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RIVER ADJUSTMENT TO CHANGES IN SEDIMENT LOAD: THE EFFECTS OF TIN MINING ON THE RINGAROOMA RIVER, TASMANIA, 1875–1984

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ABSTRACT

The mining of alluvial tin in the Ringarooma basin began in 1875, reached a peak in 1900–20, and had virtually ceased by 1982. During that time 40 million m^3 of mining waste were supplied to the main river, quickly replacing the natural bed material and requiring major adjustments to the channel.

Based on estimates of sediment supply from more than 50 widely scattered mines and the frequency of flows capable of transporting the introduced load, the river's transport history is reconstructed using a mass-conservation model. Because of the lengthy time period (110 years) and river distance (75 km) involved, the model cannot predict detailed change but it does reproduce the main pattern of sediment movement in which successive phases of aggradation and degradation progress downstream. Peak storage is predicted in that part of the river where braiding and anastomosis are best developed.

Aggradation was most rapid in the upper reaches close to major supply points, becoming slower and later with distance downstream. Channel width increased by up to 300 per cent where the valley floor was broad and braiding became relatively common. Bridges had frequently to be replaced. While bed levels were still rising in lower reaches, degradation began in upper ones, notably after 1950, and by 1984 had progressed downriver over 30 km. Rates of incision reached 0·5 m yr^{-1}, especially in the early 1970s when record high flows occurred. As a result of degradation the bed material became gravelly through either reexposure of the original bed or lag concentration of coarser fractions. Also a narrower unbraided channel has developed. The river is beginning to heal itself and upper reaches now have reasonably stable beds but at least another 50 years will be required for the river to cleanse its channel of mining debris.

KEY WORDS Mining Sediment transport Channel adjustment

INTRODUCTION

Rivers are one of the most sensitive components of the physical landscape, with an ability to respond rapidly to external disturbances. Such disturbances can vary considerably in character but they generally alter the flow regime and/or sediment load of the river, creating a disequilibrium in the channel. Changes in flow regime have received much greater emphasis than have changes in sediment load largely because sediment data are more difficult to obtain and manipulate, especially on a long-term basis. This paper attempts to remedy that imbalance, through a case study which focuses on the effects of hydraulic mining.

Mining can generate very large amounts of solid waste which, in the past at least, was often disposed of in the nearest watercourse. In California between 1855 and 1885 enormous quantities of material from hydraulic gold mining were washed into tributaries of the Sacramento River (Gilbert, 1917)—the Yuba River received over 15 million m^3 in one year (Wildman, 1981). The resulting rise in bed elevation (Figure 1) created such serious problems downstream (increased flooding, destruction of farmland, poorer navigation) that further

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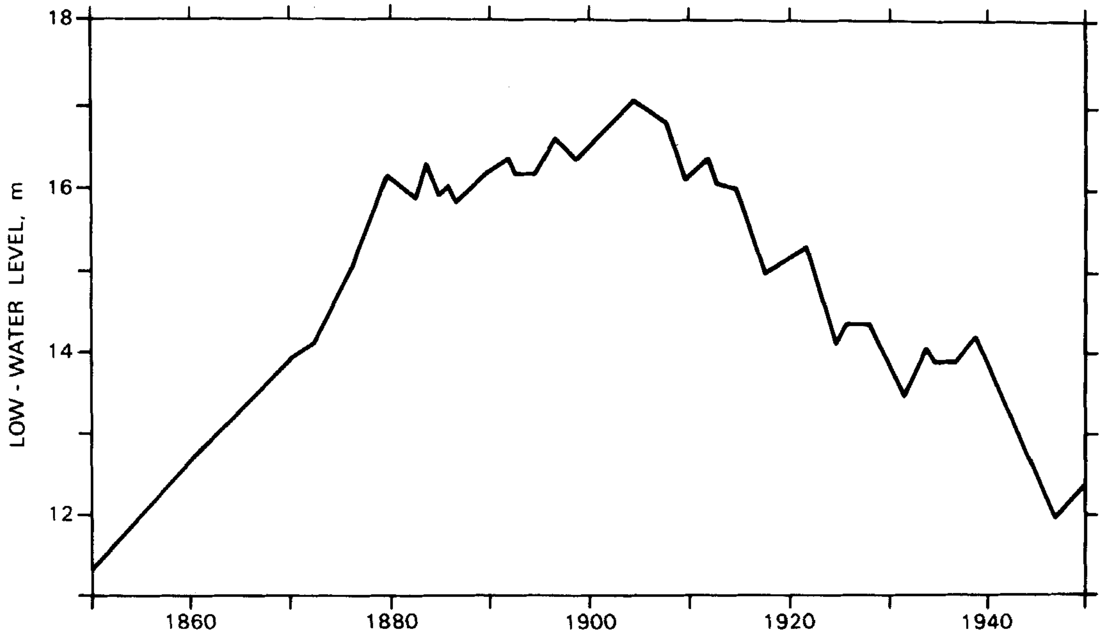

Figure 1. Changes in the annual low-water level on the Yuba River at Marysville, California, 1850–1950 (after Meade, 1982)

dumping was prohibited in 1885. By then, however, the main damage had been done and it took nearly a century for the debris to move through the river system (Meade, 1982). Even now a lot of debris remains stored, in tributary valleys and on floodplains, and its removal will take much longer than the century needed for clearance of the main channels. These and other studies (e.g. Knox, 1987; Lewin and Macklin, 1987; Macklin, 1985) illustrate not only the potential for long-term storage of introduced debris but also the variability of sediment storage patterns and movement histories both within and between river systems.

This paper is concerned with the impact of hydraulic tin mining on the Ringarooma River in northeast Tasmania (Figure 2). It has two main aims: firstly, to establish the transport history of the introduced debris over more than a century; and secondly, to analyse the response of the river to a sediment input which was particularly variable in time and space. Although mining has now virtually ceased, it will continue to have an impact on the physical landscape well into the twenty-first century.

THE STUDY AREA

The Ringarooma basin has been the major source of alluvial tin in Tasmania over the last century, the principal mining areas being between Branxholm and Derby, to the west of Pioneer, and in a ring about Mt. Cameron (Figure 2). The river below Branxholm flows at an average slope of only 0·0023 $m\,m^{-1}$ in a relatively narrow valley. Broad flats do exist in places, notably between Pioneer and South Mt. Cameron, and they play an important role as sediment stores.

The mining era began in 1875, reached its peak in 1900–1920, and had largely ended by 1982. Derelict mine sites, ranging in size from large-scale operations such as the Briseis mine at Derby to surface depressions less than 1 m deep, now litter the basin. During the mining period neither the methods, location, nor levels of production remained constant. Hydraulic sluicing in which the ore-bearing alluvium was broken down with a pressurized jet of water was the most widely used method. Dredging was also used, notably after the Second World War in downstream reaches. Its environmental impact was potentially much greater than was that of hydraulic sluicing because the channel bed was sometimes mined directly but dredging was much more limited in extent. However, both methods had one important characteristic in common—they generated very

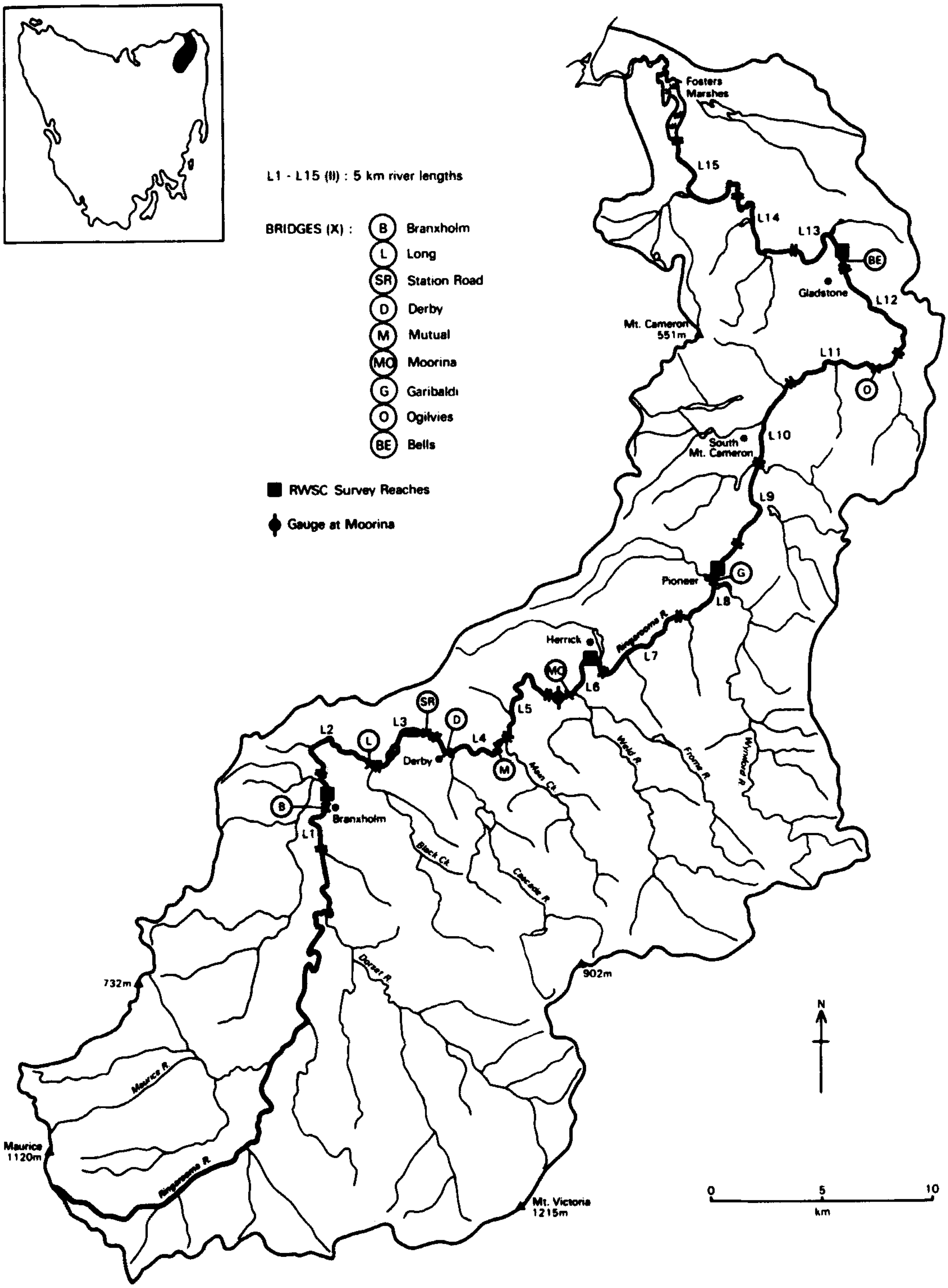

Figure 2. The basin of the Ringarooma River. The inset map shows the position of the basin in Tasmania

large amounts of waste which generally found its way into the river system, especially before 1930 when restrictive legislation was first introduced.

By 1930, however, the main production period had passed (Figure 3). Much of the readily available tin had been won and production was falling steeply when a devastating flood in 1929 accelerated the decline. The high demand for tin during the Second World War revitalized the industry but the reprieve was only temporary. More than 40 000 tonnes of tin were produced in the Ringarooma basin, with four mines (Arba, Briseis, Pioneer, Endurance) being responsible for over 75 per cent of the total (Knighton, 1987a). Of these the Briseis mine at Derby was by far the most important (Figure 3).

Figure 4, based on the records of 53 individual mines, charts the changing location of the tin mining industry over more than a century. After the initial period which was dominated by mines in the Derby area, there was a marked expansion into the southern tributary valleys and downstream along the main river. The number of mines reached a maximum in the period 1900–14 but, even though output subsequently fell, the number remained relatively high until 1940. Thereafter retreat from the tributary valleys began in earnest and, with the closures in the Branxholm–Derby area, tin production had become limited to the downstream reaches by the late 1960s.

Two significant features can be identified initially. Firstly, the proximity of many mines to the main river and the extensive use of hydraulic sluicing ensured a rapid and sustained supply of debris to the Ringarooma. Land storage of the residual drift only became important after the main production period was over. Secondly, the large number of mines and their wide distribution guaranteed a sediment input that was spatially diffuse, even though a handful of enterprises dominated production. Both features contribute to a complex history of sediment movement through the basin.

