DEGRADATION OF THE LOWER WAIKATO RIVER: AN ANALYSIS OF THE GAUGING DATA

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ABSTRACT

Historical gauging data measured at Hamilton, Ngaruawahia, Huntly, Rangiriri and Mercer have been analysed to ascertain the water and bed-level degradation of the lower Waikato River, North Island, New Zealand. Water levels adjusted to an index flow of 350 m^3s^{-1} at these gauging stations have been calculated from the gauging data using Manning's equation, and assuming the same river width (W), flow resistance (n) and energy slope (S) at both the gauging discharges and the index flow. Trends through time of these adjusted water levels have been determined using a cubic spline method. The results have been used to determine water-level longitudinal profiles corresponding to the index flow in the river reach between Ngaruawahia and Mercer. Variations of the adjusted water level over time can represent mean bed-level changes, likewise assuming constant W, n and S. It is evident that the river bed has degraded, probably due to sand extraction from the river and sediment starvation following the construction of the Karapiro Dam.

INTRODUCTION

The Waikato River, North Island, New Zealand, which is highly developed for hydro-electricity generation, has a catchment area of 14,258 km^2. From an elevation of 2,797 m at the top of Mt Ruapehu the river flows 425 km northward to the Tasman Sea (Strachan, 1979; Moturiki datum is used in this paper). Its main uncontrolled tributary, Waipa River, with a catchment of 3,059 km^2, representing 21% of the total Waikato River catchment, joins at Ngaruawahia (Fig. 1).

This paper examines evidence for bed changes in the Waikato River below Karapiro Dam, the first dam upstream of the river mouth (Fig. 1). Karapiro Dam, built in 1947, was the second dam constructed on the Waikato River, the immediately upstream Arapuni Dam being the first, in 1929. Sand has been extracted commercially at a number of locations along the river since the 1950s, and from 1984 to the present (1992) most of sand abstraction has been around Mercer and Tuakau. After extensive flooding during the 1950s, *the Lower Waikato-Waipa Control Scheme* was initiated by the Waikato Valley Authority in 1961, and most river training and control works were substantially completed by 1982 (Mulholland, 1983).

It is evident that the river bed and water levels along most parts of the lower catchment have been reduced (Mulholland, 1983; Sledger, 1987; 1989; Fenton, 1989). Sledger (1989) concluded: "*significant degrading evident since at least 1964, continues with the result that all* (cross sectional) *areas upstream of Maioro Bay are lower than they were in 1964.*" Fenton (1989) also studied the river longitudinal profile and identified a "*marked degradation evident in the Mercer to Huntly reach*".

To further investigate quantitatively these changes for river management and planning, available gauging data held in the Waikato Regional Council have been carefully checked and analysed. Possible factors influencing the trends identified in the river water and bed-level reduction are discussed.

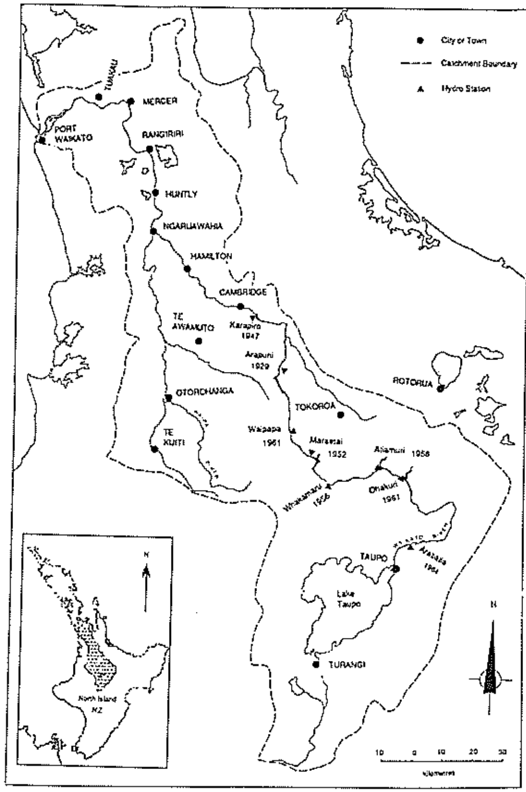


FIG. 1—Map of the Waikato River catchment and the hydro electric power stations (modified after Strachan, 1979).

RIVER GAUGING DATA AND ANALYSIS METHODS

There are five gauging stations on the Waikato River below the Karapiro Dam: Hamilton, Ngaruawahia, Huntly, Rangiriri and Mercer.

