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Quality of long flow records for New Zealand rivers

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Abstract

Residual mass curves for several long records from nearby recorders can be compared to identify discrepancies in data. For New Zealand, four of six rainfall records and two of nine discharge records extending from 1930 or earlier are shown to probably contain error. Outflows for a lake in the central North Island are shown to be inconsistent with long rainfall records; this is attributed to the works at the lake outlet to divert water to an early power station that no longer exists. Comparison of inflows for seven adjacent South Island lakes indicated serious discrepancies in the Lake Pukaki data. Corrections are suggested which reduce the estimated mean inflow for 1927-1992 from 132 m^3/s to 124 m^3/s. Standard time series analysis methods suggest that the series show no evident trends or multi-year cycles.

Introduction

Intense interest centres on the long-term variability of the hydrological cycle. This interest arises from several concerns: the impacts of global warming and climate change, and also from the need to develop and implement appropriate hazard mitigation strategies. For example a drought occurred simultaneously in the South Island Southern Alps and the central North Island of New Zealand during 1991-1992. Consequent hydroelectricity shortages during the unusually cold winter in 1992 caused a 0.5 percent loss of growth in gross domestic product.

Long-term climatological and hydrological series may be used to identify possible trends and cycles of climate change. A recent report (Lins and Michaels, 1994) links increasing U.S. streamflow to the effects of increases in the greenhouse gases. The longest records that are available are the most valuable, however, the quality and consistency of these records is often of concern.

In studies of rainfall, homogeneity of the data requires that a record be gathered using one unchanged gauge in a location where the exposure of the gauge is unaffected by building construction or tree growth. Over periods of 60 years or more this is rare: indeed the histories of long-term climate stations in New Zealand (Fouhy *et al.*, 1992) show that some shifts have occurred at most long-term rainfall recording sites.

With streamflow records, water level (also termed stage) is measured, and discharge is deduced by applying a stage-discharge rating curve. The standards for recording water levels and constructing stage-discharge rating curves have tightened over the decades (McKerchar, 1986), so that the random and systematic uncertainties of early records almost certainly exceed those of recent records.

This study examines the properties of nine of the longest streamflow records available for New Zealand. Two of these records began in 1906 and the remainder commence in the 1920s or early 1930s. Residual mass curves are used to display departures of segments of record from the long-term mean.

Periods of extreme rainfall, as measured at a raingauge in a catchment, are expected to correspond to periods of extreme runoff. Where two or more rainfall records are available within a catchment, or where several flow records for adjacent catchments are available, a departure evident in one record from a consistent pattern shown in two or more other records is suggestive of an error in the record showing the departure. Thus we use the correlation between long-term records to verify the quality of records.

Records of the long-term behaviour of discharge are of interest for climate change as each record represents the integration over a catchment area of precipitation minus evaporation. Analyses of discharge records thus complement climatological studies of precipitation and temperature, which rely on point measurements.

All the early discharge measurements in New Zealand were initiated to determine the hydroelectric potential of the catchments. Much of this potential has subsequently been developed. The findings thus have major economic significance because these catchments contain hydroelectric stations that typically generate 65% of the electrical energy produced in New Zealand. The national energy generation system is a complex assemblage of hydro and thermal plants. Since controlled water storage in which to store surplus runoff for power generation during dry periods is limited, the generating system is particularly vulnerable to sustained widespread drought. The long-term discharge series are constantly being used to schedule the operation of this system. Determining the integrity of the discharge records is thus very important.

Climatological studies

Traditionally, long-term variability is assessed using climatological records (rainfall, temperature), as these are often the only long (greater than 50 years) systematic records available. Even so, most climatological records have been affected by changes in recording instruments and instrument location, which may influence the homogeneity of the records. We define hydrological or climatological series as homogeneous if the variations observed in a series are caused by, and only by, variations in weather and climate.

Study of trends in New Zealand rainfalls and temperatures for the period 1920-1990 (Salinger *et al.*, 1992a,b) has yielded mixed results. After short-term fluctuations were eliminated using a Gaussian numerical filter, annual rainfalls were shown to contain quite large fluctuations. For the 1980s, all North Island stations, except for those in the far north, were drier than average and South Island stations, apart from the east coast, were wetter than average. There were no obvious long-term trends in any of the series. For almost all stations studied, the 1981-1990 decade was the warmest on record. Between 1941-1950 and 1981-1990 North Island temperatures increased uniformly by 0.8 degrees C. South Island temperature increases averaged 0.7 degrees C, and ranged from 0.8 degrees C in the west and south, to 0.5 degrees C in inland areas.

Data and methods

Discharge series complement climatological series. The complementarity is given by the continuity equation:

[runoff] = [precipitation] - [evaporation] - [groundwater recharge] - [increase in snow and ice volume]

Increases, or decreases, in snow and ice volume affect the runoff of some South Island basins, and both this and evaporation are at least in part a function of prevailing temperature. Thus runoff, defined as discharge per unit area, is a function of both precipitation and temperature. Moreover, runoff is the integration of a response over the entire area of a river basin, whereas rainfall and temperature measurements are point measurements and are vulnerable to changes in exposure caused by tree growth and building construction.

Discharge records are especially important in the mountainous South Island (total area 150 000 km^2). About 15 000 km^2 of the Southern Alps receives more than 4.8 m/year precipitation, (NZ Met. Service, 1985) but this region is sparsely populated, and the long-term rainfall records are mainly from raingauges at more attractive (drier) locations. The study by Salinger *et al.* (1992a) used just one gauge from this higher rainfall region (Milford Sound: mean rainfall = 6.2 m/year). The region is the source of many of the larger rivers, and their discharge records provide spatially integrated data on the moisture fluxes.

In New Zealand a useful rule of thumb for catchments that have negligible groundwater losses and receive more than about 800 mm/yr rainfall is that evaporation plus transpiration is about 700 mm/yr and varies little from year to year. In many Southern Alps catchments mean runoff plus about 700 mm is the best available estimate of mean basin rainfall.

Quality of discharge records

Long-term discharge records are not of consistent quality. Standard practice in recording discharge is to record stage (i.e. water level above a datum), and use velocity-area methods to gauge discharges in the river for a range of stage values. A stage-discharge curve, termed a rating, is fitted to the gauged data, enabling the recorded stage values to be transformed to discharges. The quality of a discharge record thus depends on the sensitivity and stability of the stage-discharge relationship (Mosley and McKerchar, 1993). Commonly this is affected by the movement of sediment in the river channel, especially during floods, and occasionally by vegetation and aquatic weed growth. Regular gaugings are necessary to confirm that the rating is still applicable, or to determine the shape of the altered rating.

Typically, the earliest readings of long-term records of levels are irregular daily staff gauge readings. Coarse resolution float-actuated chart recorders introduced in the 1930s were replaced by finer resolution instruments in the 1940s and 1950s. In the 1960s, these were displaced by electrical-mechanical recorders, also actuated by floats in stilling wells, that produced machine-readable punched tapes. In turn these instruments are being displaced by data loggers actuated by shaft encoders. Modern hydrometric practice (Mosley and McKerchar, 1993) operates to codified standards and quality assurance programmes, giving confidence about the quality of recent records. It is records from the 1960s and earlier that are of concern for homogeneity. With the changes in instrumentation, there have been changes in the level datums, and in some cases the relationship between the datums is not known. Tectonic movements (McKerchar, 1996) can cause shifts in datums that may not have been allowed for in data analysis.