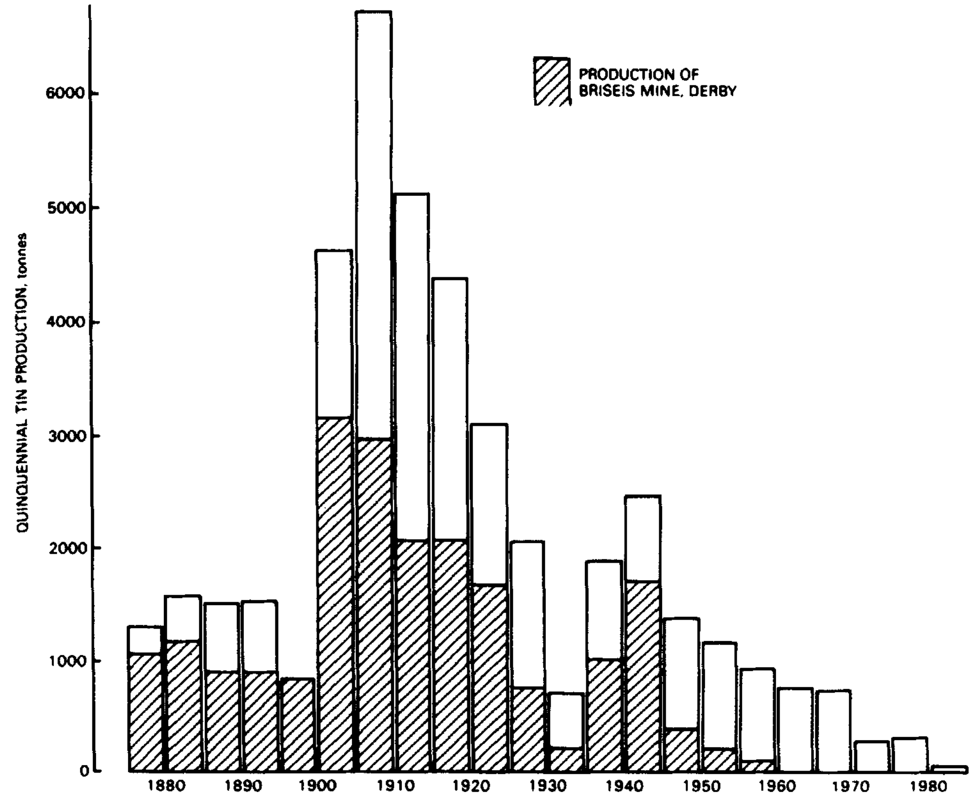

Figure 3. Quinquennial tin production in the Ringarooma basin, 1875–1984

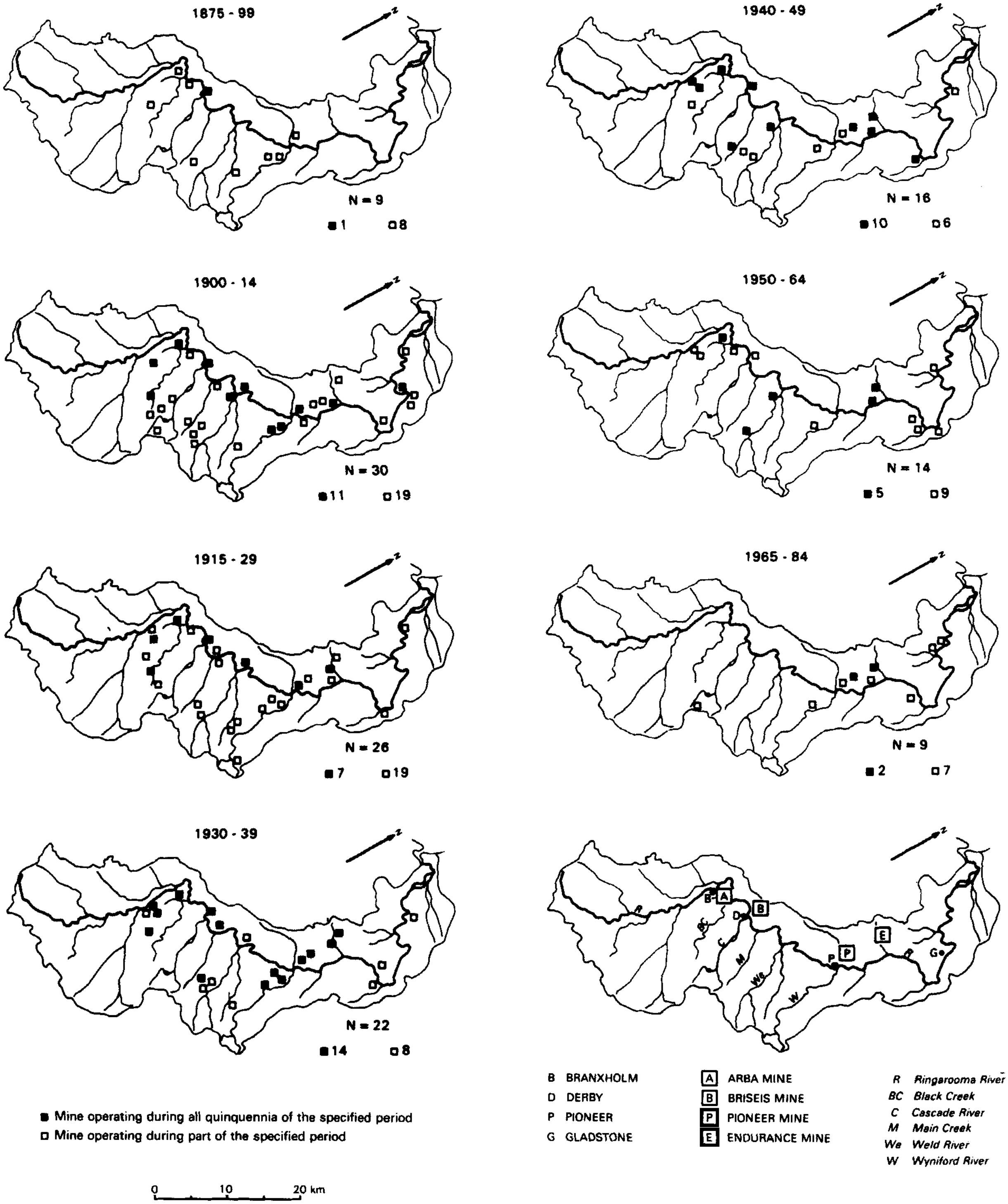

Figure 4. Changes in the distribution of tin mining, 1875–1984

RECONSTRUCTING A SEDIMENT TRANSPORT HISTORY

Reconstruction was conceived as a three-phase process which successively estimated—the variable supply of mining debris to the main river; the incidence of those flows with the capacity to transport the resultant bed material; and the pattern of downstream movement of the introduced load. It was based on information from a wide variety of sources, ranging in reliability from detailed documentary evidence to uncorroborated personal reminiscences. With adequate annual data difficult to obtain for the first 40 years, the quinquennium (five years) was chosen as the basic time period for data analysis and presentation.

Sediment supply

The comprehensive records of 53 individual mines and data from published (Montgomery, 1891; Smith, 1899; Scott, 1928; McKeown, 1938; Dunkin, 1948; Keid, 1952; Braithwaite, 1964) and unpublished sources provide the basis for estimating sediment supply. Details of the procedure are published elsewhere (Knighton, 1987a), so only an outline will be given here of the four stages involved:

1. Calculation of the tin production profile of each mine;
2. Conversion of production data into amounts of material actually worked, using information on 'values' (weight of cassiterite per unit volume of worked material)—data were often available in both forms for the larger mines;
3. Estimation of how much of that material was introduced into the nearest watercourse, using a modified version of the method developed initially by Steane (1972) for the Briseis mine;
4. Adjustment of those delivery figures to take account of distance from the Ringarooma and therefore of the potential delay in sediment arrival at the main river.

Stages 3 and 4 are the most likely sources of error. A specific test of the procedure was devised which involved the mines feeding into the Black Creek system between Branxholm and Derby (Figures 2 and 4). The difference between the total amount delivered to Black Creek from the three mines and the total amount delivered to the Ringarooma (1 193 000 m^3) was compared with the volume of material stored in the alluvial fan at the lower end of the stream (1 320 000 m^3). A discrepancy of only 10 per cent provides some justification for the procedure, especially since the chosen input point was supplied from mines in different distance categories (Table I).

There were 22 main supply points of which 10 were fed exclusively by mines $<0{\cdot}5$ km from the Ringarooma (Table I; Figure 5). Unlike the situation normally encountered elsewhere, the input was not concentrated but occurred at fairly regular intervals over a river length of more than 70 km. Nevertheless, only six points supplied more than 10^6 m^3. Much of the material was less than 5 mm in diameter (McKeown, 1938; Dunkin, 1946) and therefore significantly finer than the natural bed load (Table II). Tailings' samples taken from mine sites and downstream deposits indicate an average grain size in the range of 1–2 mm. The input probably included a large amount of silt as well as sands and small gravels but it would have tended to move rapidly through the system in suspension. The coarser fraction moving mostly as bed load is the concern here since it had the greatest effect on channel morphology.

The Briseis mine had a dominant influence on sediment supply, especially in the early years, although the secondary peak of 1940–44 is only exceeded once elsewhere, by the Pioneer mine (Figure 5). That peak is symptomatic of the progressive decline in values over time as more tin-bearing alluvium had to be processed in order to yield the same amount of cassiterite as before. During the main production period the peaks at the significant input points (11, 13, and 14) occurred later than that at the Briseis mine. Indeed the main period of supply from 14 (Endurance mine) did not occur until the 1950s and 1960s when it and Black Duck Lagoon (21) had become dominant. Peaks did tend to be progressively later further downstream during both the main and post-1940 production periods, although the pattern of sediment supply is very variable. The total input here is modest when compared with that to other mine-affected river systems (Higgins, 1979; Wildman, 1981) but 40 million m^3 does represent a significant addition to the background sediment load. To occur naturally, given the time period involved, would probably require a major change in climatic conditions.

Table I. Estimated sediment supply to the Ringarooma River, 1875–1984

Input point	Total supplied, 10^3 m^3	Distance downstream of (1), km	Number of mines at given distance (km) from main river <0·5	0·5–2	2–5	5–10	>10
(1) Blacksmiths Gully	718	0	0	2	3	0	0
(2) Black Creek (includes ARBA mine)	3111	10	0	1	1	1	0
(3) Valley Creek	367	11·8	1	0	0	0	0
(4) Briseis Mine	18 856	15·7	1	0	0	0	0
(5) Cascade River	<1	16	0	0	0	1	2
(6) Lone Brothers Mine	48	19·3	1	0	0	0	0
(7) Main Creek	140	19·6	0	1	3	0	0
(8) Weld River	163	26·8	0	1	1	5	0
(9) Echo Mine	424	27·2	1	0	0	0	0
(10) Wyniford River	796	37·7	0	1	4	0	1
(11) Pioneer Mine	8145	38·1	0	1	0	0	0
(12) ABC Creek	136	44·7	0	1	1	0	0
(13) South Mt. Cameron	1519	46·2	3*	0	0	0	0
(14) Ruby Creek (includes ENDURANCE mine)	4345	46·7	0	0	3*	0	0
(15) Star Hill Mine	36	52·2	0	1	0	0	0
(16) Ogilvies Bridge	70	54·4	1	1	0	0	0
(17) Purdue Mine	291	54·7	1	0	0	0	0
(18) Lark Creek	32	55·8	1	1	0	0	0
(19) Gladstone	183	62·0	2*	0	0	0	0
(20) Scotia Mine	167	63·8	1	0	0	0	0
(21) Black Duck Lagoon	1138	71·3	3*	0	0	0	0
(22) Aberfoyle Mine	169	72·2	1	0	0	0	0
	40854		17	11	16	7	3

* signifies the operation of at least one dredge.

Table II. Grain size characteristics

	Grain size (mm) D_{84}	D_{50}	D_{16}
Natural bed material*	88·8	47·8	15·7
Introduced load†	3·5	1·4	0·6

* Averages of the samples taken at Branxholm, Long Bridge and Mutual Bridge, which are assumed to reflect the pre-1875 bed.
† Averages of tailings' samples taken at Herrick and South Mt. Cameron.