Gauging records for the Hamilton station, at the Hamilton Traffic Bridge (cross section 151 - Fig. 2), commence from 1960. A total of 158 gauging records in the period 1960–1991 have been used for analysis.

The gauging station at Ngaruawahia is located at the Ngaruawahia Cableway (cross section 132 - Fig. 2), and 157 gauging records from 1958 to 1991 are available for analysis.

The site of the gauging station at Huntly changed. Prior to and including 1986, the gauging station was located at the Huntly Rail Bridge (cross section

123 - Fig. 2), with 119 records available for 1958–1986. Some water-level measurements at the Huntly Power Station for 1986 have been adjusted using the following equation (r^2=0.998, n=17) obtained for the 1983–1990 period (Fig. 3):

$$WL_{R.B.} = 0.25929 + 1.0016 WL_{P.S.} + 0.038 \quad (1)$$

where $WL_{R.B.}$ is the water level (m) at the Huntly Rail Bridge and is $WL_{P.S.}$ the water level (m) at the Huntly Power Station. The constant 0.038 is added because zero of the staff gauge at the Huntly Rail Bridge has been found to be about 0.038 m higher than the Moturiki datum (Waikato Regional Council field books) since 11 August 1982 when the staff gauge was reinstalled.

The new gauging station was set up at the Tainui Bridge with 81 gauging records available from 1984–1991. Water levels for the new gauging data were measured at Huntly Power Station. In order to use the new and old gauging data together, their water levels have been adjusted to those at the Huntly Rail Bridge using Eq. (1), and their discharges have been multiplied by 0.988 based on analysis of discharges at the Ngaruawahia Cableway, Tainui Bridge and the Huntly Rail Bridge (Wo, in prep.).

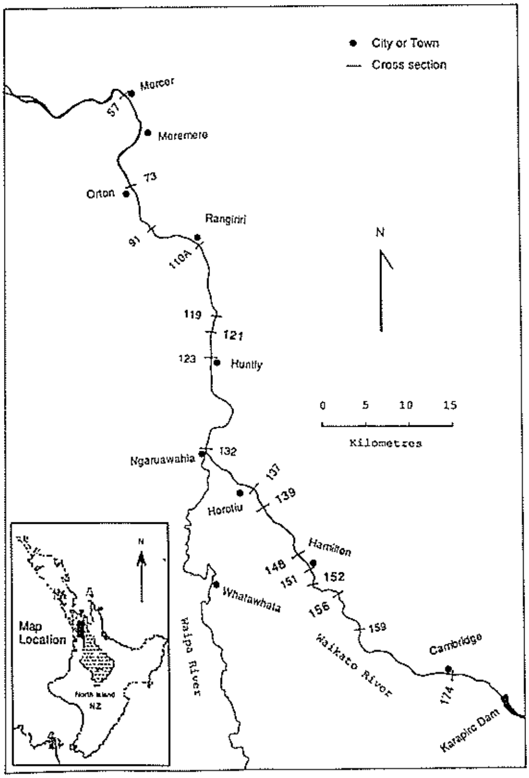


FIG. 2—Map of some key cross sections along the lower Waikato River (data from the Waikato Regional Council).

The site of the gauging station at Rangiriri was shifted when the new Rangiriri Bridge (cross section 110A - Fig. 2) was built in 1969. For the period 1970–1991, a total of 189 records have been analysed. Before that time 17 records are available.

The site of the gauging station at Mercer also changed. Discharges were measured at Mercer Wharf between 1960 and 1982, and since 1980 they have been taken at Mercer Bridge, about 100 m downstream. Assuming equivalent discharge, 140 records from Mercer Wharf for 1960–1982 and 97 records from the Mercer Bridge for 1980–1991 have been combined for a time trend analysis.

For each set of gauging data, the variables of time (*T*), water level (*WL*), cross-sectional area below the water level (*A*), river width at the water level (*W*) and discharge (*Q*) are available.

For a wide river channel, the following equations apply (Chow, 1959):

$$V = C\sqrt{HS} \qquad (2)$$

$$C = \frac{1}{n} H^{1/6} \qquad (3)$$

$$Q = WHV \qquad (4)$$

where V is the mean flow velocity, C and n are Chézy's and Manning's coefficients respectively, $H = A/W$ and S is the energy slope. From Eqs. (2–4), we have:

$$Q = W\frac{1}{n}H^{5/3}S^{1/2} \qquad (5a)$$

$$\frac{350}{Q} = \frac{W_{Q=350}\dfrac{1}{n_{Q=350}}\left(H_{Q=350}\right)^{5/3}S_{Q=350}{}^{1/2}}{W\dfrac{1}{n}H^{5/3}S^{1/2}} \qquad (5b)$$

in which $H_{Q=350} = A_{Q=350}/W_{Q=350}$, $A_{Q=350}$, $W_{Q=350}$, $S_{Q=350}$ and $n_{Q=350}$ are, respectively, cross-sectional area, river width, energy slope and flow resistance at a discharge of 350 m^3s^{-1}, and 350 is an index flow (m^3s^{-1}).

