.

Silting is inferred from the water level record when the recession is zero or unduly slow. Most of these periods of silting noted in Ibbitt (1979a) appear to result from partial blockage of the intake pipe and, with the exception of the period in 1968 which has already been discussed, have been of minor significance.

Total blockages did occur in 1958 and 1965, which effectively caused the water level to be lost. Owing to the low correlations between the flows at the Gorge and other flows measurements within the catchment, even when available, constructing a credible record would be difficult and has not been attempted. Thus seven monthly means have been lost in the period 1958-78 (January to April, August, and September 1958, and January 1965). The effect of not using the January and February 1958 flows in the calculation of long term monthly means is significant because they were months of extremely high flow arising from a very wet period. Rainfall for the period September 1957 to February 1958 was 61% above normal at Hokitika. Coarse estimates of the monthly flows for January and February 1958 show them to be greater than any of the 20 subsequently measured January and February flows. These flows lie outside the reliable range of the rating curves and are approximately twice the average monthly flow.

From the foregoing it is apparent that silting has had a substantial effect upon the flow statistics of the Rakaia River at the Gorge. Fortunately close examination of the water level record coupled with comparison with rainfall data has identified the periods when errors were greatest.

DISCUSSION

The flow record for the Rakaia at Gorge Bridge can be divided into three periods:

1957-1964 The water level record was affected to varying degrees by silting and few gaugings were conducted, making the estimating of rating changes less certain than in later records.

1964-1970 The water level record was affected by silting which reached serious proportions in 1968 when it probably caused the flow estimates to be overestimated by approximately 7%. Rating changes for this period are based on gauging data which on the whole was of a good standard, i.e., most gaugings had more than 20 verticals and velocities were taken at the surface and at 0.8 and 0.2 of the depth.

1970-1978 Apart from some minor silting in 1972-1974 this period appears to have the best water level records. Rating changes are based on gauging data which was not up to the standard of earlier work, i.e., many more gaugings had measured velocity only at 0.6 of the depth. (Compare the bed movements for the gaugings done between 22 June 73 and 21 Feb 77 (Fig. 10) with those for the period 2 to 25 Aug 67 (Fig. 4)).

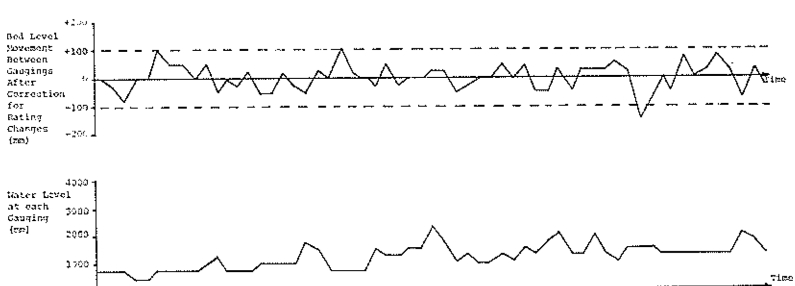

FIG. 10—Apparent bed level movements between gaugings, when the gauging technique used only measured point velocity at 0.6 of the depth.

Examination of the gaugings has highlighted two aspects of the gauging programme needed for unstable rivers like the Rakaia. Firstly, periods of intense gauging, preferably on a long recession following a major storm, are needed. For the Rakaia this period could typically be anytime from the end of June through to the end of August. Secondly, the river must be gauged regularly, i.e., every two to four weeks irrespective of whether the stage at which the previous gauging was conducted was similar. The reason for this is that each gauging's prime purpose is to establish whether or not a change of bed level has occurred. Use of a type curve based on the intensive gauging programme determines the shape of the rating.

The shape of the type curve developed for the Rakaia using data from periods of intensive gauging is regarded as reliable from a flow of 86 m^3/s to flows of about 350 m^3/s. Above 350 m^3/s high velocities through the gauging section cause gaugings to be inaccurate as well as few in number. Gaugings at the new Fighting Hill station should allow improvements to the high stage rating.