Flow history

The Ringarooma River has a typical temperate oceanic regime and a mean annual flood at Moorina of over 100 $m^3 s^{-1}$. The following information provided the basis for reconstructing its flow history: daily flows for the Moorina gauge from 1978, and for a neighbouring basin (North Esk) from 1923; rainfall records for various stations stretching back to 1883; a regional analysis of flood flows in northeastern Tasmania (Knighton, 1987b).

As a preliminary step the annual/quinquennial runoff totals were estimated using:

1. 1978–84: observations at Moorina
2. 1923–77: the average of two values calculated from relationships based on 1978–84 data—between the

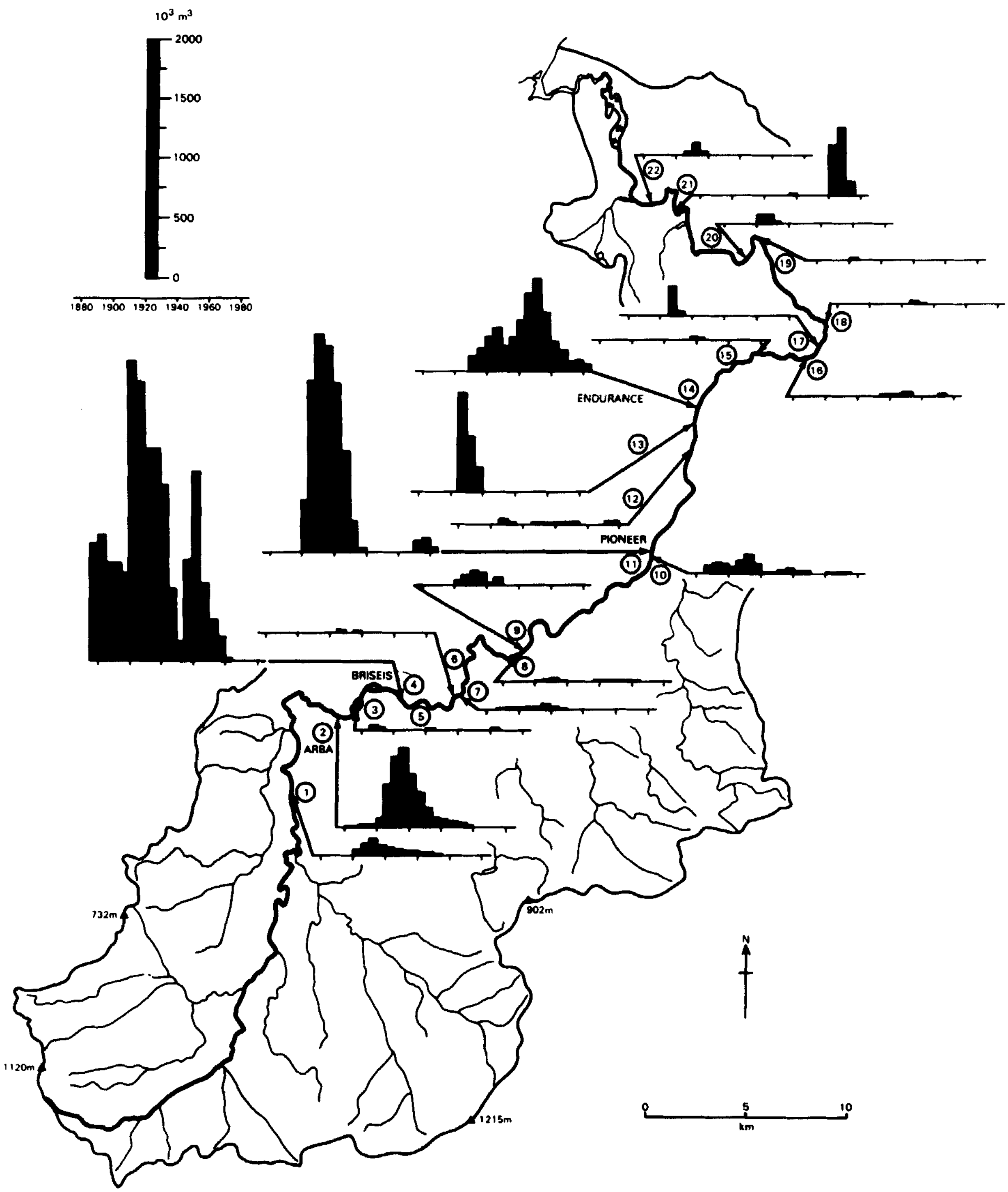

Figure 5. Fluctuations in the level of sediment supply from tin mining over more than a century. The supply points are numbered in accordance with Table I

annual runoffs at Moorina and at Ballroom on the North Esk (correlation coefficient (ρ) = 0·96); between annual runoff at Moorina and annual rainfall at Derby, Branxholm, and Ringarooma (ρ = 0·98)

3. 1883–1922: the above rainfall–runoff relationship and others associated with rainfall gauges having longer records in neighbouring catchments
4. 1880–84: the quinquennial average for 1885–1904
5. 1875–79: the quinquennial average for 1880–99

The resultant plot (Figure 6a) corresponds very well with Steane's (1972) reconstruction for 1910–68 which was based on a statewide rainfall–runoff relationship. 1915–30, 1945–60, and the 1970s stand out as periods of high runoff but the most interesting feature is the low runoff in the early 1900s and 1940s when, significantly, the supply of sediment was at a maximum from the Briseis mine in particular (Figure 5).

The main task was to estimate the number of days in each year/quinquennium on which flows having transportational significance occurred. Field observations suggested that a flow duration of 20 per cent was a suitable lower limit for transport and estimates were made according to:

1. Mean daily flows occurring between 20 per cent and 5 per cent of the time—for each 25-year period the number of days on which such a flow range is expected (namely, 1369) was allocated to the five quinquennia according to their relative contribution to the total runoff;
2. Mean daily flows in the ranges 5 per cent–2 per cent, 2 per cent–1 per cent, 1 per cent–0.5 per cent, 0·5 per cent–0·1 per cent, <0·1 per cent are likely to be less well related to annual runoff, so a more definitive procedure was devised—
   1978–84: as observed at Moorina
   1917–77: a combination of two strategies—definition of rainfall thresholds for each flow range, and direct use of the North Esk flow record (extended beyond 1923 by reference to rainfall data)—having established the degree of correspondence of each with the Moorina record in the overlap period; the two gave similar results and any discrepancies were checked with special care
   1883–1916: based on rainfall data, particularly the threshold strategy used above
   1875–82: in the absence of any flow or rainfall information, the difference between the flow distribution estimated for 1883–99 and that expected for a 25-year period (such as 1875–99) was assumed to apply to the eight years and was equally divided between them.

The estimated annual data were combined into quinquennia (Figure 6b) so that any errors in individual years should become proportionately less important. Overall a Kolmogorov–Smirnov test indicated no significant difference between the estimated number of days in each flow category and that expected for a 110-year period.

The 10 largest floods since 1900 are also indicated on Figure 6b, the biggest probably being in 1936 when the discharge at Derby was about 460 $m^3 s^{-1}$ (McKeown, 1938). Major floods seem to be concentrated into two periods, 1923–36 and 1970–74, the first of which includes the severe flood of 1929 when a dam on the Cascade River was breached and the floodwaters inundated the Briseis workings before continuing downstream to destroy most of the bridges. The second stands out as the quinquennium with by far the largest number of days on which flows exceeded both Q_5 per cent and Q_{20} per cent. However, neither a high incidence of floods nor a high runoff total guarantees a quinquennium of sustained high flow conditions (e.g. 1925–9).

This reconstructed flow history inevitably contains inaccuracies, especially in the early years for which only rainfall data are available. However, it is a vital component of the final phase of estimation (that of sediment transport) and at the quinquennial scale is believed to be reasonably accurate for the twentieth century at least.

Sediment transport

Mining waste introduced into a natural river can either be transported alongside the indigenous load without causing disruption or lead to a complete metamorphosis of the transportational system, two ends of a spectrum of response termed respectively 'passive dispersal' and 'active transformation' by Lewin and Macklin (1987). The Ringarooma River lies toward the latter end of that spectrum. The introduced waste was

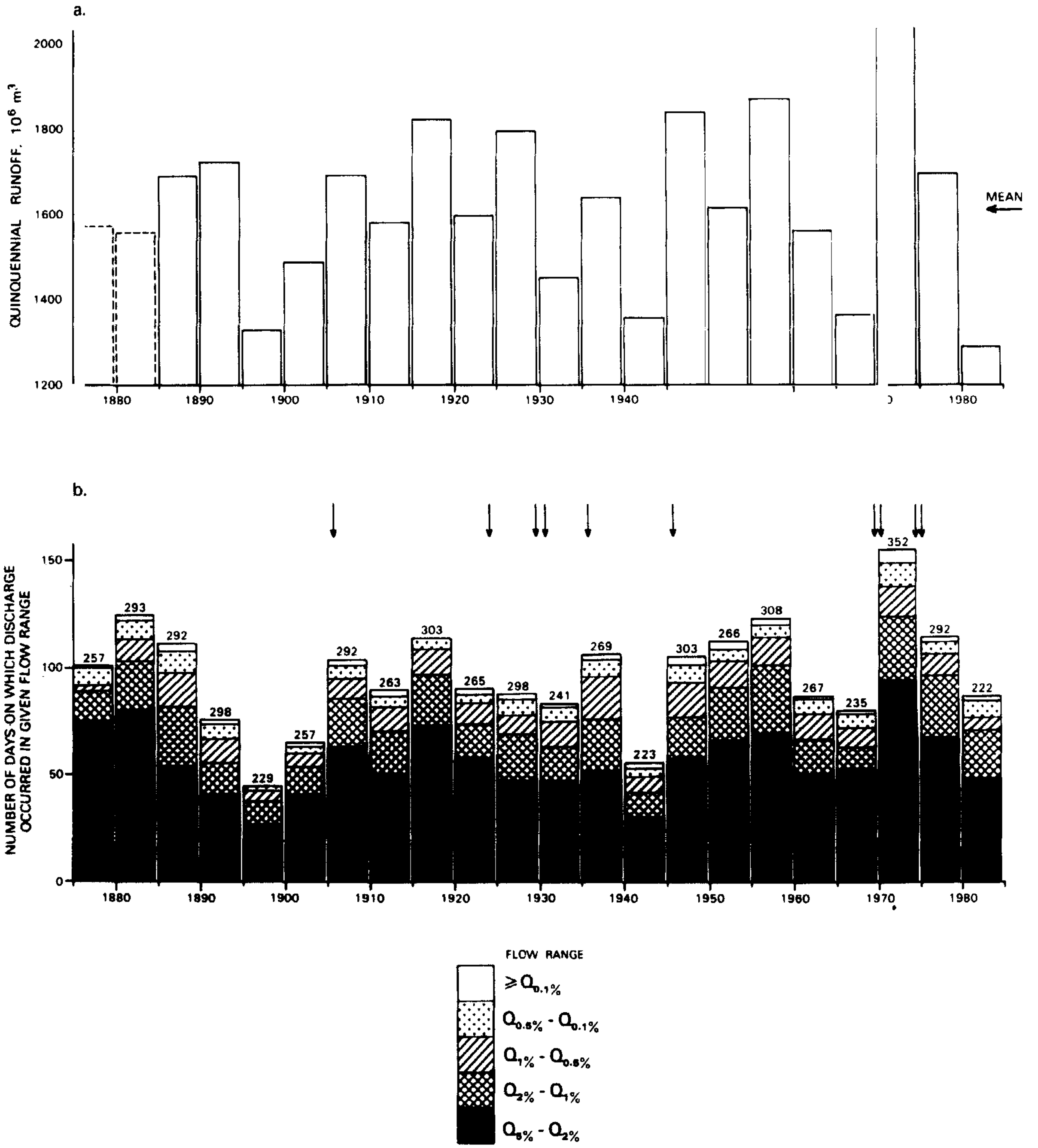

Figure 6. A reconstructed flow history of the Ringarooma River, 1875–1984: (a) Quinquennial runoff. The dashed bars indicate that the estimates for 1875–1884 are less certain than they are for the others; (b) The frequency of flows in six categories defined in terms of flow duration (Q_x per cent denotes a discharge which is equalled or exceeded x per cent of the time). The numbers refer to flows in the range Q_{20} per cent–Q_5 per cent. The arrows indicate the 10 largest floods since 1900

finer than the natural bed material and, because of the volumes involved, quickly replaced it. The few attempts which have been made to model river response to an increased sediment load have tended to visualize the subsequent movement as a sediment wave travelling slowly downstream, becoming longer and flatter as it progresses (Gilbert, 1917; Pickup *et al.*, 1983). The Ringarooma presents a particularly complicated problem because of the large number of widely-separated supply points and because of the lengthy river distance (75 km) and time period (110 years) involved.