The river width (*W*), flow resistance (*n*) and energy slope (*S*) can be a function of time (*T*) and discharge (*Q*). For each individual gauging, if the following conditions

$$\frac{W_{Q=350}}{W} = \frac{n_{Q=350}}{n} = \frac{S_{Q=350}}{S} = 1 \qquad (6a)$$

or

$$\frac{\partial W}{\partial Q} = \frac{\partial n}{\partial Q} = \frac{\partial S}{\partial Q} = 0 \qquad (6b)$$

are satisfied, from Eq. (5b) we have

$$\frac{350}{Q} = \left(\frac{H_{Q=350}}{H}\right)^{5/3} \qquad (7)$$

Because the mean bed level (BL) is defined as

$$BL = WL - H = WL_{Q=350} - H_{Q=350} \tag{8}$$

from Eqs. (7–8), the water level adjusted to the index flow 350 m^3s^{-1} ($WL_{Q=350}$) can be obtained by the following equation:

$$WL_{Q=350} = WL - \frac{A}{W} + \frac{A}{W}\left(\frac{350}{Q}\right)^{0.6} \tag{9}$$

All variables in the right hand side of the equation are available from the gauging data. A time series of adjusted water levels ($WL_{Q=350}(T)$) can then be established.

Eq. (9) also shows the relationship between adjusted water level ($WL_{Q=350}$) and mean bed level ($BL = WL - A/W$), and variations of adjusted water levels reflect river mean bed-level changes.

In summary, to derive the adjusted water level ($WL_{Q=350}$) from individual gaugings, results of the gauging are interpolated or extrapolated to an index flow, eg. 350 m^3s^{-1}, by the Manning's equation, and it is assumed that Eq. (6a) or Eq. (6b) applies.

TABLE 1—Characteristics of gauging stations on the Waikato River below Karapiro Dam.

Station	Hamilton Traffic Bridge	Ngaruawahia Cableway	Huntly Rail Bridge	Rangiriri Bridge	Mercer Wharf
Period	1960-1991	1958-1991	1958-1986	1970-1991	1960-1982
Q (m^3s^{-1})	200-500	250-550	350-650	400-750	
No. of Records	112	83	63	74	61
Water Level (m)	112.28-15.35	9.28-11.17	7.47-9.16	6.00-7.23	2.92-4.91
Mean Width (m)	84.85	151.0	229.8	226.1	123.2
Sd. of Width (m)	5.6	5.4	8.6	12.5	2.7
Mean Depth (m)	3.18	3.00	2.37	2.68	5.60
Width/depth	26.7	50.3	97.0	84.4	22.0

The method above is applied to gaugings in the lower Waikato River to obtain a time series of adjusted water levels. The index flow is taken as 350 m^3s^{-1}, which has been used as a standard flow in the lower Waikato River (Mulholland, 1983). To satisfy the assumptions, only gauging data within a certain range of discharges (equivalent to elevations) have been used (Table 1).

For the time series of $WL_{Q=350}(T)$, Eq. (9) can be rewritten as

$$WL_{Q=350}(T) = BL(T) + \left(\frac{350n(T)}{W(T)\sqrt{S(T)}}\right)^{0.6} \tag{10}$$

If the following assumptions are held,

$$W(T) = \text{const.},\ n(T) = \text{const.},\ S(T) = \text{const.} \tag{11a}$$

or

$$\frac{\partial W}{\partial T} = \frac{\partial n}{\partial T} = \frac{\partial S}{\partial T} = 0 \tag{11b}$$

then variations of the adjusted water levels represent the mean bed-level changes, and a unit slope exists between the adjusted water level ($WL_{Q=350}(T)$) and the mean bed level ($BL(T)$).

It is difficult to test the assumptions indicated by Eq. (11a) or Eq. (11b) using field data. A validation of the unit slope between adjusted water level and mean bed level is possible from gauging data, and may be an indirect way to test both assumptions in Eq. (6a or 6b) and Eq. (11a or 11b).