Since rivers fed by lakes are attractive for hydroelectric development, most of the long records available are actually lake levels. The rating curves to obtain discharge are for hydraulic conditions at the lake outlet, which is generally stable and unaffected by sediment movement.

Where the outflows have been controlled, or where lake inflows have been augmented by diversions from other basins (e.g., Lake Pukaki, Lake Taupo) the series are no longer homogeneous. It is routine practice to use records of diversions, lake levels and outflows to compute a series of inflows for the natural lake catchment that should be homogeneous.

Change in land use, particularly the large-scale conversion of short pasture to exotic forest, may affect evaporation and runoff. The forest canopy intercepts precipitation, affecting evaporation. Less rain reaches the ground, and soil moisture is depleted through both lessened moisture input and the greater rooting depth of trees; hence there is less runoff. Afforestation has been extensive in the North Island. Much of the conversion, however, has been from scrub to forest, rather than pasture to forest, so the effect may be minor.

Residual mass curves

Long-term discharge records should be scrutinised to ensure that possible errors are not attributed the status of trends or changes in long-term discharge. This paper uses residual mass curves, also termed cusums, to investigate the homogeneity of long-term discharge records in New Zealand by comparing curves for adjacent records. Residual mass curves are generally better for visually detecting changes in observations than plots of the observations themselves.

A residual mass curve for a times series x_t is defined as:

$$C_t = \sum_{i=1}^{t}(x_i / \bar{x} - 1) \qquad (1 \le t \le N)$$

where C_t is residual mass and $\bar{x} = \sum_{i=1}^{N} x_i / N$ is the mean of the series. The quantity C_t can be interpreted as the cumulative departure from the mean to time t, in units of time. At time t, it gives the number of time units (e.g. months) of the mean by which the accumulated x_t departs from the mean.

Where the series x_t contains a sequence of lower than average values, a plot of corresponding C_t values against t will show a negative gradient. Where the series x_t has a sequence of above average values, a plot of the corresponding C_t will have a positive gradient. A x_t series containing a trend is expected to produce a C_t series with a parabolic shape. A shift in the mean value of the x_t series should be evident as a change in gradient of the C_t plot.

Rhoades and Salinger (1993) use residual mass curves to guide adjustment of temperature and rainfall records to allow for site changes. Also, the curves have been used for more than a century to help determine the capacity required for storage reservoirs.

Records used

Nine long-term discharge records used in this study are described in Table 1, and the locations of the drainage basins are shown in Figure 1. Rainfall series used to complement the analysis of the discharge records are listed in Table 2 and located in Figure 1. In this study the data are handled at a time interval of a "standard" month equal in length to 365.25/12 days. To eliminate seasonal cycles and focus attention on between-year term properties, a 12-month moving average is applied to each raw series and the first 12 months of data are not used in the subsequent analysis. Averaged values are indexed by date at the end of each time interval.

Monthly totals for each raingauge were checked for omissions by examining each value of zero to ensure that it was matched by low values for other records for gauges in vicinity, and with recession flows for the flow record. Values missing in rainfall records were estimated by copying monthly totals for another nearby record, scaled by the ratio of 1951-1980 normals.

The most serious deficiency was in the Waiotapu Forest record, which had 31 months of data missing in the period 1987 - 1991. The missing values were estimated using scaled values from the nearby Whakarewarewa record. These recent deficiencies, also evident in a number of other records considered for use in this study, relate to a time of rapid restructuring of government agencies which had operated long-established manual raingauges in many locations.

All the discharge records are for lakes, and as most of the lakes have had control structures at their outlets during the period of recording, series of inflows have been calculated using the continuity equation for discrete time steps.

[mean inflow] - [mean outflow] = [increase in lake storage] / [time step]

Outflows are used for Lake Rotoiti, which although controlled by gates since 1981 has modest storage changes. Details of the inflow calculations are in Gilbert (1978).

Results

Kaituna River

The residual mass curve for the Kaituna River at the Lake Rotoiti outlet

Table 1 - Lake records used in this study

Lake	Year level record starts	Basin area (km^2)	Mean inflow (m^3/s)	Runoff (mm/yr)	Year raised & controlled	Notes
Rotoiti	1906	632	21.7	1080	1981	1
Taupo	1906	3289	127	1220	1941/42	2
Ohau	1923	1135	81.6	2250	1979	3
Pukaki	1925	1420	123	2890	1948/54,1979/80	3,4
Tekapo	1925	1440	81.7	1770	1951/53	3
Wakatipu	1924	3133	160	1610	1926	5 ,6
Wanaka	1930	2628	193	2320	not controlled	5
Hawea	1930	1428	65.3	1440	1958	5
Te Anau	1926	3124	267	2700	1973	-

Notes:

1 The record after December 1981 is from site 1114609, Kaituna at Taaheke. It is multiplied by 0.961 to allow for lateral inflow between the lake outlet and this recorder.

2 Inflows calculated are for the natural catchment of Lake Taupo: diversions into Taupo from the Tongariro Power Development since 1971 have been subtracted.

3 Detailed histories of the Waitaki lake records are in Jowett (1981).

4 The Pukaki lake inflow excludes the Tekapo B Power Station discharge which has added water to the lake from August 1977.

5 Detailed histories of the records for these lakes are in Jowett and Thompson (1977).

6 There are low-level gates at the outlet which are usually open.

Table 2 - List of rainfall records used in this study (Normals from NZ Meterological Service, undated)

Station number	Name	Record start	Record end	1951-1980 normal (mm/yr)	Notes
861204	Rotorua	1906	1990	1510	1
863401	Waiotapu Forest	1906	1990	1440	
858201	Taumarunui	1916	1992	1460	
866002	Taupo	1906	1992	1190	2
307101	Hermitage	1930	1992	3990	
476901	Milford Sound	1930	1992	6210	

Notes:

1 This record was compiled by Salinger *et al.* (1992a) using data from several gauges with adjustments for homogeneity.

2 Uses gauge 866001, until November 1949 adjusted by ratio of the 1951-1980 normals.

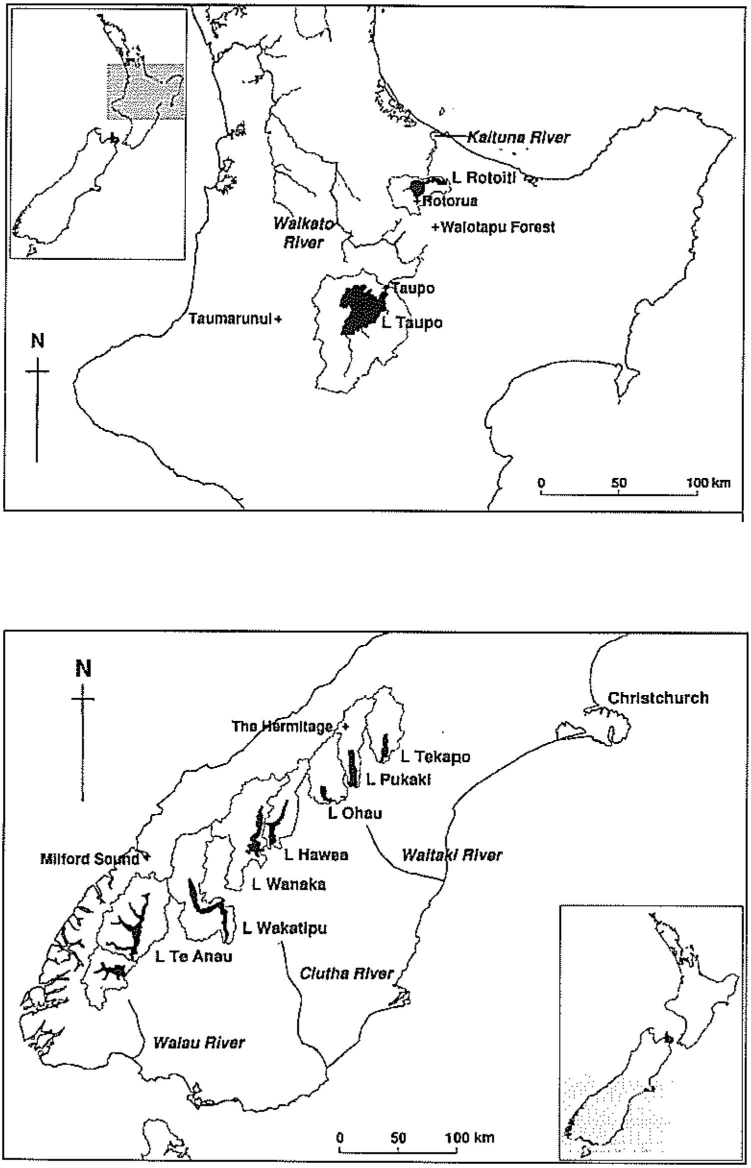


Figure 1 - Maps showing locations of North and South Island catchments listed in Table 1 and raingauges listed in Table 2.

for the 84 year period 1907-1990 is compared in Figure 2a with the curves for Rotorua and Waiotapu Forest rainfalls for the same period. These plots show general agreement between the series, with a positive trend for the period 1953 through 1972. However, there are discrepancies between the series which affect the plots.

For 1911-1912 the Waiotapu rainfall curve drops rapidly whereas the other two drop at much lower rates. For 1986 the Rotorua rainfall curve rises, in contrast to virtually constant values for the other two records. Further, there is an apparently anomalous peak in the curve for Kaituna flows just before 1940.

Comparisons of plots of daily rainfalls for the periods noted revealed no sequences of missing data. The rise seen in Rotorua in 1986 may relate to site changes for the gauges used in compiling the Rotorua record (Table 2). When the residual mass curves are recalculated for the period 1913-1983, the result (Fig. 2b) is a set of curves showing a much greater consistency. In particular, the two rainfall curves agree well, suggesting that any further anomalies probably lie in the flow data.

The only documentation for the Kaituna recorder site that could be found was the comments that accompany the archived water level data. These report that the data until 1942 are from intermittent staff gauge readings. In 1942 a Littlejohn chart recorder was installed, with a time resolution of 1.2 days/mm recorded and a stage resolution of 24 mm stage/mm recorded. There is a note that most "Early Littlejohn record should be treated with caution due to little or no routine periodic inspection/checking". Subsequent replacements with instruments with progressively finer resolutions occurred in 1956 and 1965.

Clearly the standard of measurement has improved over the years. The residual mass curve since the 1950s when the recorder was upgraded shows reasonable agreement with the rainfall curves and the Kaituna record must be flagged as unreliable for the 1920s - mid 1950. The departure of the flow residual mass curve from the rainfall residual mass curve indicates that Kaituna flows from the mid 1920s to 1940 are overestimated, and flows for 1940 - about 1950 were underestimated. Any analysis of the long-term properties of the whole series is likely to be distorted by these apparent errors.

An early hydroelectric development at the Okere Falls, on the Kaituna River just below the Rotoiti outlet, is a possible cause of the discrepancy. The scheme began operating in 1901, by diverting lake outflows through a timber water race to two 50 kW generators that utilized a head of 14 feet (Martin, 1991). Assuming an efficiency of 50% for these plants, the diverted discharge would have been 4.8 m^3/s. In 1907 and 1908 the capacity

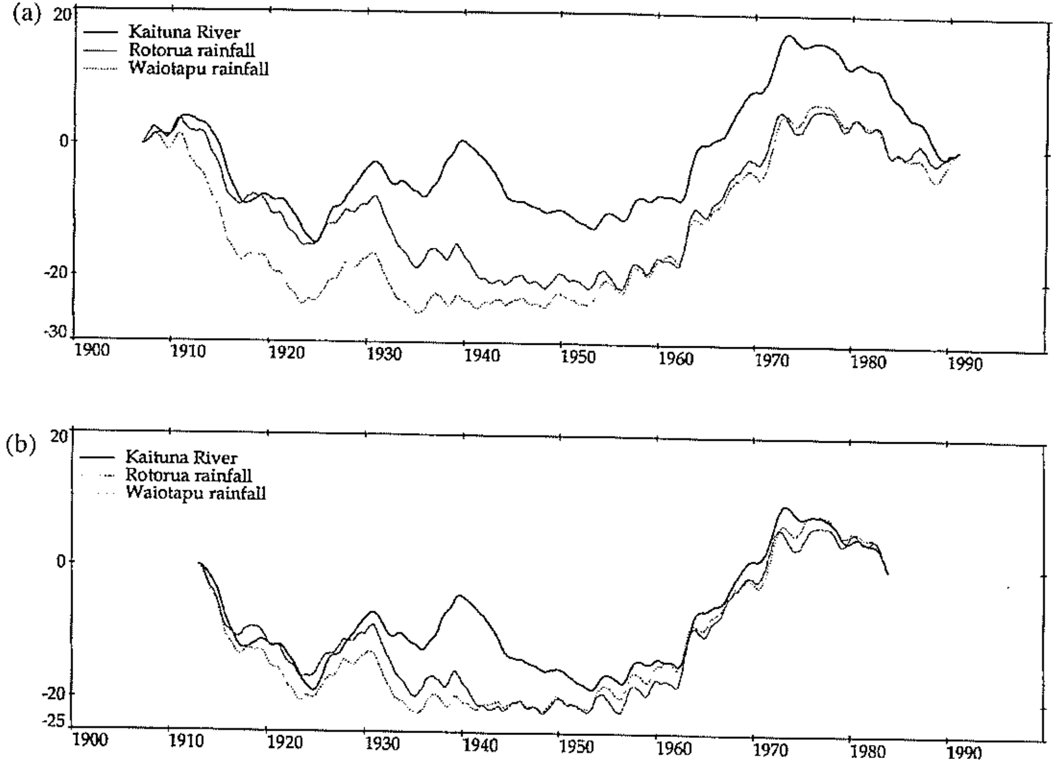


Figure 2 - Residual mass curves for Kaituna River flows and Rotorua and Waiotapu raingauges: (a) all data; (b) data for 1913-1983. Linear interpolation has been used for some short gaps in the Kaituna record.

was increased to 205 kW by constructing wing dams into the lake and adding another 100 kW generator, suggesting a flow of up to about 10 m^3/s (nearly 50% of mean outflow) was diverted. Martin (1991) reports that when the large Arapuni station on the Waikato River began generating (in June 1929) the Okere Falls plant was used only for the evening peak period and for stand-by. The Okere Falls plant ran continuously for nearly two years when Arapuni closed in the period 1930-1932, fell into disuse in 1936 and was dismantled in 1941.

Just one rating curve is used to estimate discharge from lake levels for the period 1906-1956. It is clear that this rating curve is inadequate to calculate discharges over the period when flow was diverted to the power station. It appears that the Kaituna discharge record can be considered reliable only from 1949, when gaugings are available to confirm the rating.