The river was initially divided into 15 lengths of 5 km (Figure 2), and subsequent calculations were made separately for each length. The procedure for determining the transport history consisted of two main stages—calculation of the sediment transport potential in each quinquennium; modelling of the downstream movement of the introduced load. The first involved:

1. Estimation of a representative discharge for each flow category using regional flow equations (Knighton, 1987b);
2. Estimation of corresponding flow properties (width, depth, velocity) using regional downstream hydraulic geometry equations (Knighton, 1987c);
3. Calculation of the transport capacity of each discharge using the Engelund and Hansen (1967) total load equation;
4. Calculation of how much material could be transported in each quinquennium given the number of days on which specific flows occurred (Figure 6b).

The characteristics of the introduced load used in estimating transport capacity were assumed to be similar to those of the tailings' samples, with an average grain size of 1 mm. Other transport equations, those of Ackers and White (1973) and Rottner (1959), were also explored but the Engelund and Hansen equation seemed to provide the most reliable results. It is quite sensitive to slope, however, so that, despite the higher discharges of lengths further downstream, transport capacity was significantly at a maximum along that part of the river (15–45 km: Derby to Pioneer) where most of the mining debris was supplied (Figure 5).

In the second stage the data on sediment supply and transport potential were combined in a standard mass-conservation model expressed in finite-difference form (see Pickup *et al.*, 1983, p. 295) to give the pattern of downstream movement of the introduced load. Although Pickup *et al.* (1983) found that this type of model does not perform as well as a dispersion model, the level of information available in this case was not sufficient to warrant a more sophisticated approach. Indeed a time increment of five years and a reach length of 5 km (subdivided into 5 at this stage) can be regarded as rather coarse intervals but then sediment modelling usually deals with transport over much shorter times and distances than are considered here.

There was very little information with which to calibrate the model. However, the bed elevation surveys made between 1971 and 1984 in the RWSC reaches at Herrick and Pioneer (Figure 2) provided a crude check on performance. Some slight adjustments were made by changing the size composition of the introduced load (specifically, the coarsest fractions (>16 mm) were excluded from the transport capacity calculations). Finally a moving-average filter was applied to smooth out the transitions from one reach length to the next and thereby produce a more realistic picture (Figure 7).

The fact that 1875–90 was a period of relatively high flows (Figure 6b) and low supply (Figure 5) is reflected in the small amount of deposition predicted for 1890 (Figure 7). That deposition is represented by a single wave whose apex lies 17 km downstream of the Briseis mine (the main source of debris), although the curve does have a slight upward inflection at 48 km. In the next three quinquennia when flows were low and input was rising steeply, deposition builds up quickly close to the main supply point. In addition, a second peak is beginning to develop just beyond 40 km, a product of past inputs from upstream (especially points 4 and 10, Figure 5) and fresh input from the Pioneer mine. By 1920 that peak has become dominant and remains so through to 1980, indicating considerable storage in the reach between the Pioneer and Endurance inputs where, significantly, braiding and anastomosis are highly developed. Between 1920 and 1935 when production fell sharply, especially in the Derby area (Figure 3), and three major floods occurred (Figure 6b), the model predicts a change from net gain to net loss in those reaches close to the Arba and Briseis mines. Whether or not this is a reliable prediction cannot now be determined but the net loss of 1920–35 continues into 1935–50. However, it occurs at a slower rate, presumably because of the renewed supply from the Briseis

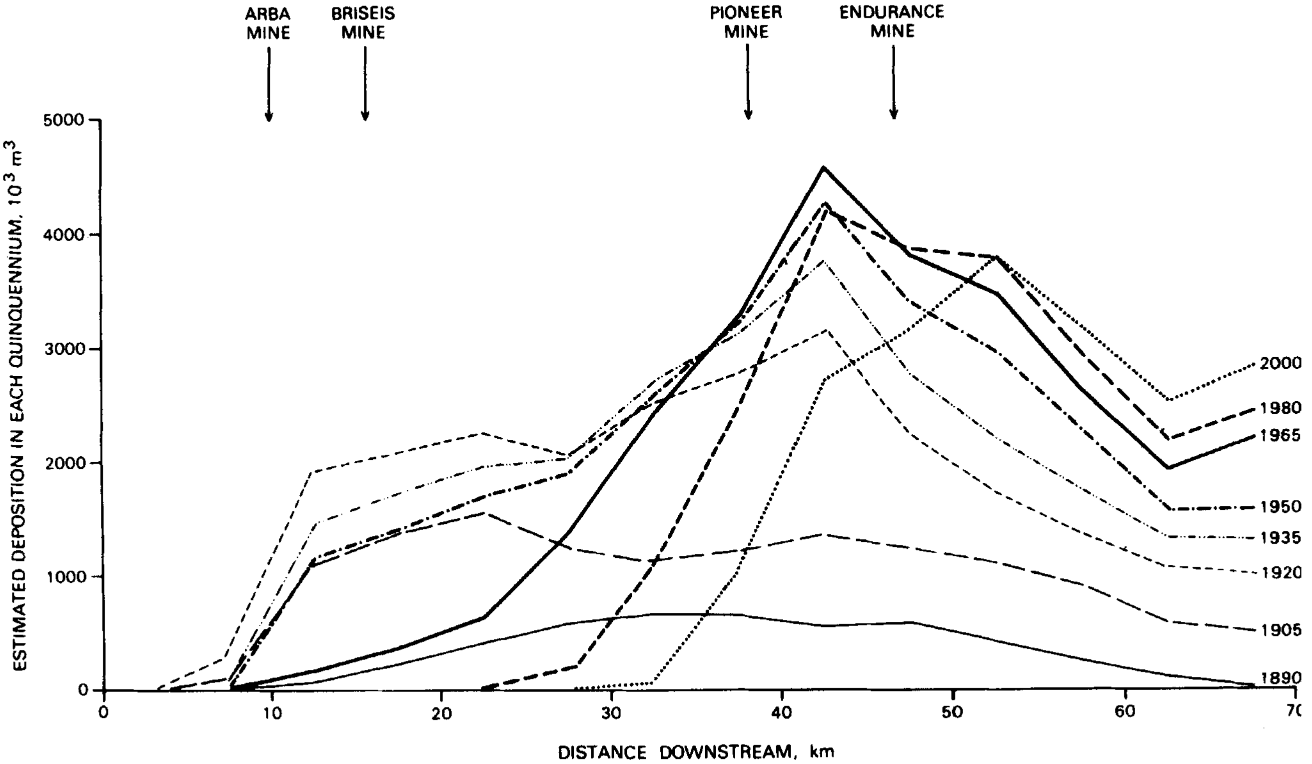

Figure 7. Deposition of mining debris downstream of supply point 1 predicted by a sediment transport model

mine during the Second World War (Figure 5), and by 1950 the volume of deposition has only returned to the 1905 level. 1950–65 is the period of significant sediment losses in these upper reaches. Further downstream, in contrast, the peak at 43 km reaches its maximum in 1965, while the beginnings of another peak can be discerned at 53 km, in part a reflection of the large input from point 14 during the 1950s (Figure 5). Up to this time the model predicts a relatively slow downstream movement of the null point (which separates eroding from accumulating reaches)—from 28 km in 1935 to 36 km where it remains stationary for 30 years. However, by 1980 it has made a significant shift downstream to 47 km. All reaches above 23 km should have lost their mining debris by then, while lower reaches continue to gain sediment as indicated by the sharpening of the 53 km inflection and the upturn at the downstream end where material is stored before entering Fosters Marshes.

The pattern of sediment movement predicted by this model does not have the simple wave-like form proposed by Gilbert (1917) for the Sacramento River tributaries, except possibly in the recession period from 1965 onwards. In California sediment was added over a fairly short and abruptly-ended period of time from upriver sources, whereas here sediment was added over more than 100 years from a variable number of sources along a considerable length of river. Major features of the plot are the peaks just downstream of the Briseis and Pioneer inputs (Figure 7) which together supplied 66 per cent of the total (Table I). The latter quickly becomes dominant and remains more stable in position and strength, indicating the important storage role played by this part of the river. Assuming that each quinquennium has the same flow characteristics as the average for 1960–85, the model can be used to predict the future course of sediment movement. By 2000 there will still be a large amount of material temporarily stored in the downstream parts of the river system (Figure 7). Indeed a further 50 years will be required for the river to cleanse its channel of mining debris. Even then, as in other mine-affected river basins (Wildman, 1981; Meade, 1982; Lewin and

Macklin, 1987), much will remain stored on floodplains and therefore be a potential source for future sediment supply.

RIVER CHANNEL RESPONSE

Aggradation and degradation

The most conspicuous effect of an increased sediment load is a rise in channel bed height. If sediment supply subsequently declines or ceases, the opposite is likely to occur and the river will degrade its bed. Figure 1 illustrates these changes very well. The Yuba River raised its bed by more than 5 m, peak elevation being reached only 22 years after the crest of the sediment wave had left the mines more than 100 km away.

The volumes of deposition previously predicted for each 5 km length can, through division by a mean width, be converted into estimates of bed height. In this case the required width was obtained by averaging the values measured from three sets of aerial photographs spanning 30 years. The scaled vertical axis of the resultant graph (Figure 8) is labelled 'relative depth' to signify that the estimated depth of deposition is relatively correct from one reach to another but may not be absolutely correct. Hence the units are given in brackets.

Length 4, which includes the Briseis mine toward its upper end, shows minor fluctuations in bed height before the main period of aggradation begins (Figure 8). The bed rises very rapidly at first and reaches its maximum height in 1925, to be followed by a small decline before the renewed input of 1935–45 reverses the trend. However, the reversal is short-lived and degradation sets in again once the supply decreases significantly, a relatively constant rate being maintained between 1950 and 1975. By 1984 the river should be back to its original elevation.

In contrast to Length 4, the initial increase in sediment depth is maintained in Length 6. After 1900 it experiences a delayed response (of 5^+ years) relative to Length 4, in terms of rise to peak, attainment of peak, and onset of degradation. The pace of degradation quickens noticeably in 1970–80, presumably because of the very high flows (Figure 6) and the accelerated depletion of upstream sediment supplies.

Length 8 displays similar tendencies (with delay) to Length 6 until about 1925. Thereafter the bed continues to rise, albeit at a steadily decreasing rate, and does not reach a peak until 1970, 40 years later than in Length 6. Only then does degradation set in. The approximate constancy of bed height over such a long period (1930–70) contrasts strongly with behaviour in the two previous lengths where the bed fluctuates quite quickly (Length 4) or maintains a constant level for a shorter time (Length 6).

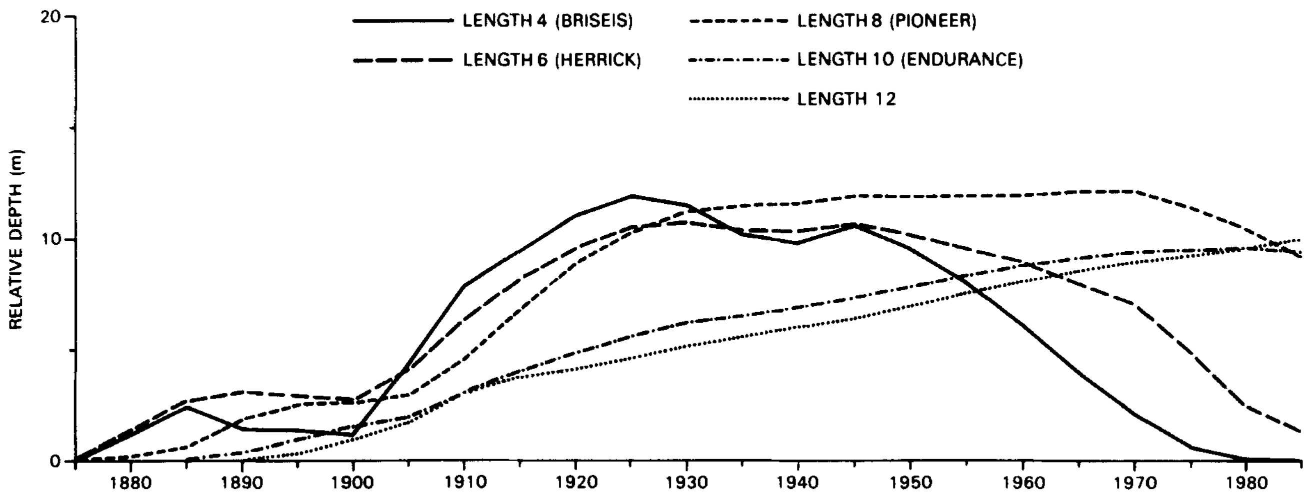

Figure 8. Predicted changes in the relative depth of deposition along 5 km study lengths

The graphs for Lengths 10 and 12 are quite different from the others but are similar to one another, being dominated by a relatively steady rise in bed height but for a mild acceleration during the main mining period. However, they do begin to differ from 1970 onwards—the former levels off and then starts to fall, whereas the latter continues to rise. Reaches downstream of Length 10 should therefore be either stable or still experiencing aggradation.