For the lower Waikato River, the relationship between adjusted water level and mean bed level at the Hamilton Traffic Bridge, Ngaruawahia Cableway and Mercer Wharf within a certain range of discharges (Table 1) is shown in Figure 4. Plotted points of the relationship at the Hamilton Traffic Bridge from 1960–1991 (Fig. 4a) and at the Ngaruawahia Cableway from 1958–1991 (Fig. 4b) group around the unit slope line, especially for the data at the Hamilton Traffic Bridge. These results demonstrate that the assumptions in Eqs (6a or 6b and 11a or 11b) may be acceptable. Points at Mercer Wharf vary from the unit slope line (Fig. 4c). This may be caused by a tidal influence, so that energy slope becomes a function of time when bed level is lowering, or bed level at Mercer Wharf may not be representative because of local sand removal.

There are many ways to interpret a time series of data and some can be used for forecasting (Box and Jenkins, 1976). To interpret time variations of the adjusted water levels, we selected a cubic spline method, with minimisation of a linear combination of the sum of squares of the residuals of fit and the integral of the squares of the second derivative (Reinsch, 1967), using the software SAS (1985).

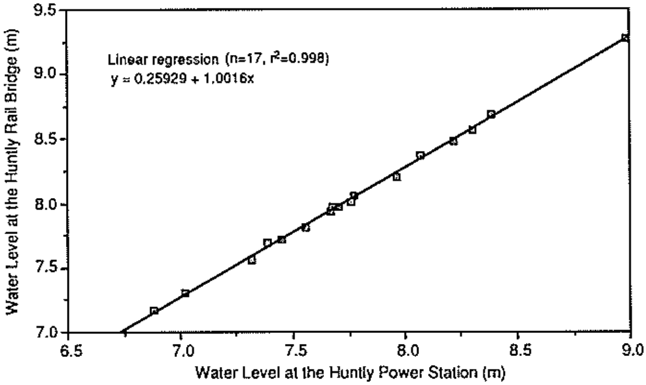


FIG. 3—Relation between the water levels at Huntly Power Station ($WL_{P.S.}$, m) and the Huntly Rail Bridge ($WL_{R.B.}$, m) (Moturiki datum, data from the Waikato Regional Council in 1983-1990).

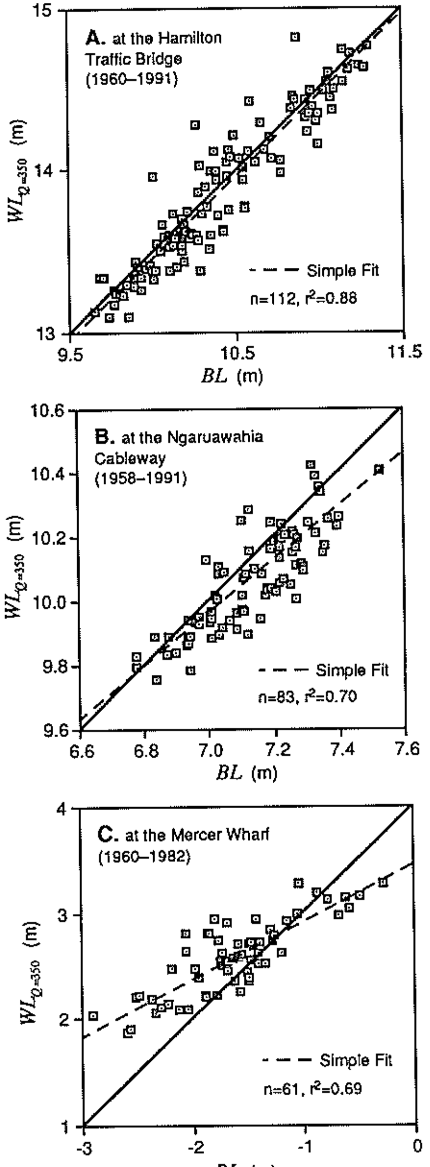


FIG. 4—Relation between adjusted water levels ($WL_{Q=350}$, m) and mean bed levels (BL, m). The solid lines are the unit slope lines and the dashed lines are the simple fits of the data. Data of $WL_{Q=350}$ and BL at the Hamilton Traffic Bridge (A), and to a lesser extent at the Ngaruawahia Cableway (B) group close to the unit slope lines, but data for Mercer Wharf (C) show more variation (Moturiki datum, data from the Waikato Regional Council).

The water-level profiles corresponding to the index flow of 350 m^3s^{-1} between Ngaruawahia and Mercer on 25 June 1958, 3 Sept 1973, 21 May 1982 and 17 Dec 1990 are determined using results of the adjusted water-level analysis and their original water-level profile measurements. On these days, river flows were close to 350 m^3s^{-1} and water levels along the river were measured within about 12 hours. The difference between the water level measured in the field and the adjusted water level at each gauging station is linearly distributed along the river between two gauging stations. The water-level profiles at the index flow of 350 m^3s^{-1} are then obtained by adjusting their original measured water levels by a proportion of the difference.