Comparison of flows with preciptation at various rainfall stations showed the flow pattern to compare most favourably with West Coast rainfall. This is probably because West Coast gauges more accurately reflect the north-westerly conditions prevailing in the upper catchment. Gauges to the east of the divide within the lower part of the catchment are not representative of catchment rainfall.

In some of the months of record, the change in flow estimate has been more than ±10%. Differences of this magnitude arise from errors in the shape of some of the previous rating curves and also from rating changes that had been missed. Detailed examination of the errors in flow estimation indicate that instantaneous flow values can be expected to be within ±10% of their true value on 95% of all occasions. From April 1969 the 95% confidence intervals reduce to ±3% owing to a regular frequency of gaugings and minimal silting problems.

Table 3 summarises the old and revised estimates. For comparison, data using the old ratings and all water level data in spite of silting problems are included. Using all the data with the new ratings has reduced the estimate of long term mean flow by 5% and the mean of some of the monthly mean flows by more than 10%.

	Value at Start Of Investigation	Value After Revision	% Change Over
Month	m^3/s	m^3/s	Initial Values
Jan	266	238 (254)	−11 (−5)
Feb	221	190 (204)	−14 (−8)
March	220	202 (206)	−8 (−6)
April	202	201	0
May	193	192	−1
June	156	156	−4
July	136	126	−7
August	150	145	−3
Sept	181	186	+3
Oct	216	213	−1
Nov	263	262	0
Dec	255	247	−3
Annual	206	196 (199)	−5 (−3)

TABLE 3—Changes in monthly and annual mean flows, for the period 1958-1978.

The large percentage changes for January, February, and March arise because, owing to silting problems and missing records, the values for all three months in 1958 have now been omitted from the revised calculations. Making a rough estimate of the data for the missing months gives the figures enclosed in parentheses. The significance of the missing months in early 1958 is considerable. Their exclusion from the calculation of the statistics for the record is debatable, but on balance it was considered that they should *not* be included because they are of dubious accuracy and are not typical of mean conditions. They arise from extreme weather conditions and cause indicator statistics of average river behaviour to be overestimated.

Whether or not the missing 1958 statistics are included in the estimation of the mean monthly mean flows, there are still significant differences between the two sets of values. For example the annual mean has been reduced by 5% (3% if 1958 values included). This change is the direct result of improved processing techniques.

CONCLUSIONS

Although this paper has described an investigation into the data for a particular river, many of the conclusions that have been reached have application to similar rivers in New Zealand and elsewhere as follows:

1. Scatter of gaugings about rating curves is sensitive to the quality of the gauging technique.
2. For natural channels, particularly ones where rating changes can be attributed mainly to rises and falls in the general level of the bed, and the flow occupies the full width of the channel at all times, all ratings will have a single shape for flows less than those needed to fully mobilise the bed load and so cause a change in channel resistance.
3. Where the shape of ratings are the same the gauging programme should have:
   a. a series of gaugings over a range of flows during a long recession to establish rating shape;
   b. a regular programme of gaugings preferably over a limited range of flows to establish when rating changes occur; and
   c. flood gaugings as opportunities allow to determine the high stage of rating.
4. Monthly flow variation within a catchment, particularly where there is a high orographic barrier in the path of the prevailing rain bearing winds, may be explained by rainfall records collected outside the catchment but in the track of the prevailing winds.
5. Careful application of data processing techniques can make substantial improvements in the values and reliability of flow statistics.

Conclusions particular to the Rakaia are that:

1. field measurement errors were not responsible for the large differences between the gaugings and the rating curves except at high flows;
2. rating changes had been missed and that the shapes of some ratings existing at the start of the investigation were distorted because they had been constructed using gaugings relating to different ratings;

3. West Coast rainfall is a good indication of the monthly variation in Rakaia flows; and
4. improved data processing techniques have caused a decrease in the recorded mean flow for the Rakaia of approximately 10 m^3/s.

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