Overall, the model predicts increasingly regular change with distance downstream (Figure 8)—rises and falls are steadier, transitions are smoother. Also, the main influx of the early 1900s and the large supply from the Briseis mine in WW2 have a progressively smaller influence on the rate of change of bed height downstream. These tendencies would be more understandable if there had been only one upstream source of debris rather than many widely distributed along the Ringarooma, although sediment supply was dominated by the Briseis mine. Of the five graphs shown in Figure 8, that for Length 4 conforms most closely to the Marysville plot (Figure 1). That plot illustrates the erratic nature of both the aggradational and degradational phases, the details of which cannot be reproduced by this relatively coarse model.

Effective testing of the model is hampered by various data problems, not least of which is the lack of any quantitative observations before 1929. Bridge survey data provide a major source of information (Table III). Aggradation had certainly begun by the end of the nineteenth century (Smith, 1899) and increased considerably over the next 30 years (Blake, 1928; Scott, 1928), even as far downstream as Bells Bridge (Length 13) where a dam had to be dismantled because of sediment overtopping (Mr 'Cocky' Groves, personal communication). These characteristics are represented in Figure 8. Available records for 1929–46 indicate aggradation along much of the river (Figure 9), which again the model reproduces, although the change predicted in Length 4 is less than that actually recorded. Between 1946 and 1970 more than 2 m of degradation were reported in each of the Lengths 2, 3, and 4 (Figure 9), with bedrock being exposed at the Station Road Bridge just upstream of Derby (Table III). A comparison of aerial photographs (1952, 1964, 1969, 1980) suggests that up to 1969 the limit of incision was between Herrick and the Garibaldi Bridge—it is perhaps significant that degradation is predicted to begin in Length 8 in 1970. 1970–84 was a period of high flows which scoured the bed as far downstream as Length 8, undermining bridge piers and exposing the stumps of riparian trees which had previously been inundated by mining waste. Again the model fits with observation.

More definite annual data are available from survey reaches established by the Rivers and Water Supply Commission in the early 1970s (Figure 2). Indeed the results from two of these reaches, and particularly the one at Herrick, were used to check the performance of the model. The channel bed at Branxholm is stable (Figure 10) and has probably been so for some considerable time given that there was only one input point upstream (Figure 5). Considerable degradation characterizes the Herrick reach, the annual amount of which is significantly correlated with the incidence of high flows (the best correlation was obtained for flows in the range $Q \geqslant Q_2$ per cent). It is interesting to note also that the plot (Figure 10) has the kind of exponential form commonly assumed for relaxation paths (Graf, 1977; Brunsden and Thornes, 1979), which may indicate that the bed is approaching its former level. Bed height changes are less variable at Pioneer and in certain years run counter to those at Herrick. Considering that erosion from one represents supply to the other, contrary behaviour is not entirely surprising. The Gladstone Reach shows no net change in bed elevation but the plot suggests that sediment waves are moving through the reach. The potential for significant aggradation may still exist in the lower parts of the river.

As regards overall performance, the model seems to reproduce the main pattern of change reasonably well—that of downstream progressing aggradation and degradation. It is less accurate for predicting the actual amounts of bed level change between specified dates but, judging from the depths of tailings observed at the three downstream bridges (Table III), the gross amounts of aggradation indicated by the model are of the correct order of magnitude. Considering the volume of material involved, the river seems to have been able to respond quite rapidly to the fluctuating levels of sediment supply. In Length 4 the river regained its former level in about 35 years after upstream mining had ceased. However, response tends to become more sluggish with distance downstream.

The transition from aggradation to degradation is expected to change the composition of the bed material when, as in this case, the introduced load is finer than the natural one (Table II). Degradation will either return

Table III. Bridge information

Bridges—river length in brackets	Construction dates	Bed height change	Relative bridge height	Tailings depths	Comments
Branxholm (1)	1907, 1969				1959: sandstone bed; no evidence of scour
Long (2)	1913, 1950	−2 m (1963–70)			
Station Road (3)	1950, 1962	−3·5 m (1959–84)			1971: bedrock exposed. Scour during floods in 1969, 1974 and 1980
Derby (4)	?(−1929), 1930, 1973	+1·5 m (1936–45) −3 m (1952–62) at maximum			1970: severe scour during flood 1974–8: scour (3 m) caused by mining of stream bed and knickpoint recession (see Mutual) 1981: bridge footings exposed
Mutual (4)	?, 1936, 1963	+1·7 m (1937–46) −0·9 m (1947–49)		1974: maximum pile penetration of 5·5 m	1974: mining of stream bed 100 m downstream and knickpoint recession have caused 4 m of scour and undermined bridge
Moorina (6)	?, 1957				
Garibaldi (8) (Pioneer)	1910(−1929), 1930, 1946, 1976	+2 m (1929–44) +0·2 m (1947–49)	1946 bridge: 1·3 m higher	1976: maximum pile penetration of 13 m (mostly tailings)	1969, 1971: 1·3 m of scour during floods
Ogilvies (11) (downstream of Endurance mine)	?(−1929), 1930s, 1951, 1979	+3 m (1946–80)	1930s bridge: 10 m higher 1951 bridge: 3 m higher 1979 bridge: 4 m higher	1979: maximum pile penetration of 13 m (mostly tailings)	1949: deck is 1 m below normal flood level 1978: water at deck level
Bells (13)	?(−1929), 1934, 1946, 1975	+2·5 m (1934–44) +0·3 m (1947–49) +3·5 m (1946–69)	1934 bridge: 4 m higher 1946 bridge: 4 m higher 1975 bridge: 2·5 m higher	1944: 6–9 m of tailings 1983: maximum pile penetration of 12 m (mostly tailings)	1944: stream bed level with bridge beams

Sources: Department of Main Roads, Launceston; Mr. J. Davidson, retired highway engineer; Steane (1972); Bridge Plaques
?: bridge known to exist but construction date not known.

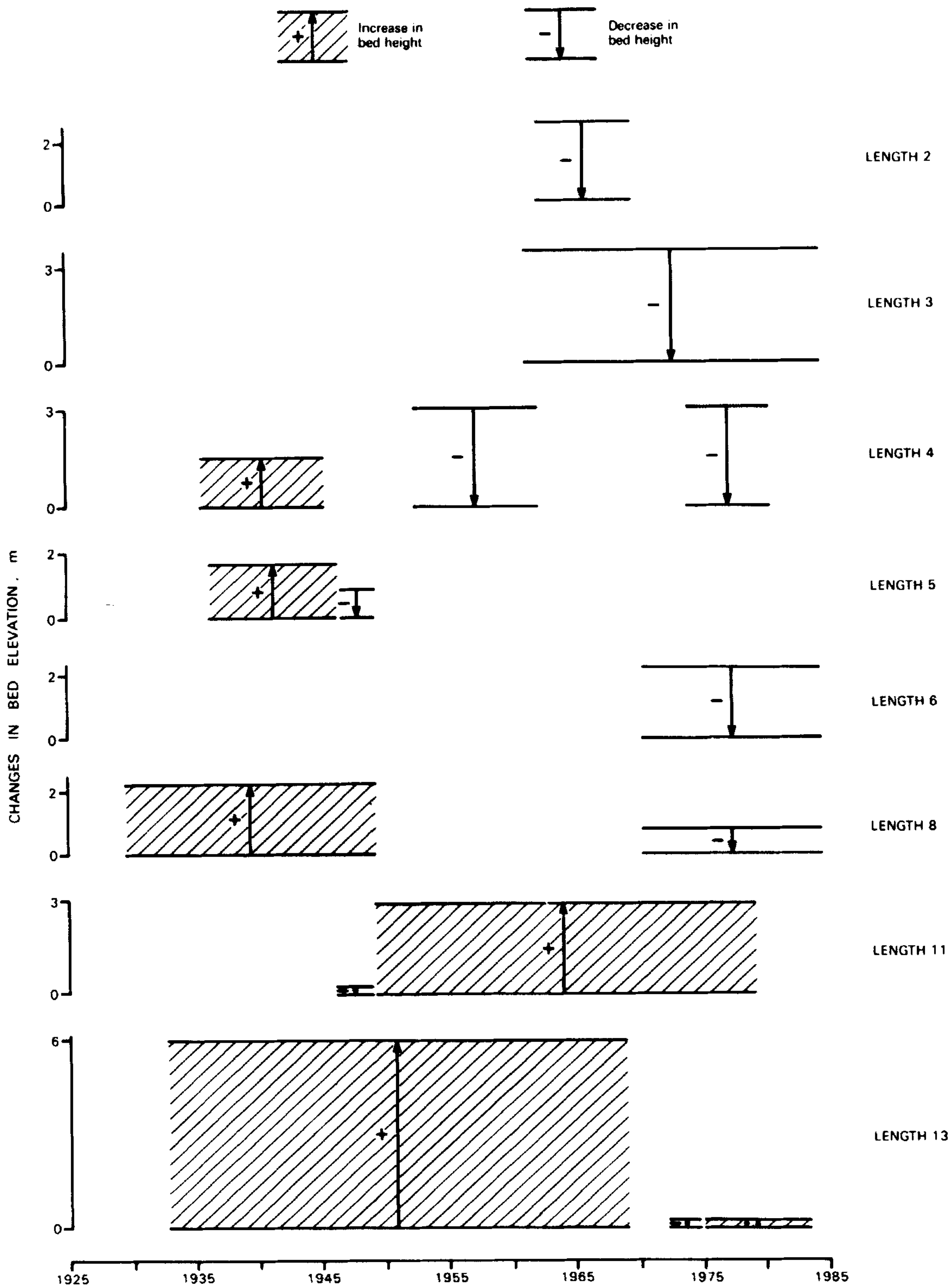

Figure 9. Changes in bed elevation observed in 5 km study lengths over specified time periods