RESULTS AND POSSIBLE INFLUENCING FACTORS

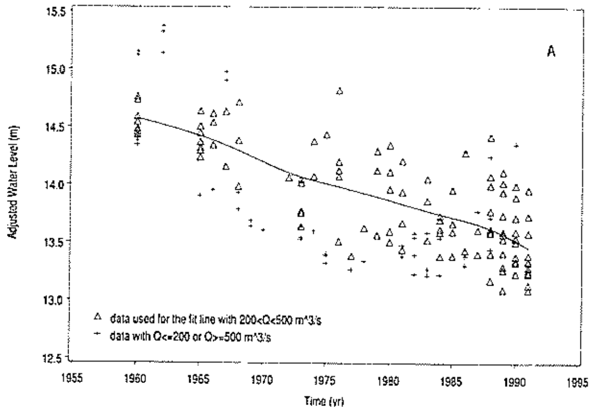
Figure 5 shows the temporal variations of the adjusted water levels at the five gauging stations at Hamilton, Ngaruawahia, Huntly, Rangiriri and Mercer. Table 2 lists the number of records used to determine the lines of fit and their standard deviations.

TABLE 2—Number and standard deviations of records used for time trend analysis

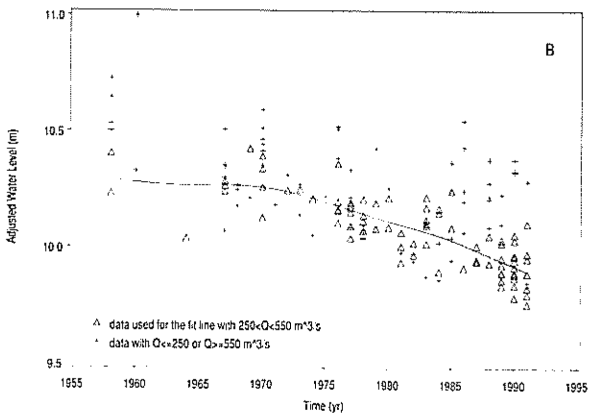
Station	Hamilton Traffic Bridge	Ngaruawahia Cableway	Huntly Rail Bridge	Rangiriri Bridge	Mercer Wharf
Period	1960-1991	1958-1991	1958-1991	1970-1991	1960-1991
Q(m^3s^{-1})	200-500	250-550	250-550	350-650	400-750
No. of Records	112	83	115	74	97
Sd.(m)	0.280	0.087	0.087	0.075	0.163

Figure 6 shows the water profiles at a discharge of 350 m^3s^{-1} between Mercer and Ngaruawahia on 25 June 1958, 3 September 1973, 21 May 1982 and 17 August 1989.

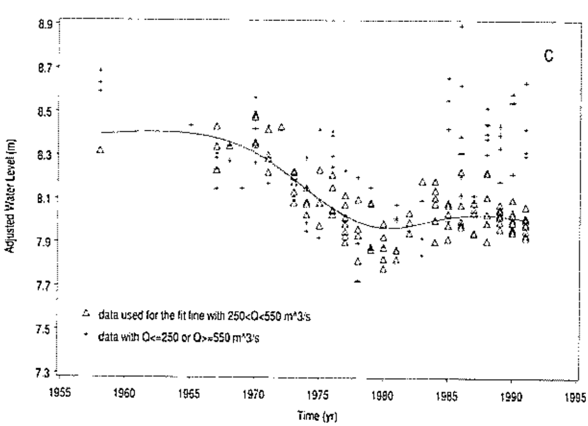
It is evident that water levels at the reference discharge of 350 m^3s^{-1} ($WL_{Q=350}$) have decreased over time in the lower Waikato River (Figs. 5 and 6). The adjusted water levels at Hamilton have dropped by about 1 m from 1960–1991 (Fig. 5a). Mean bed levels at Hamilton seem to be stable from 1960–1965 and start to degrade about 1965 (Fig. 7a). Cross-section surveys confirm this (Fig. 7b) and the stable-bed period may extend back to 1951. The degradation shown in the analysis, beginning 18 years (1947–1965) after the Karapiro Dam closure and 36 years (1929–1965) after the Arapuni Dam closure, could be caused by sediment starvation downstream of the dams. It might also be caused by sand extraction from the river around Hamilton (Fig. 8) with its consequent destruction of the partially armoured bed surface, where the bed materials are of gravel and sand mixtures (Wo, in prep.). The continued bed degradation after cessation of sand abstraction in 1976 (*New Zealand Herald*, 6 April 1976) may be attributed to the disturbance or destruction of the bed surfaces, as well as effects of the dams on the downstream flow and sediment load (Williams and Wolman, 1984).