Nevertheless, the residual mass curve for Kaituna agrees with the rainfall residual mass curves for the early data and for the period 1954-1983. Based on this agreement, and the conformity between the two rainfall records for 1913-1983, flows were above the long-term mean for 1954-1973, and below the long-term mean for 1974-1983. (Figs 2a and 2b)

Lake Taupo inflows

Inflows to Lake Taupo have been estimated for the period 1906-1992. These are inflows for the natural Lake Taupo catchment. Additional flows diverted into the catchment since 1971 to augment flows for a power scheme (the Tongariro Power Development) have been subtracted. The catchment is larger than that for the Kaituna River and just two rainfall records cover the bulk of the record. The first, at Taupo township located near the north east boundary (Fig. 1), is a composite record from two sites for which the normal rainfall (Table 2) is less than the mean annual mean runoff (Table 1). The second, Taumarunui, is located beyond the western boundary (Fig. 1) and began in 1916. The normal rainfall is just 240 mm more than mean annual runoff, so neither record provides a wholly reliable index of rainfall. Flow records for the Tongariro River at the southern end of the lake show that about 59% of the Taupo inflow enters by this river. There is no long-term rainfall record for this part of the Taupo catchment.

Residual mass curves for the three records are displayed in Figure 3a. These show a general consistency between the inflows and Taupo rainfall, and a departure in the residual mass curve for Taumarunui for the period 1942/1944. Therefore the curves are recalculated in two segments, before 1942 and from 1945 to 1992 (Fig. 3b). These curves display an encouraging degree of consistency and this result suggests that there are deficiencies in the Taurmarunui data in the mid 1940s. Although the trends on the curves

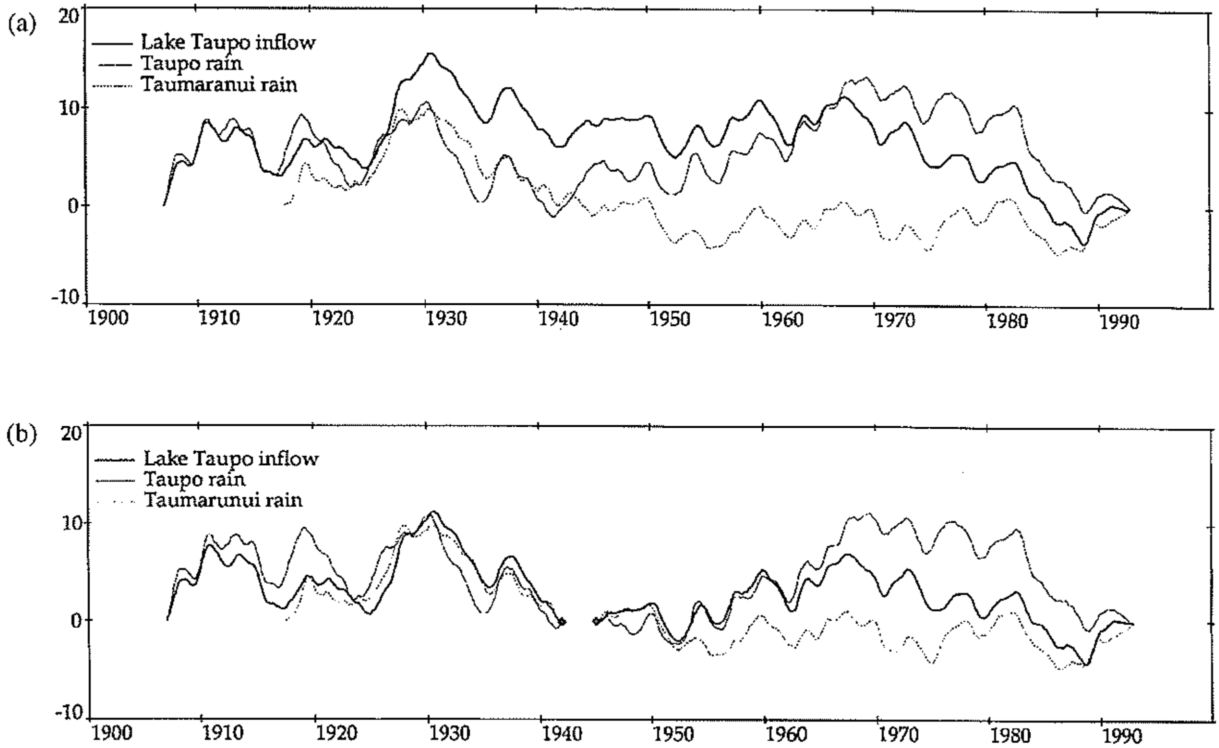


Figure 3 - Residual mass curves for Lake Taupo natural inflows and Taumaranui and Taupo raingauges (a) all data; (b) calculated for two segments 1906-1942, 1945-1992.

are not as marked as for Kaituna, the period 1925-1930 is notable as a sequence of wet years, 1931-1941 was dry, and the two decades 1968-1987 were dry.

South Island lakes

As the catchments for the seven South Island lakes are adjacent to each other and are affected by the same weather systems, their flow records show similar patterns. Thus the records have a substantial degree of cross-correlation, which may be used to check the quality of the records, rather than using rainfall records.

Residual mass curves for the seven records are shown in Figure 4. Features evident from these curves are:

- a remarkable conformity of behaviour of the curves between catchments, except Pukaki with years of extremes (e.g., 1957/1958) showing clearly,
- anomalous behaviour of the curve for Pukaki in 1973/76,
- a rapid divergence of the residual mass curves for the Waitaki lakes for the late 1920's,
- increased inflows for 1978-1991,
- most extreme apparent variation for the Hawea catchment.

The anomalies in the Pukaki curve may be due to systematic error in the early discharge records due to uncertainties in the stage/discharge rating applied to the lake levels to yield outflows. There are two sets of ratings: one set for the natural outlet before the lake was first raised in 1946, and that applying for sluice and spillway flows between 1946 and September 1964 when discharge measurement began at a site on the river draining the lake. Both sets of ratings were based on minimal gaugings, and cannot now be verified by further discharge measurements because the lake was raised further by a dam in 1979/1980. Adjustments to the early inflow records are therefore justified to shift the mass curve so that it conforms better with the other curves.

After some trials, the adjustment factors listed in Table 3 were determined. Figure 5, identical to Figure 4 except for the Pukaki residual mass curve, shows the effect of these adjustments. The Pukaki curve now conforms much better to the other series, but there is still some anomalous behaviour, notably in 1931/32 and 1973/1976.

Table 3 - Adjustments applied to Pukaki inflows

Record	Multiplier	Period
Pukaki inflow	0.93	1926 - 18 June 1952
Pukaki inflow	0.85	19 June 1952 - 29 Sept 1964