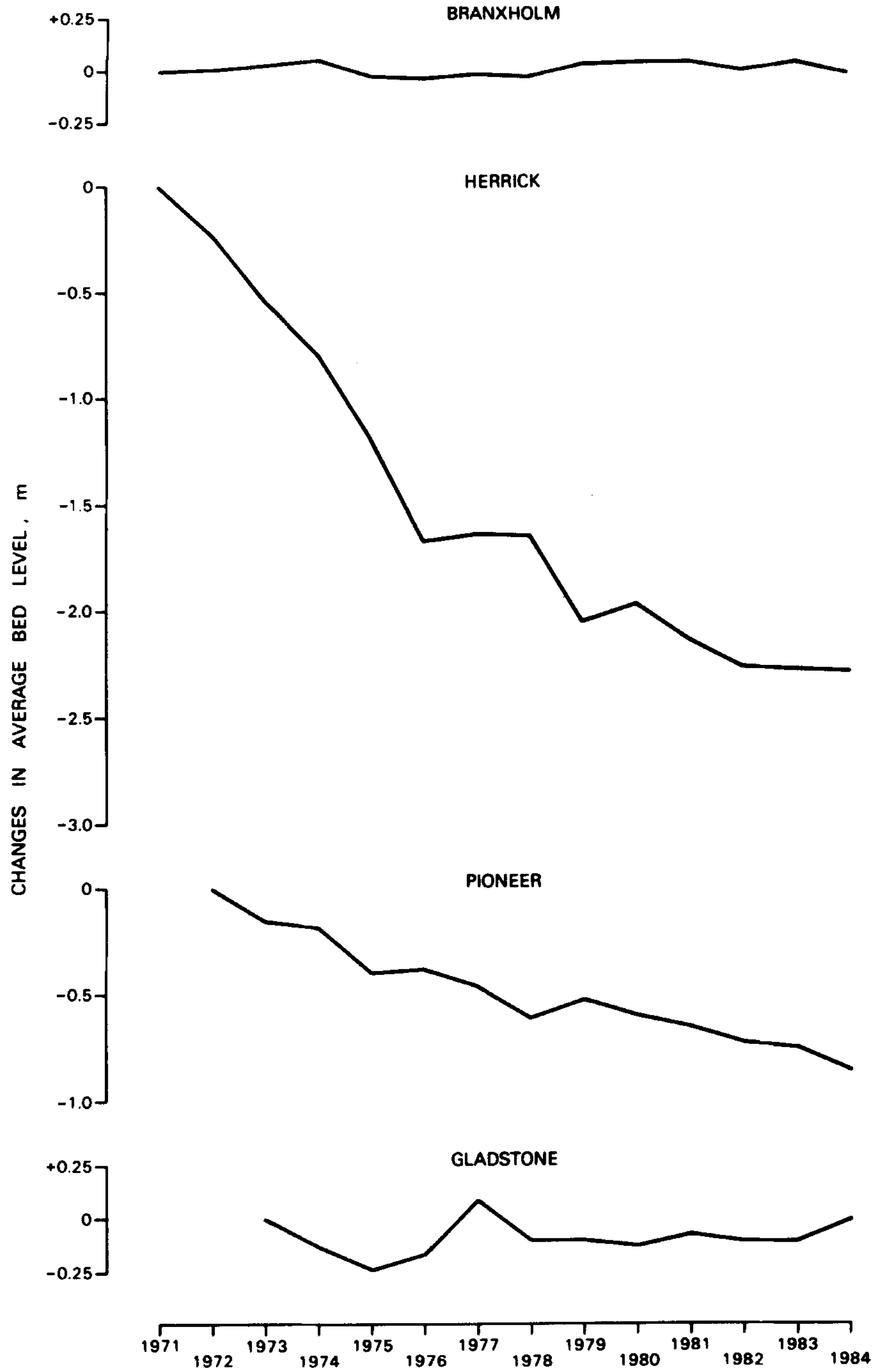

Figure 10. Changes of bed elevation in the Rivers and Water Supply Commission survey reaches (see Figure 2 for locations)

a reach to its original bed or appear to do so by forming a lag concentrate of the coarser fractions in the introduced load. Samples of bed material were taken from 15 points along the Ringarooma, over a distance of 100 km between Mt. Maurice and Fosters Marshes. Due to the variable character of the bed, different methods had to be used: discrete sampling by Wolman's (1954) technique in the upper part, bulk sampling and sieving in the lower part. This difference could have affected the results but not to the extent shown in Figure 11. The dramatic decrease in median grain size between Herrick and Pioneer separates a gravel-dominated bed, which has either been unaffected by mining (upstream of 30 km) or experienced sufficient degradation for the reexposure/concentration of coarse material (30–65 km), from a sand-dominated one which is still largely under the influence of mining debris. It is not certain that the natural channel downstream of 65 km would have a gravel bed but extrapolation of the upstream curve with its characteristic exponential form would support such a claim. In a broad intermediate zone the bed material is poorly sorted (Figure 11b), either because coarse particles have underlying fines which are irregularly exposed (samples at 51·5 and 56·5 km) or because an otherwise sandy bed is beginning to develop a concentration of gravel-size particles in the surface layer (samples at 68 and 71 km). Outside this zone the sorting coefficient seems to vary in the quasi-periodic way noted elsewhere (Knighton, 1980). Thus the characteristics of the bed material reflect the transitional nature of the river's behaviour. The striking change at about 65 km does not mark the downstream limit of degradation but it does indicate where degradation has been operating long enough to armour the bed.

Adjustment during degradation can be episodic, with periods of rapid incision being separated by periods of gradual change or relative stability (Figure 1; Graf, 1977; Schumm, 1977). In such circumstances terrace sequences may develop (Wildman, 1981). Parts of the Ringarooma system as far downstream as Length 7 have unpaired terraces where the valley floor is wide enough. The speed with which the process can be accomplished is well illustrated by the Herrick section (lower section, Figure 12) where 5 m of incision has occurred in about 20 years. The uppermost level was probably the floodplain in the early 1960s (Figure 13). Even where the valley floor is narrow, some hint of terracing may be evident (middle section, Figure 12).

A main river and its tributaries are not independent of one another. It is not surprising therefore that tributaries reacted to the changes in the Ringarooma as it successively aggraded and degraded its bed. A distinction is drawn between those tributaries with mines and those without. In the former case during the aggradational phase tributaries tended to build small-scale deltas at their mouth or experience backwater deposition, the type of response being determined by the relative rates of aggradation in the tributary and main river. The consequent reduction in slope at the lower end of the tributary encouraged further deposition in a kind of positive feedback, the most extreme form of which is represented by the large alluvial fan at the mouth of Black Creek. Those tributaries without mines responded to aggradation in the Ringarooma by developing lagoons (Blake, 1928), the largest of which was Surrey Lagoon near Herrick with an overall length of 2 km (Figure 13). When the degradational phase set in, the fall in local base-level produced an increase in tributary slope which stimulated incision. Degradation progressing upstream, as opposed to downstream in the main river, led either to the formation of terraces in mining tributaries (upper section, Figure 12), or to the draining of lagoons and the incision of lagoonal sediments in non-mining tributaries. Thus can tributary deposits held in temporary storage be released to provide a slow but steady supply to the Ringarooma for some time to come.

The Ringarooma has had to make substantial and extensive adjustments to its bed over more than a century in order to cope with the input of mining waste from many sources. The effects were not confined to the channel bed, however. Aggradation increased the frequency of flooding and thereby the rate of floodplain deposition, the depth of which can be appreciated from Figure 12. Public road bridges had to be replaced long before their natural lifespan had elapsed (Table III), because of either burial beneath a rising bed level (Figure 14) or undermining during degradation. And still the process of adjustment has not run its full course—the bed in the upper parts (as far as Length 5 at least) should now be stable, that between Lengths 7 and 10 is being actively degraded, but beyond Length 10 the transition from an aggrading/stable mode to a degrading one has yet to begin.

Channel form

The relationships assembled by Schumm (1969) predict that an increase in bed-material load will lead to a decrease in depth and increases in width and slope. The increase in width need not always be realized (Park, 1979), especially if the material tends to be rather fine, and in Chang's (1986) model no increase occurs until a load-related threshold is crossed. However, Chang (1984, p. 157) does point out that: 'Changes in channel-bed

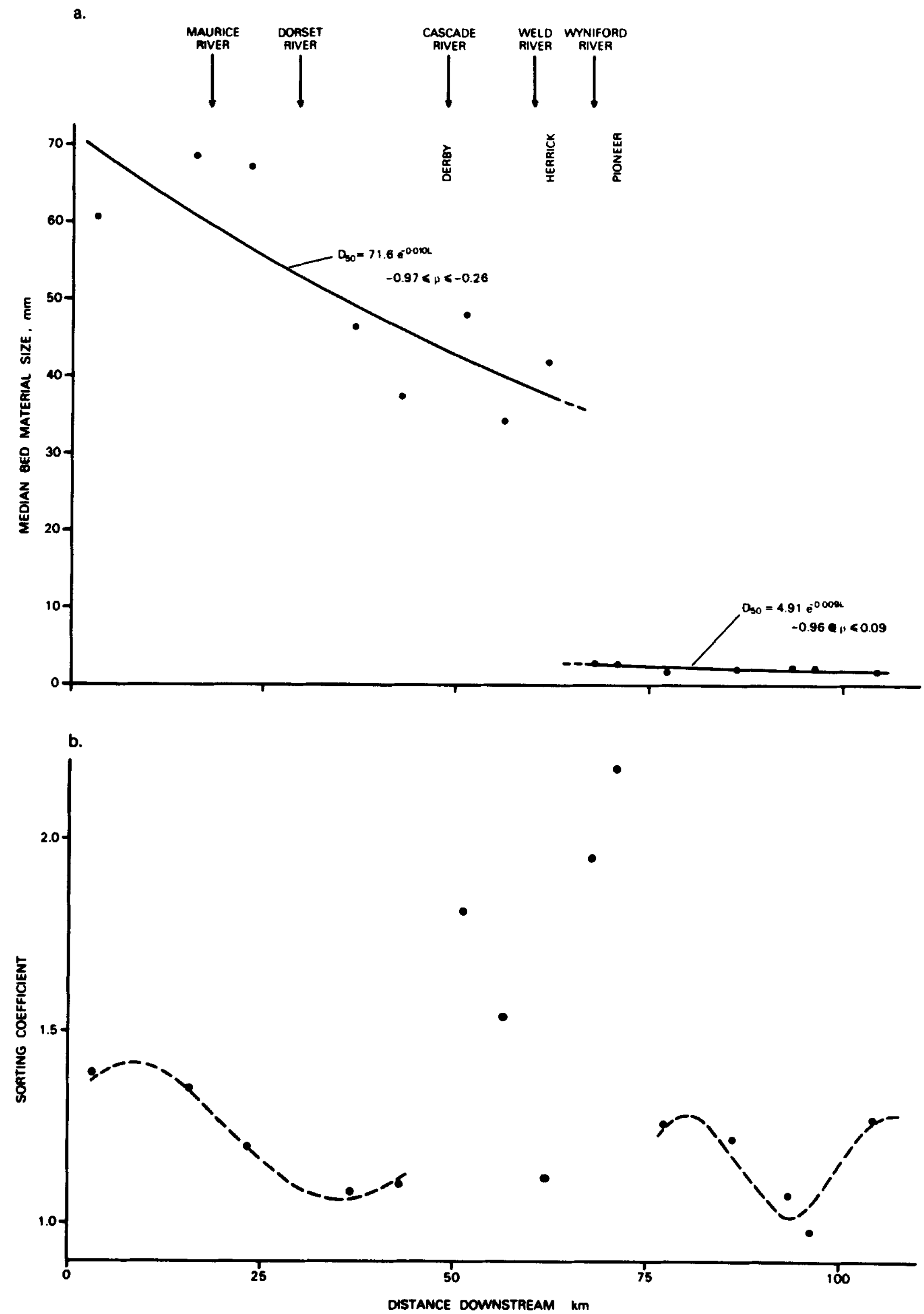

Figure 11. Changes in bed material characteristics measured along the Ringarooma River in 1984: (a) Median grain size—the 95 per cent confidence limits of the correlation coefficients are given; (b) Folk and Ward's (1957) sorting coefficient