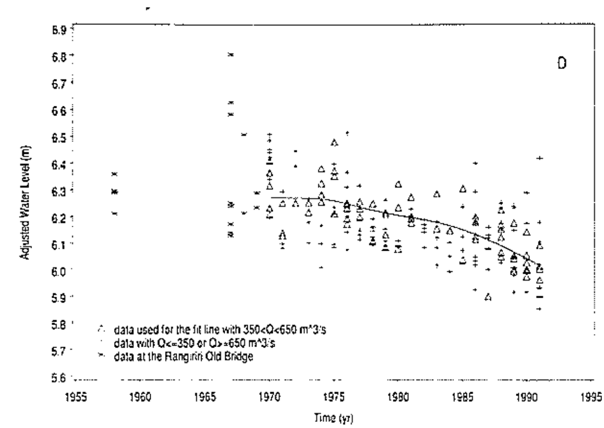
A
Adjusted Water Level (m)
15.5
15.0
14.5
14.0
13.5
13.0
12.5
data used for the fit line with 200<Q<500 m^3/s
data with Q<=200 or Q>=500 m^3/s
1955
1960
1965
1970
1975
1980
1985
1990
1995
Time (yr)



B
Adjusted Water Level (m)
11.0
10.5
10.0
9.5
data used for the fit line with 250<Q<550 m^3/s
data with Q<=250 or Q>=550 m^3/s
1955
1960
1965
1970
1975
1980
1985
1990
1995
Time (yr)



C
Adjusted Water Level (m)
8.9
8.7
8.5
8.3
8.1
7.9
7.7
7.5
7.3
data used for the fit line with 250<Q<550 m^3/s
data with Q<=250 or Q>=550 m^3/s
1955
1960
1965
1970
1975
1980
1985
1990
1995
Time (yr)



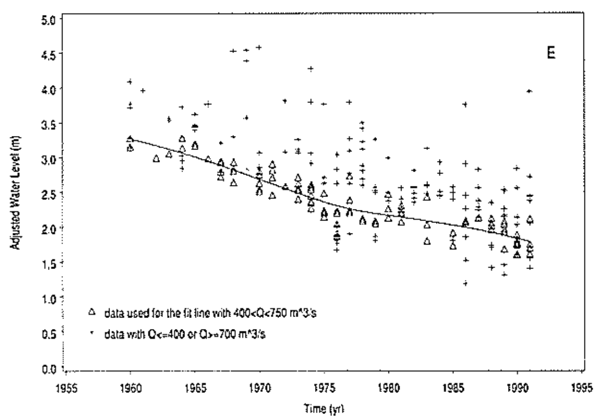


FIG. 5—Variations of the adjusted water levels ($WL_{Q=350}$, m) over time at the five gauging stations in the lower Waikato River. The smoothed curves are determined using the cubic spline method from SAS with option I=SM65 (Moturiki datum, data from the Waikato Regional Council).

(a) Hamilton Traffic Bridge (n=112, sd=0.280 m)

(b) Ngaruawahia Cableway (n=83, sd=0.087 m)

(c) Huntly Rail Bridge (n=115, sd=0.087 m)

(d) Rangiriri Bridge (n=74, sd=0.075 m)

(e) Mercer Wharf (n=97, sd=0.163 m)

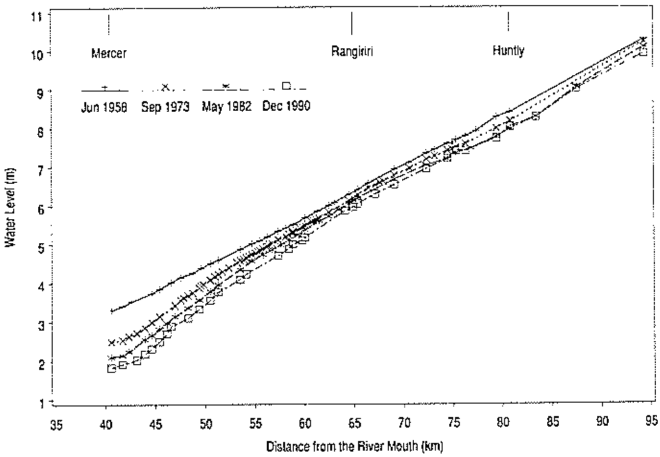


FIG. 6—Water-level profiles between Ngaruawahia and Mercer in the Waikato River at the discharge of 350 m^3s^{-1} (Moturiki datum, based on data from the Waikato Regional Council).