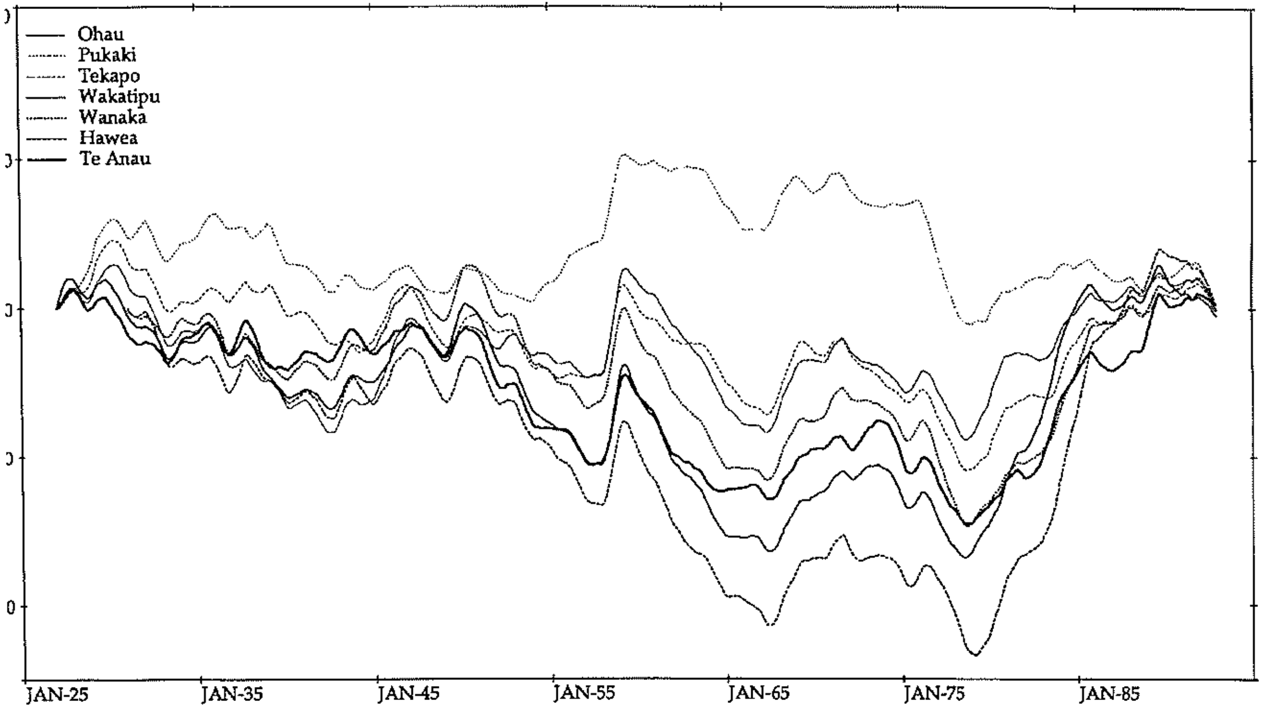


Figure 4 - Residual mass curves for South Island lake inflows: raw data.

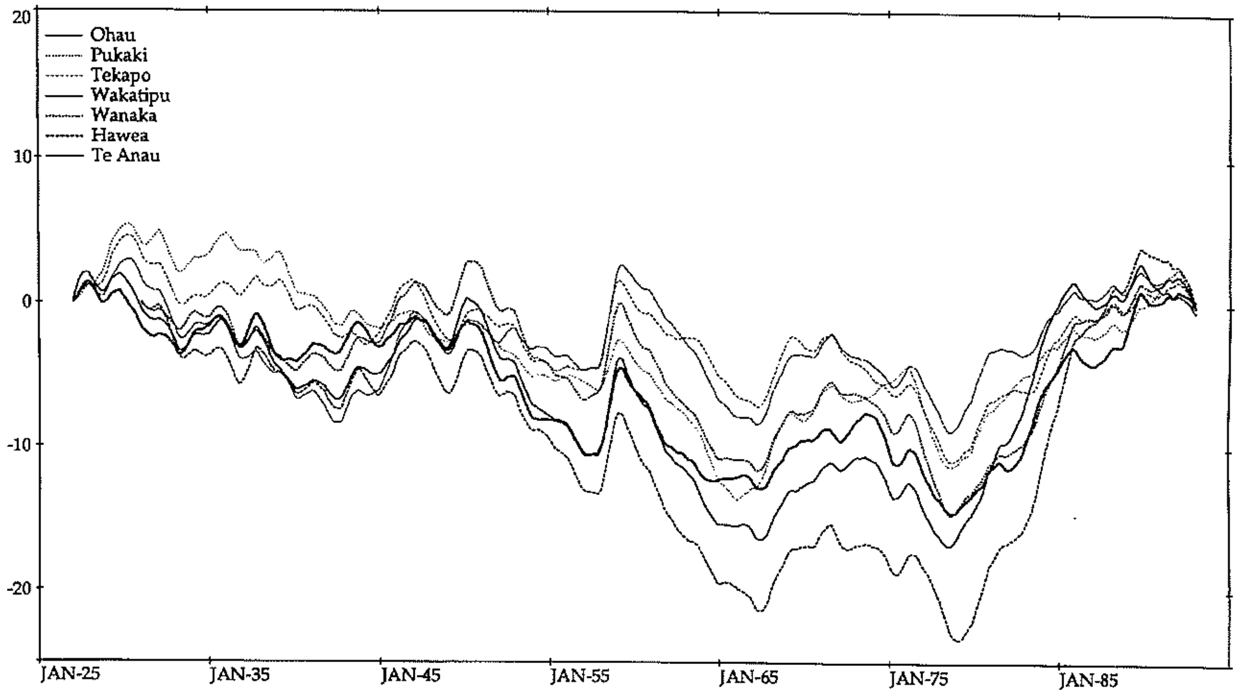


Figure 5 - Residual mass curves for South Island lakes inflows: Pukaki adjusted as in Table 3.

To examine the data in more detail and better isolate anomalies in the data, sets of residual mass curves were prepared for the data for overlapping two-decade long sequences as follows: start (1927 or 1931) through 1942; 1933 through 1952; 1943 through 1962; 1953 through 1972; 1963 through 1982; 1973 through 1992. The resulting residual mass curves are displayed in Figure 6. These plots repeat the features noted in Figure 5 including:

- coherency between the curves, especially for the plots commencing in 1943, 1953 and 1963,
- possibly anomalous data for Pukaki and Tekapo for the period 1927-1945 approximately, and for Ohau for 1935-1945 approximately,
- anomalous Pukaki inflows for 1973-1976.

The anomalous Pukaki inflows for 1973-1976 occur before the lake was raised over the period 1979/1980, and may have been caused by construction activity for the high dam: further investigation of these data are necessary. Problems with the earlier records were examined by plotting the original records of levels for the Waitaki lakes for the period 1926-1937. A high degree of correlation was evident between these records, which are of natural levels before any of the lakes were controlled. Study of the plots suggested that the Tekapo and Pukaki records in particular contain periods when the variations in levels have not been recorded with sufficient time resolution. Several minor hydrograph peaks are absent at points where the other records indicated they should be present, and for Pukaki the recession of a major event in January/February 1931 is inadequately represented. These deficiencies probably account for the anomalies noted for Pukaki and Tekapo in Figure 6.

Greater detail of January/February 1931 is shown in Figure 7, where daily rainfalls for the Hermitage raingauge at Mt Cook are also plotted. This figure shows the lake levels all dropping after a storm on February 1, 2 and 3 when the rainfall was 461 mm. A further storm of 395 mm on February 21-24 causes Ohau and Tekapo to rise, but there is no rise in the Pukaki levels. This happens because there are insufficient data values archived to properly monitor the levels of the lake. There should have been a steeper recession after the storm of February 1-3, and then a rise in levels for the storm of February 21-24. Over the critical period, Pukaki levels are archived for 16 February and 24 February, indicating a 415 mm fall in lake level, and leaving an eight day gap when 395 mm of rain fell. This causes the outflow and hence inflow for Pukaki to have been overestimated for this period. The estimated summer (December/January/February) mean inflow to Pukaki is 307 m^3/s, nominally the second highest in 68 years of record. However inflows to Ohau and Tekapo are respectively 6th and 11th largest on record.