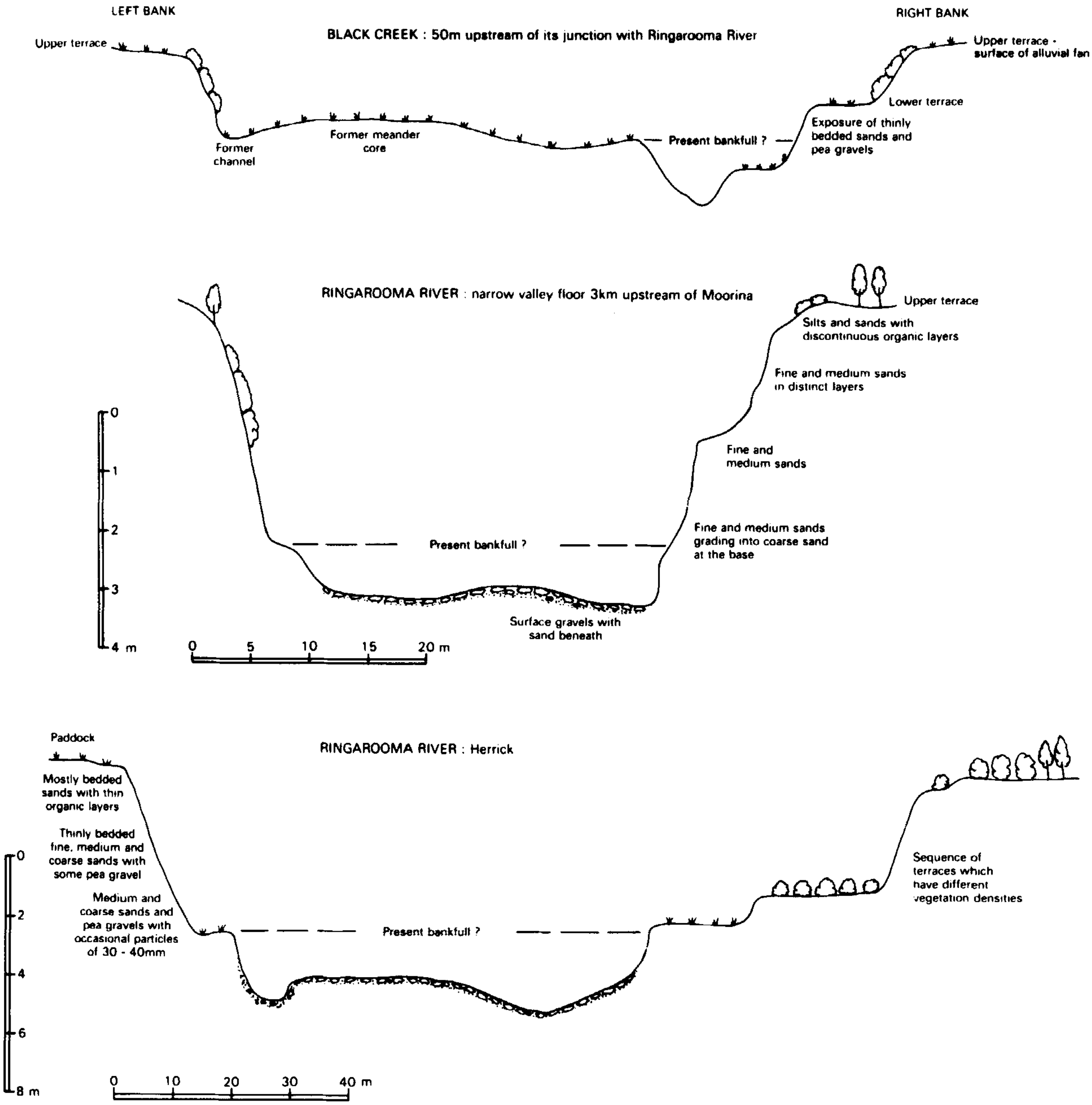

Figure 12. Sample sections surveyed in the Ringarooma basin to illustrate the effects of aggradation and degradation

elevation are almost inseparable from width variation because a channel tends to become narrower during degradation and . . . to widen during aggradation. In addition, aggradation is often associated with the development of braiding (Higgins, 1979; Lewin *et al.*, 1983) as a stream becomes overloaded or locally incompetent to transport the coarser fractions of the introduced load.

The available information relates principally to planform properties. It is insufficient to decide on the behaviour of depth, although bed aggradation would be expected to produce a decrease and aerial photographs taken around 1950 indicate a shallow-bedded river (see also Figure 14). As bed material coarsens

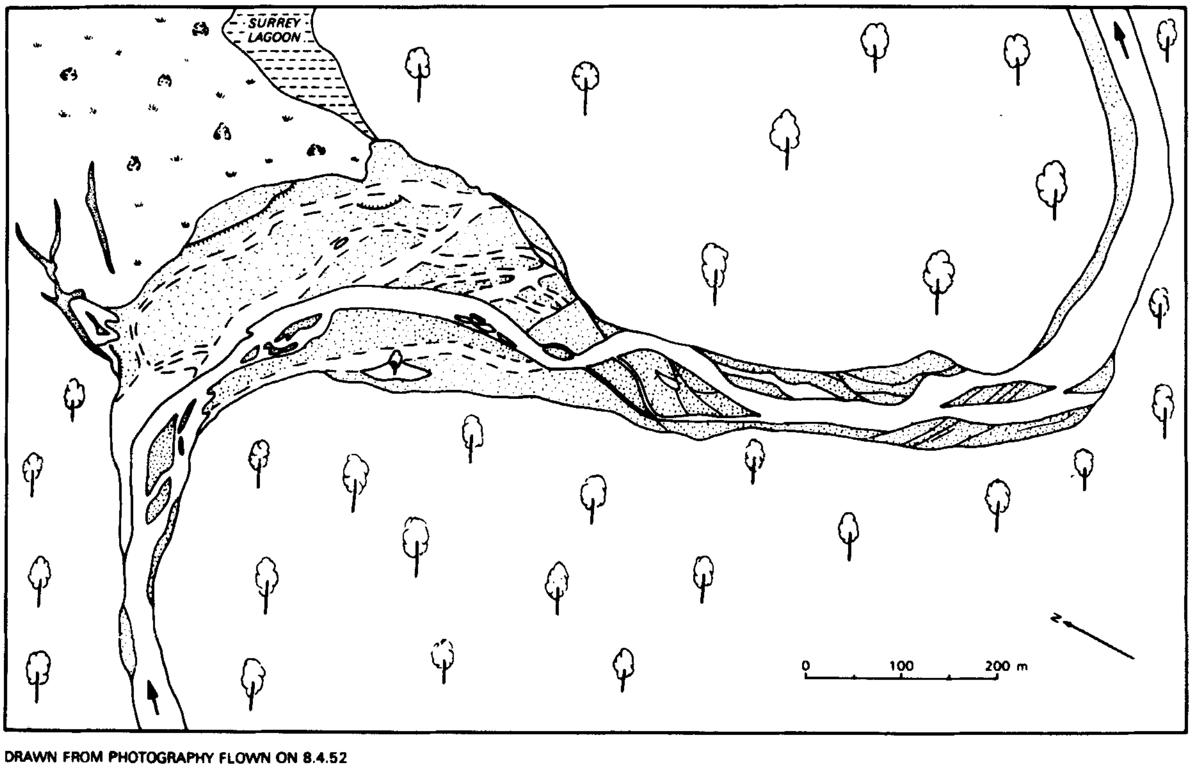

Figure 13. Braiding and lateral deposition along the Ringarooma River near Herrick, 1952

during degradation, the potential for depth adjustment should become progressively less. That appears to be the case at Herrick but at Pioneer where the onset of degradation is more recent no such tendency is apparent (Figure 15).

Aerial photographs taken between 1949 and 1982 are the primary source of evidence for changes in channel form. Channel width, or more strictly width of the channelled area (which would include, for example, the lateral deposits of Figure 13 since they were probably part of the bankfull channel), was measured on a magnified vernier scale every 0·25 km along the river below Branxholm Bridge. A five-point moving average was used for smoothing purposes but even so the level of variation remains quite considerable (Figure 16). The overall behaviour is shown at the top of the diagram and, where two states are given, the first refers to the change from 1952/1949 to 1964 and the second to that from 1964 to 1980/1978/1982.

There is a clear distinction in the behaviour of width associated with the transition from a gravelly to a sandy bed. In the gravel sector width is either constant (where a narrow valley floor has limited adjustment) or decreasing. As regards the latter, the main period of decrease occurs later further downstream, thereby paralleling the pattern of degradation which is downstream progressing. The largest decreases are located in those reaches below major supply points (notably the Briseis mine) and where the valley floor was wide enough to allow considerable expansion initially (Herrick section, Figures 12 and 15). Judging from the cross-sectional changes measured at Herrick and Pioneer (Figure 15), the narrowing process is episodic and occurs not through lateral deposition but through increasingly concentrated incision.

In the sand sector stable reaches also exist but, where change has occurred, one of the time periods has generally experienced an increase in width. The increase between the first and second periods in the 35–42 km reach is probably a real one but the limits of the channelled area were difficult to define on the 1952 photography and only the main channel was measured. As with the decrease of width in the gravel sector, the

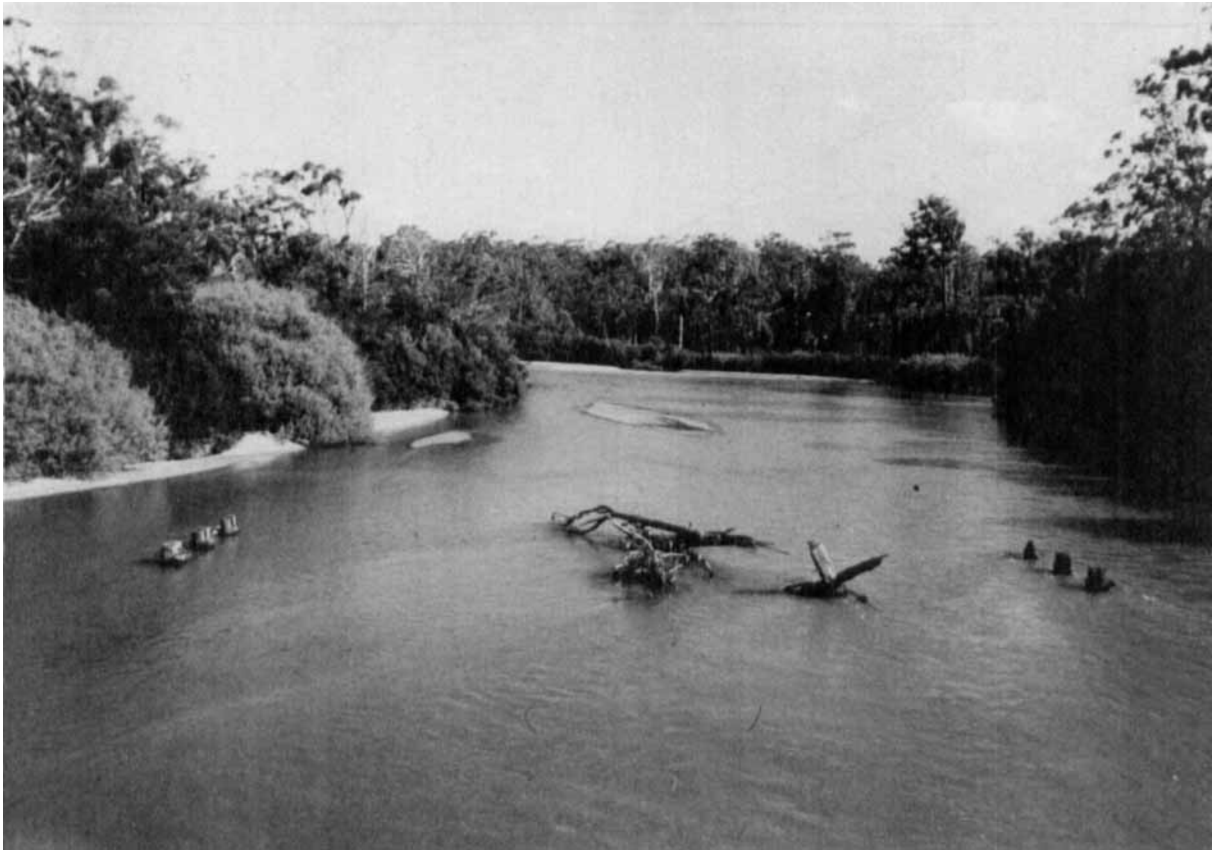

Figure 14. Upstream view of the Ringarooma River from Bells Bridge. Note the piers of the previous bridge and the extensive deposits (both lateral and central) even though the flow was quite high (20 per cent duration)

increase here tends to be later further downstream, although part of the increase between 62 and 66 km is due to dredging rather than natural channel expansion. Thus changes in width parallel those in bed elevation according to Chang's (1984) prescription but with the addition of a longitudinal dimension—the earlier the upstream degradation the earlier the decrease in width, the later the downstream aggradation the later the increase in width.