Adjusted water levels at Ngaruawahia dropped by about 40 cm from 1958–1991 (Fig. 5b). The water-level reductions might result from the upstream effects (*cf.* Begin, et al., 1981) of extraction of large volumes of sand around Huntly (Fig. 9a) and Mercer (Fig. 9b) as well as from decline of sediment supply from the upper catchment.

Only one gauging record has been used at the Huntly Rail Bridge to determine variations of the adjusted water levels in the period 1958–1966, and there is thus less confidence in the trends during this period. It is evident that considerable lowering of adjusted water levels occurred from about 1970–1980, and the adjusted water level seems to have become more or less stable after about 1984 (Fig.5c). The degradation might be the result of local sand extraction (Fig. 9a) around Huntly Power Station.

The adjusted water levels at Rangiriri have dropped from 1970–1991 (Fig. 5d). The reduction might be caused by long-term sand extraction downstream around Mercer and Meremere (Fig. 9b) and the river training works (Mulholland, 1983).

Figure 5e shows that the adjusted water levels at Mercer have dropped from 1960–1991. These changes can be attributed to local long term sand extraction (Fig. 9b). Figure 10 shows the correlation between cumulative sand extraction around Mercer and adjusted water levels at the Mercer gauging station.

SUMMARY AND CONCLUSIONS

Variations of the adjusted water levels $WL_{Q=350}(T)$ based on available historical gauging data at Hamilton, Ngaruawahia, Huntly, Rangiriri and Mercer in the lower Waikato River have been plotted and a cubic spline method used to interpret their time trends for data within a certain range of discharges. The results have been used to determine the water-level profiles corresponding to an index discharge of 350 m^3s^{-1} between Ngaruawahia and Mercer.

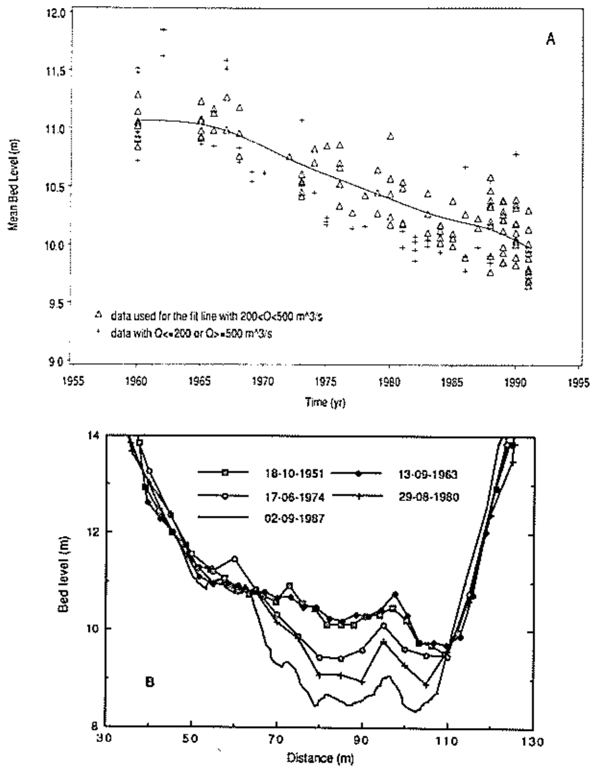


FIG. 7—River-bed changes at the Hamilton traffic Bridge. Fig. 7a shows variations of the mean bed levels over time. The smoothed curve is obtained using the cubic spline method from SAS with option I=SM65 (n=112, sd=0.189). Fig. 7b shows variations of the cross section (Moturiki datum, data from the Waikato Regional Council).

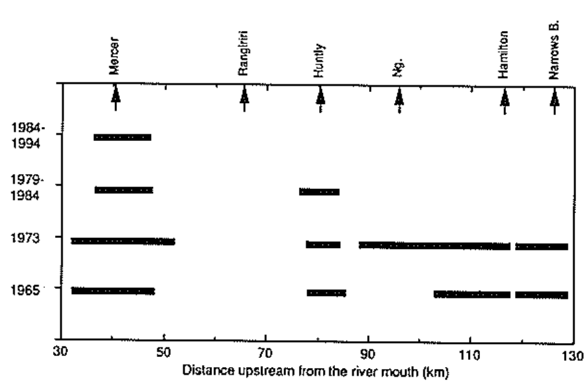


FIG. 8—Positions of commercial sand extraction licensed on the lower Waikato River in 1965, 1973 and 1979–1994 (data from the Waikato Regional Council).