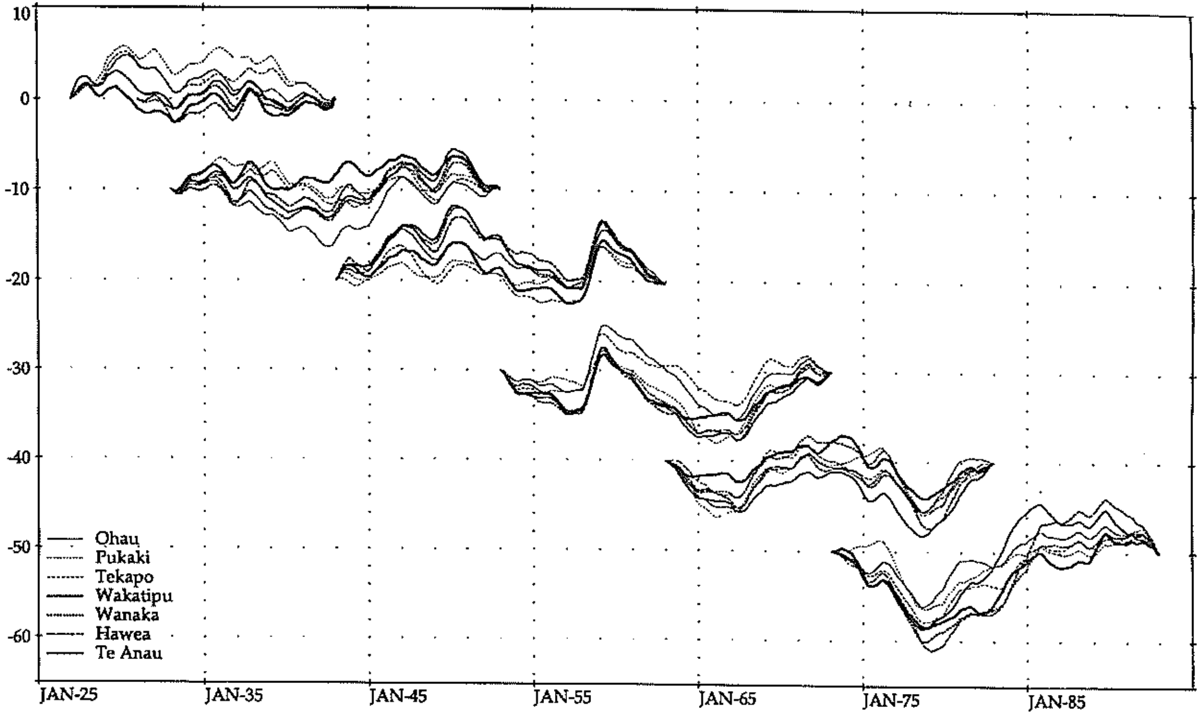


Figure 6 - Residual mass curves for two decade long South Island lake inflow sequences. Plots for successive sequences have been offset by 10 units.

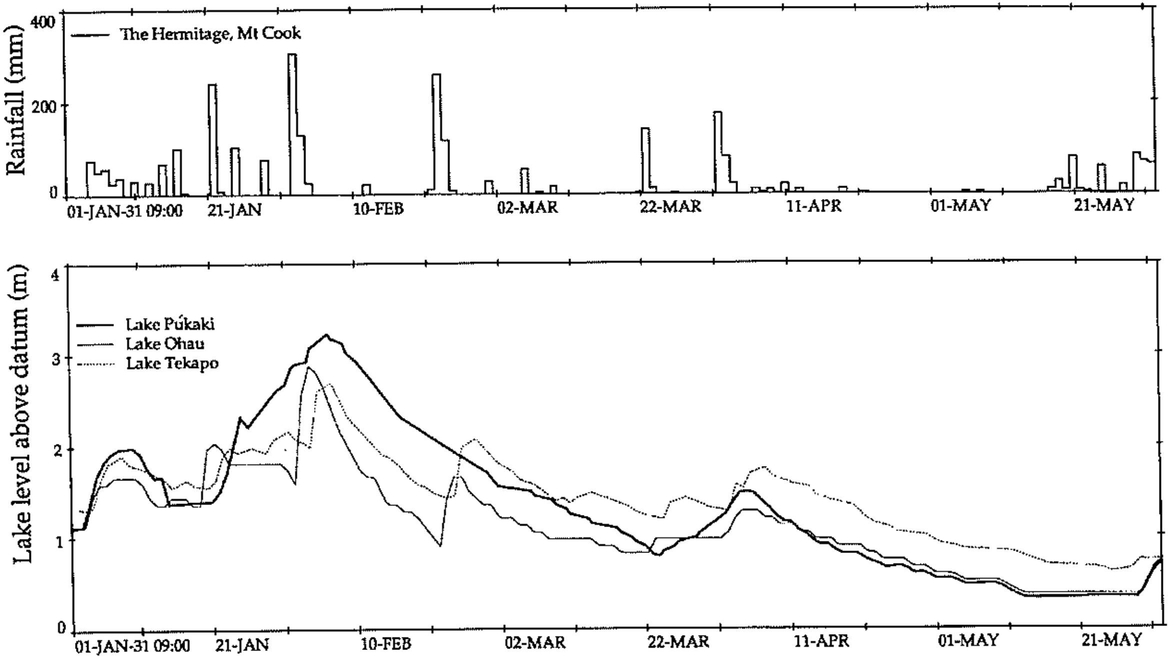


Figure 7 - Plots of lake levels for Ohau, Pukaki and Tekapo for January-May 1931, and daily rainfalls for The Hermitage, Mt Cook. Insufficient data points are filed to correctly plot the recession of Pukaki levels after February 10th.

Detail of these early records illustrates well the problems with the early data, and the need for caution in interpreting results. To improve the data, all the data for this early period need to be checked. The best solution may be to predict inflows for the deficient record as a function of inflows for another lake with a more comprehensive data set. The early Ohau records are more complete than those for Tekapo or Pukaki.

Another feature evident in Figure 6 is the degree of variability in the residual mass curves for the last two decades (1973 through 1992). Over this period good quality recorders have been installed (Waugh and Fenwick, 1979) and archiving methods developed (Ibbitt, 1979), so the variability evident between the plots is probably inherent in the data.

Figure 5 highlights runs of years when flows were high and low. Notably high sequences were 1957/58 and 1979/88. Notable low sequences were 1950/56, 1959/66 and 1976/78. Shorter term droughts are evident for 1932 and 1992.

Annual means

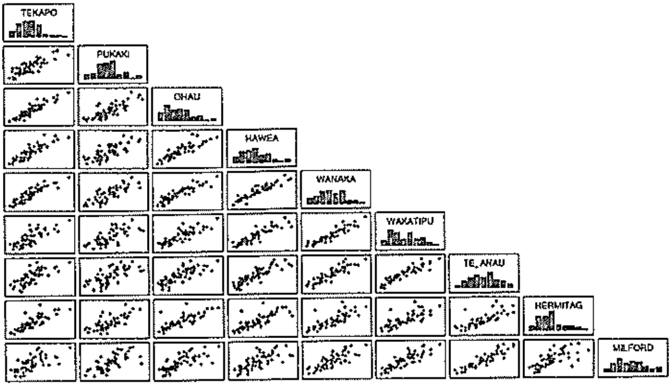
Annual mean values for the lakes inflow series are also examined. These quantities are calculated over a "water year" defined as March-February. These months are used because the end of February, noted as the end of summer, is the time when seasonal snow accumulation is least. Data for two relevant South Island raingauges, Hermitage and Milford Sound, are available for the period 1930 - 1992 and their annual values are also used.