An abundant bed load and erodible banks are two of the conditions necessary for the development of braiding (Knighton, 1984). Here the first was easily satisfied by the supply of mining debris but the second could not everywhere be met because of the restricted valley floor along parts of the Ringarooma. Consequently large-scale expansions of the channelled area were confined to a few suitable localities ('sedimentation zones')—Herrick (Figure 13; at 23 km, Figure 16), downstream of Pioneer (34–38 km), South Mt. Cameron (39–42 km), the flats in the neighbourhood of Ogilvies Bridge (48 km), and downstream of Bells Bridge (55–57 km). Braiding and anastomosis are particularly well developed in the Pioneer and South Mt. Cameron reaches where, significantly, peak storage of introduced load is predicted by the transport model from 1920 onwards (Figure 7). Central and lateral bars did and do form in other reaches provided the valley floor is not too narrow (Figure 14), so that low intensity braiding was common along the Ringarooma during much of the mining period. Even as late as 1961 the river above Derby was flowing in two distinct channels (Steane, 1972). However, by the late 1970s the river upstream of Herrick had reverted to a single channel and incision had left previous lateral deposits as terrace-like remnants on the valley walls. As degradation continues to progress downstream and a narrower channel is cut, the incidence and intensity of braiding should gradually decline. The unusual downstream variation of width (Figure 16), which follows no known

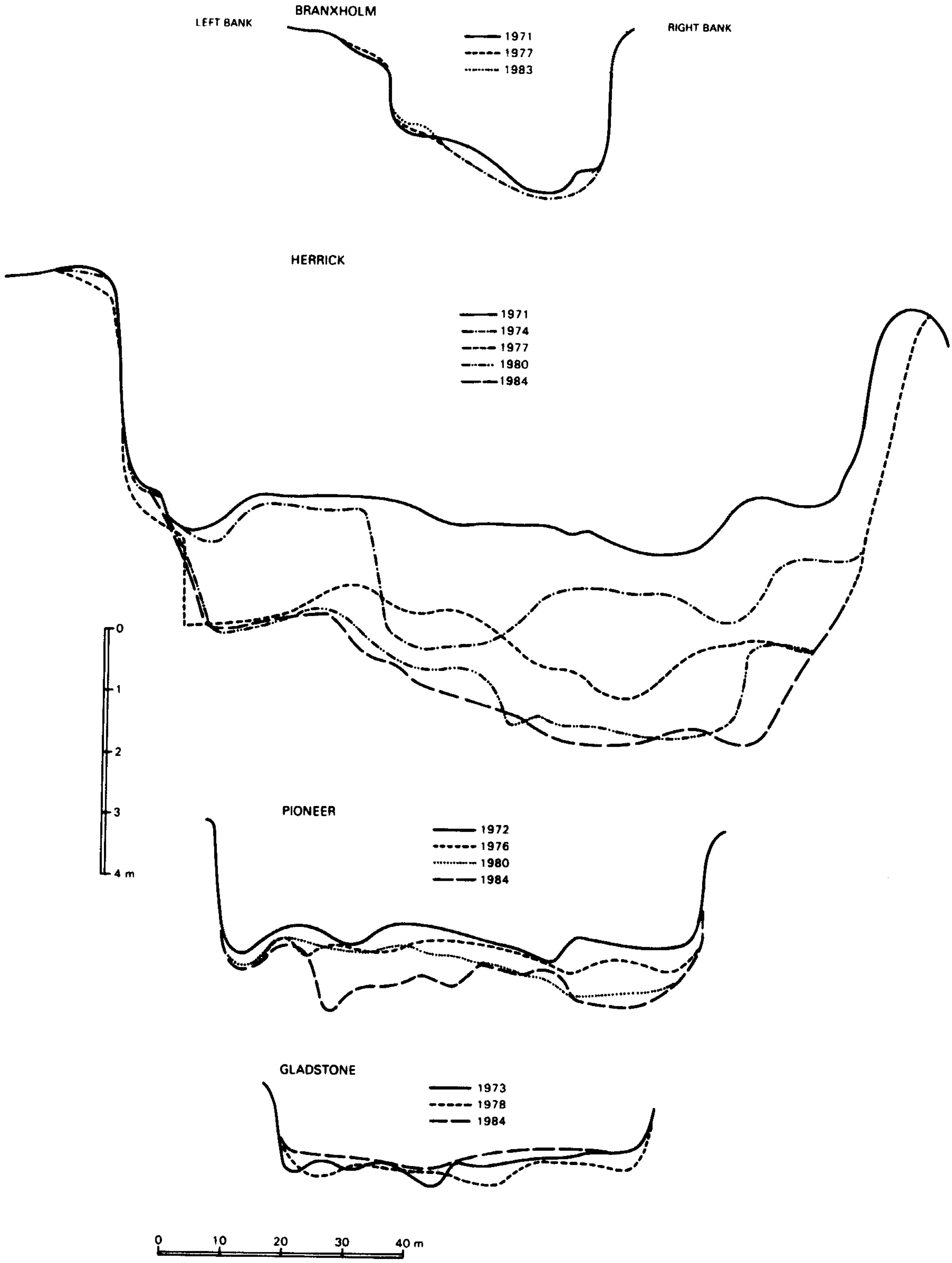

Figure 15. Changes at representative cross-sections in the RWSC survey reaches

trend, reflects in part the planform adjustments made by a river subject to valley-side constraints and the translational action of aggradational and degradational processes.

CONCLUSION

Prediction in geomorphology becomes more problematic and less accurate over longer timespans, particularly where the transport of a sediment load is involved. However, there is a growing need to understand how a river will respond to modifications of the physical environment. This study has demonstrated how information from a wide range of sources—documentary evidence, flow and rainfall data, aerial photographs and maps, personal interviews, field observations—can be assembled to provide a coherent account of changing conditions over more than a century. The input, transport, storage, and output of sediment have been quantified at the catchment scale, an approach strongly recommended by Newson and Leeks (1987) for examining problems of river instability.

The Ringarooma River has suffered the consequences of alluvial tin mining since the 1870s. The introduced waste was finer than the natural bed material (Table II) and, because of the volumes involved, quickly replaced it. The transport history of the river, which is summarized in Figures 7 and 8, was reconstructed using a tripartite procedure which successively estimated—sediment supply, the frequency of flows with the capacity to transport the introduced load, and the pattern of sediment movement downstream, the final stage being based on a mass-conservation model. Unlike many mine-affected basins the input to the main river came not from a few concentrated sources but from many widely distributed ones, which complicates the predictive process further. Given the time period (110 years) and river distance (75 km) involved, the final model cannot be expected to predict change at small spatial and temporal scales but it does seem to reproduce the general character of sediment movement reasonably well. In particular, it predicts maximum storage of debris just downstream of Pioneer where, significantly, the development of braiding and anastomosis is most intense. Also, the gross amounts of aggradation estimated by the model are of the correct order of magnitude (compare Figure 8 and Table III). The pattern of sediment movement does not have the simple wave-like form favoured by Gilbert (1917), largely because of the multiple inputs, but the downstream progression of successive phases of aggradation and degradation is clearly established.

The introduction of more than 40 million m^3 of mining debris has probably been the most significant event in the recent history of the Ringarooma. Extending over more than a century, it has resulted in considerable instability in the river. The proximity of many mines to the main river and the widespread use of hydraulic sluicing were of major importance in ensuring a rapid and sustained supply of debris. That supply had its earliest start in upper reaches and its latest finish in lower ones (Figure 5). Consequently, aggradation built up the bed most rapidly in the former at first, response becoming progressively later and slower with distance downstream (Figure 8). Peak levels were predicted to exceed 10 m. Bed aggradation was accompanied by the development of braiding and by increases in width of up to 300 per cent (Figure 16) but that level of increase was only attained where the valley walls did not limit expansion of the channelled area.

Degradation was predicted to start in the upper reaches rather earlier than might have been expected but the fall in bed level was arrested by renewed inputs of debris during the Second World War (Figure 5) and did not begin in earnest until 1950 (Figure 8). Its downstream progression and intensity were especially marked during the early 1970s (Figures 8, 10, and 15), a period of very high flows (Figure 6) when incision rates reached $0{\cdot}5\ m\,yr^{-1}$, and by 1984 degradation had begun as far downstream as Length 10. Where incision has been taking place long enough, the river has changed the composition of its bed material from sand- to gravel-dominated through reexposure of the original bed and/or lag concentration of coarser fractions in the introduced load. Such armouring of the bed slows the rate of degradation considerably. The sharp transition from a gravelly to a sandy bed (Figure 11) demarcates a change in the behaviour of width—from an upstream decrease to a downstream increase in at least one of the measurement intervals (Figure 16). Reversion to a single-channel planform has accompanied narrowing of the channel. The episodic nature of adjustment during degradation is indicated by the development of terrace sequences, not only in the main valley but along tributaries as well (Figure 12).

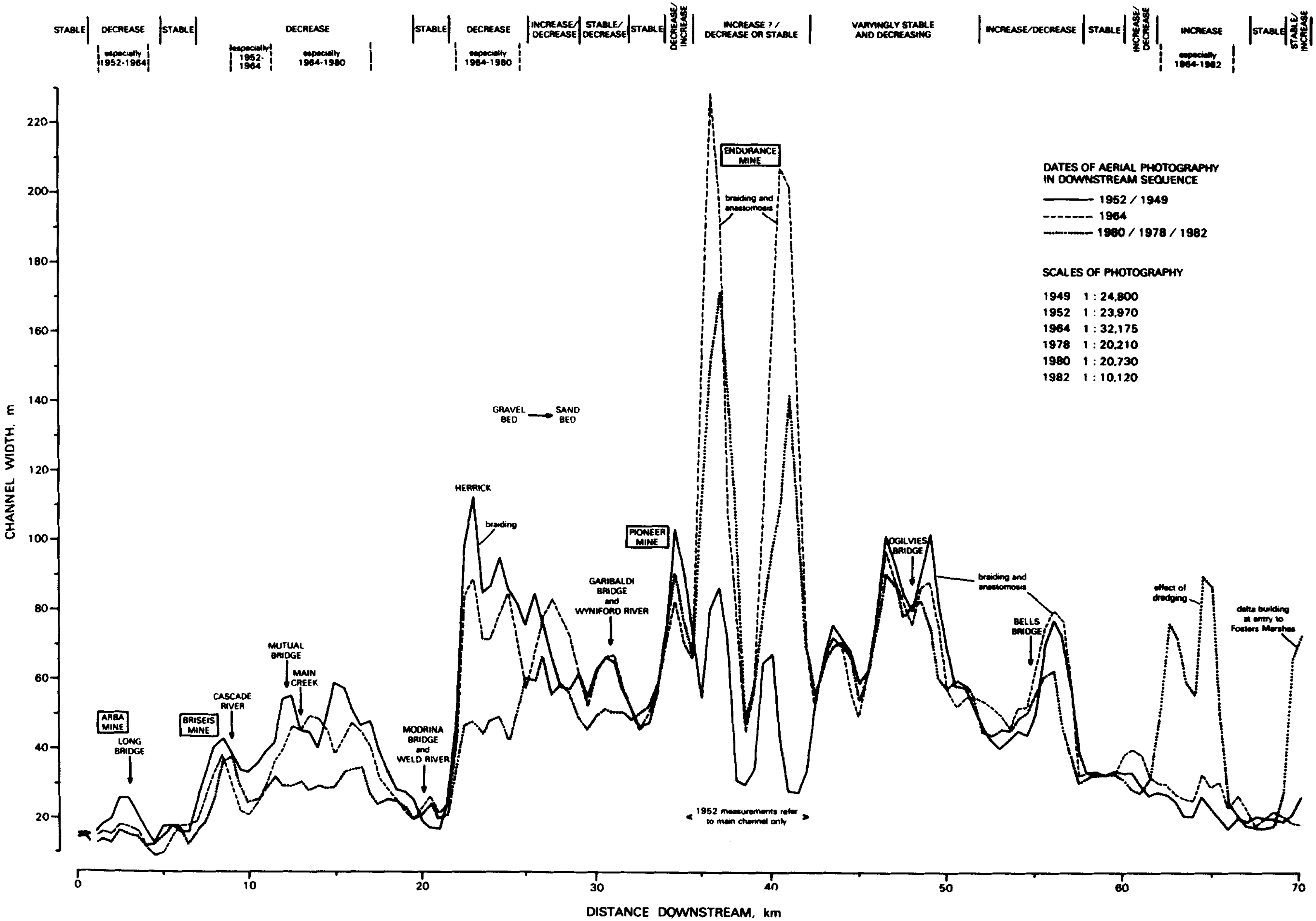

Figure 16. Downstream variation of channel width measured as a spatial series from aerial photographs, with a five-point moving average applied. The heading indicates the behaviour of width between survey dates

The Ringarooma River was in a parlous state in the 1950s (Steane, 1972). It is beginning to heal itself and upper reaches have regained their former level in about 35 years after the cessation of mining. However, recovery is increasingly sluggish with distance downstream and at least another 50 years will be required for the river to cleanse its channel of mining debris. Even then the valley-side sediments, the scarred landscape, and the silted estuary will remain as stark reminders of a mining era which profoundly affected the physical environment.

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