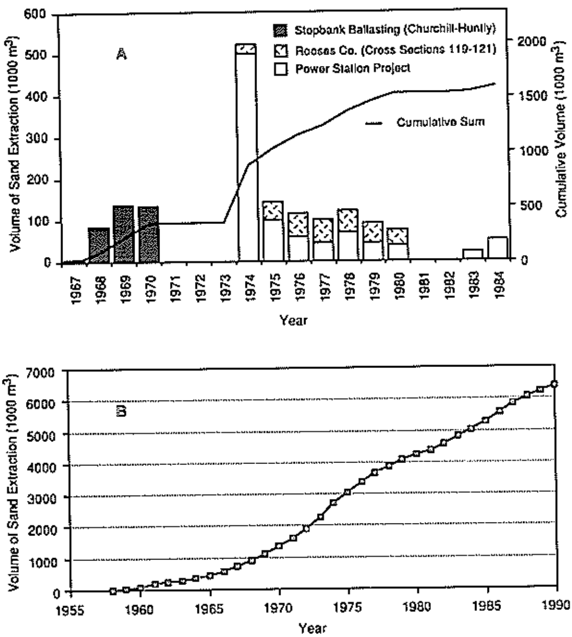


FIG. 9—Sand extraction from the lower Waikato River. Fig. 9a shows 1967-1984 data for sand abstraction around Huntly and its cumulative volume (data from the Waikato Valley Authority, 1982; Mulholland, 1983; Fenton, 1989). Fig. 9b shows the cumulative volume of sand taken from the Waikato River around Mercer between 1955-1990 (data from Fenton, 1989; the Waikato Regional Council).

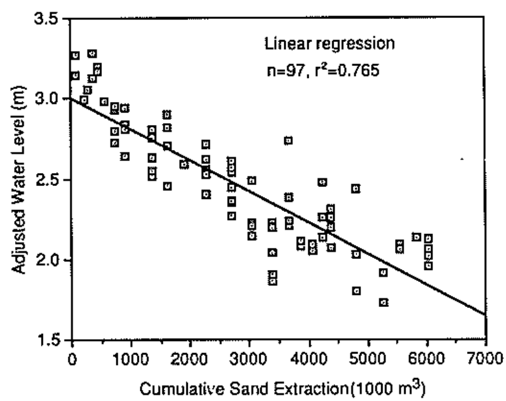


FIG. 10—Relationship between cumulative sand extraction from the Waikato River around Mercer and adjusted water levels at the Mercer gauging station ($WL_{Q=350}$, m) (Moturiki datum, data from the Waikato Regional Council; Mulholland, 1983; Fenton, 1989).

Water levels adjusted to an index flow can be obtained from gauging data assuming a wide channel and the same width W, flow resistance n and energy slope S at both gauging and index discharges. Variations of adjusted water levels may represent the mean bed-level changes assuming W, n and S are constant over time. For the lower Waikato River, gauging data within a certain range of discharges are used for this analysis to try to satisfy these assumptions in Eq. (6a or 6b). Values of $WL_{Q=350}$ and BL from the gauging data at Hamilton and at Ngaruawahia group close to a unit slope line (Figs. 4a and b), which may confirm that the assumptions in Eqs. (6a or 6b and 11a or 11b) are acceptable. Variations from the unit slope line for the gauging data at Mercer Wharf (Fig. 4c) may reflect a non-constant energy slope, or mean bed level may not be representative because of the local sand extraction around Mercer. Analysis of water levels at an index flow determined from rating curves would show similar trends to those presented here using the Manning's equation to interpolate or extrapolate each individual gauging.

The adjusted water levels ($WL_{Q=350}$) at the gauging stations at Hamilton, Ngaruawahia, Huntly, Rangiriri and Mercer have dropped during their gauging periods (Fig. 5). The reduction results from bed-level degradation.

For Hamilton gauging station, significant degradation of mean bed levels seems to have started about 1965 (Fig. 7). Degradation may be related in part to sand extraction from the river (Fig. 8) and its consequent destruction of the bed surfaces, as well as downstream effects of the dams.

The 350 m^3s^{-1} water profiles between Ngaruawahia and Mercer have gone down in the period 1958–1990 (Fig. 6). River bed degradation might result from local sand abstraction, river training works along the river, long-term sand abstraction around Mercer, as well as downstream effects of the dams.

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