A matrix of scatter plots of the annual values is shown in Figure 8. This figure is shows both the raw and edited data. In these plots, the data are ordered in the same way that the lakes lie in a northeast to southwest axis, followed by the two rainfall series. The scatterplots for adjacent lakes are thus next to the diagonals of the matrix, and these are the plots with the least scatter.

Figure 8a shows all data for each series. Notable features are the tight bands in the plots for data from adjacent, or nearly adjacent, lakes - e.g., Tekapo/Ohau, Ohau/Hawea, Hawea/Wanaka, Wanaka/Wakatipu, Wakatipu/Te Anau. Plots of Pukaki water year values against those of its neighbours (Ohau and Tekapo) show more scatter. The last two rows give the scatter plots for rainfall data. These show that the Hermitage data correlate best with the northernmost lakes, which might be expected because the gauge is located within the Lake Pukaki catchment, and the Milford data correlates best with the more southern lakes (Te Anau, Wakatipu, Wanaka).

The rainfall plots have several outlying values. Two Hermitage values are clear outliers compared with all the inflow series. These values, which

Matrix plots of annual water year values, all data



Matrix plots of annual water year values, defective years removed.

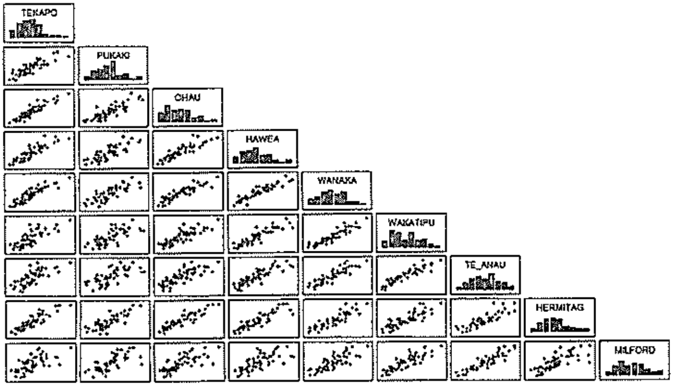


Figure 8 - Histograms and scatterplots of March-February annual means for the South Island lakes and the two South Island raingauges: (a) for all data; (b) with faulty years eliminated.

correspond to water years 1934/35 and 1935/36, were eliminated from the data set: it is concluded that the Hermitage rainfalls over this period are incorrect. Also 1944/45 is eliminated because six months of record are missing and values had been estimated by scaling another record.

Pukaki correlates least well with other series. The residual mass curve has demonstrated that values for 1973-1976 and 1930/31 may be incorrect, so these values are eliminated also.

Scatter plots for the edited series (Fig. 8b) show a more consistent pattern, particularly for the Hermitage annual rainfalls. Scatterplots for Pukaki against its neighbour catchments (Ohau and Tekapo) still show a larger scatter than plots for other adjacent catchments. This may be because of

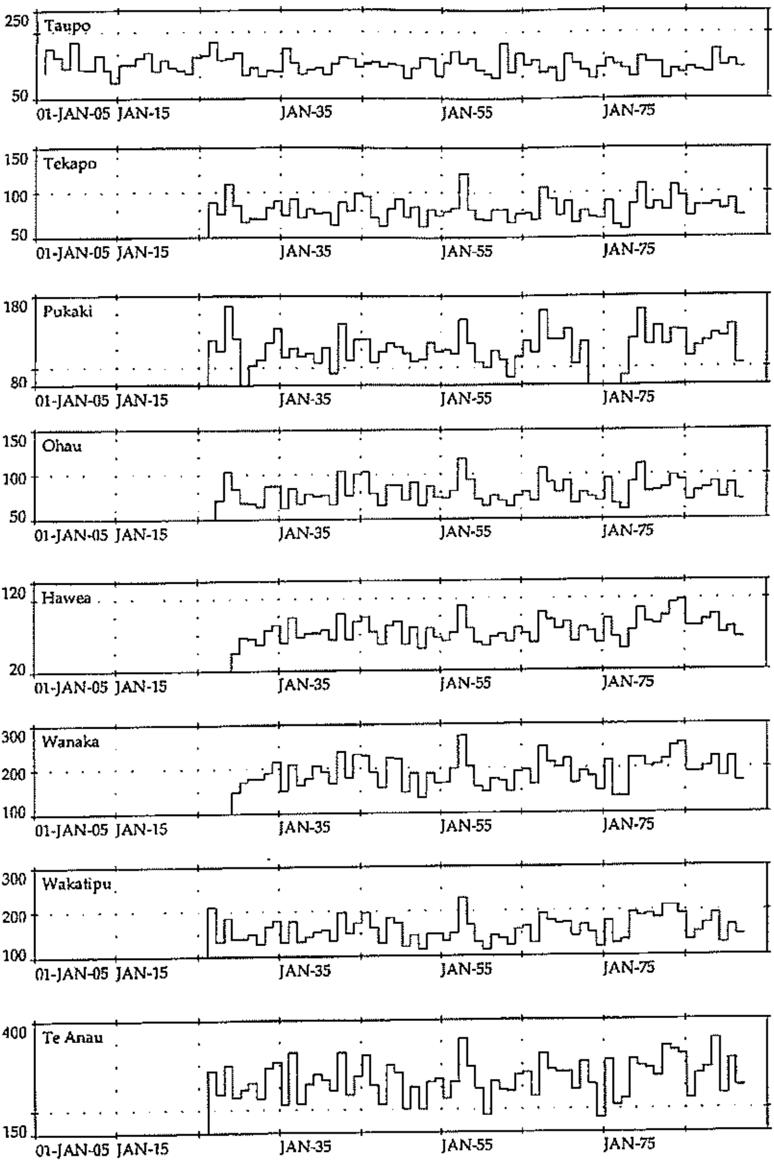


Figure 9 - Hydrographs of annual series inflows for Lake Taupo and the seven South Island lakes.

the greater influence of snow in the Pukaki catchment.

The correlation of annual inflows with annual rainfalls for Hermitage (second last row) and Milford (last row) are now shown without the distraction of the outliers. As before these show that Hermitage correlates better with the northern catchments (Tekapo, Pukaki, Ohau, Hawea) and Milford correlates better with the southern catchments (Te Anau, Wakatipu).

Tests for trends, persistence and cycles

The annual inflow series for Taupo and the seven South Island lakes are displayed in Figure 9 with the faulty Pukaki values eliminated. This figure also shows the cross-correlation evident in Figure 8, and quantified by cross-correlations coefficients in Table 4. These range from 0.66 between Milford rainfall and Tekapo to 0.92 for Hawea and Wanaka, Wanaka and Wakatipu, and Te Anau and Wakatipu. All are highly significant. The year 1957/58 is particularly prominent, with the highest value for five of the seven South Island records, and also as the wettest March-February year for Hermitage and Milford Sound (data not shown).

Correlations between Taupo inflows and the South Island series are not statistically significant and are not reported.

The year-to-year variability of the hydrographs displayed in Figure 9 is encapsulated in the Box and Whisker plots of Figure 10. These show the scale of the variability of each series, which is consistent between the

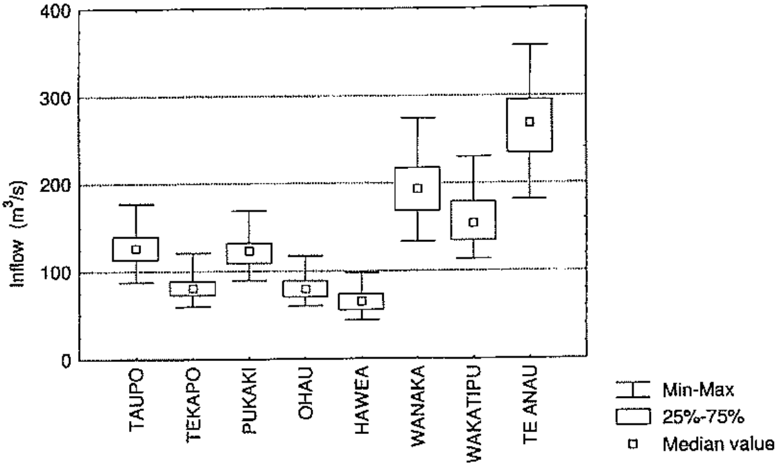


Figure 10 - Box and Whisker plots of the annual series plotted in Figure 9.

Table 4 - Cross correlation matrix of annual quantities for a March-February water year. All the correlations are significant for $p<0.05$

	Tekapo	Pukaki	Ohau	Hawea	Wanaka	Wakatipu	Te Anau	Hermitage	Milford Sd
Tekapo	1.00								
Pukaki	.83	1.00							
Ohau	.92	.85	1.00						
Hawea	.88	.78	.88	1.00					
Wanaka	.87	.80	.90	.93	1.00				
Wakatipu	.79	.74	.86	.89	.92	1.00			
Te Anau	.75	.70	.82	.86	.89	.93	1.00		
Hermitage	.88	.81	.90	.87	.86	.84	.87	1.00	
Milford Sd	.65	.71	.75	.72	.82	.86	.91	.77	1.00

Table 5 - Kendall Tau correlations

	No of data pts	Kendall Tau	Z	p-level
Taupo	86	-0.091	-1.25	0.22
Tekapo	66	0.055	0.65	0.52
Pukaki	61	0.125	1.42	0.16
Ohau	65	0.089	1.05	0.29
Hawea	62	0.177	2.04	0.04
Wanaka	62	0.129	1.48	0.14
Wakatipu	66	0.096	1.13	0.26
Te Anau	66	0.126	1.50	0.13

series. Coefficients of variation for the series are in the range 15% (Taupo, Tekapo, Pukaki, Te Anau) to 19% (Hawea). Figure 10 suggests that most of the series are somewhat skewed toward high flows, so normal distributions may not adequately represent the data.

The hydrographs of annual series (Fig. 9) offer little suggestion of trends or cycles in the data. Formally, the absence of trend is confirmed using the Kendall Tau correlation which provides a nonparametric test for trend. (Helsel and Hirsch, 1992). None of the results (Table 5) provide evidence to reject the null hypothesis that the series show no trend.

Autocorrelations for each series for 1 to 16 lags (years) were calculated. These provided an intriguing result for the South Island series: most values did not differ significantly from zero, but for the lag seven autocorrelations, five of the seven cases were more than twice the standard error. The overall significance of the autocorrelation functions to order K is assessed using the Portmanteau lack-of-fit test statistic $Q = N.(r_1^2 + r_2^2 + ... r_K^2)$ which is distributed as chi-square with K degrees of freedom, where N is the number of data points and r_k is the lag k autocorrelation (Box and Jenkins, 1976). In no case is the significance level less than 19%, offering no reason to discard the hypothesis of independence of the annual values. It is concluded that the prominent lag seven value may be attributed to chance and that multi-year cycles are not present.

Discussion

Two of nine long-term flow series examined have been shown by residual mass curve analysis to contain systematic errors. For the Kaituna River in the North Island, which comprises the outflows of Lake Rotoiti, the pre-1950 data are inconsistent with two long-term rainfall records. This inconsistency probably is caused by modifications of the geometry of the lake outlet to provide flows for an early hydroelectric development that is now defunct. Insufficient detail is available to suggest how the pre-1950 data might be adjusted.

Lake Pukaki inflows prior to September 1964 are shown to contain systematic error. The similarity of residual mass curves for adjacent catchments is used to suggest adjustments for the Pukaki records. As a consequence, the mean natural inflow to Lake Pukaki for 1927-1992 reduces from 132 m^3/s to 124 m^3/s. These systematic errors arise because early rating curves for the lake outflows were constructed using very limited gauging data.

The residual mass curve analysis also shows systematic error in the Pukaki inflows for 1973-1976. This may be a consequence of changes to the lake outflow ratings at a time when the Pukaki High Dam was being constructed. The lake level was raised over the period 1979/1980. The original data for this period, and also for the early part of the record need further scrutiny.

Scatter plots of annual data for each series complement the residual mass curves. They illustrate well the high level of correlation between annual inflows to adjacent lakes. As expected, scatter about the best fit lines is greater for lakes that are further apart.

Pukaki is an exception: its adjusted data correlates less well with its adjacent catchments than any of the other adjacent pairs. Its cross-correlations with Tekapo and Ohau are respectively 0.83 and 0.84, whereas correlations between the other adjacent lakes are in the range 0.88 to 0.93. More seasonal snow accumulates and melts in this catchment than in any other, and future work could examine temperature records to account for the greater variation of the Pukaki inflows.

Scatter plots also show substantial correlations between rainfall records for the Hermitage (Mt Cook) and Milford and the South Island lakes, with the extent of correlation varying broadly as the distance between the raingauge and the catchment. The scatter plots show that the rainfall data for the Hermitage, Mt Cook, are faulty for the years 1934-1936.

Box and Whisker plots usefully summarise the annual natural inflow series and display their year-to-year variability. They show, for example, that Tekapo and Ohau inflows, and Taupo and Pukaki inflows are quite similar in magnitude and range of variation. Hawea inflow is least and Te Anau is greatest. Coefficient of variation for Hawea annual inflows (i.e., standard deviation/mean) is 19% and all the other inflow series are in the range 15 to 17%. Most of the histograms for the annual series are somewhat skewed to the right, and only Te Anau would be satisfactorily represented by a normal distribution.

Time plots of the annual series offer no particular evidence for trend in the series, and the non-parametric Kendall Tau correlation offers no reason to reject the null hypothesis of no trend. No useful results could be obtained using statistical tests available for testing residual mass curves for trend, as these tests would flag years of extreme high flows (e.g., 1957/58) or sequences of low flows. They appear unsuitable for detecting error of the kind encountered in the Kaituna and Pukaki data.

Autocorrelation analysis showed most of the South Island lake inflows had a lag seven autocorrelation exceeding two standard errors, but overall there is no reason to reject the null hypothesis of independence. That is, the tests used offer no evidence of trends or cycles in the inflow series. For Taupo inflows, the null result for the Chi-square test applied to the autocorrelation function confirms a previous finding of Yevdjevich (1963, 1964), who used Taupo inflows for 1905-1955 as part of a world-wide study of fluctuations in wet and dry years.

Comparison of the series suggests that four of the six rainfall records used contain defective data, and points to the need to examine multiple series if reliable conclusions about climate change are to be developed.

Conclusions

The similarity between the residual mass curves for correlated hydrological records is a tool for identifying anomalies in long-term records. This comparison of residual mass curves complements scatter plots of annual values.

Anomalies were indicated in four of six rainfall records and two of nine discharge records. Because of the importance of one of the discharge records (Pukaki) for assessing flow for hydroelectric power generation, correction factors are suggested to remove some of the major errors.

However this record requires further attention to eliminate other identified discrepancies.

No evidence was found in eight discharge series that date from 1930 or earlier to reject the hypothesis that cycles and trends are absent from the series.

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