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BEACH CHANGES ON LAKES MANAPOURI AND TE ANAU, 1973 - 1988

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and to the Guardians of Lakes Manapouri and Te Anau.

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1. INTRODUCTION

This report concerns trends in erosion, accretion and overall stability of a selection of beach profile sites on Lakes Manapouri and Te Anau over the 15 year period since 1973. Beach profiles are survey lines at right angles to the water line that show the beach in transverse section, the plane in which the principle gradients in wave energy are active. Erosion of a beach profile is evident as net landward retreat of the beach contours with or without a net loss of sediment. Beach accretion is net lakeward displacement of the contours with or without vertical accretion of the foreshore surface.

For this investigation a particular focus is the relationship between trends in shoreline change and the management objective of conserving beach character and amenity while both lakes are continuously utilised for hydro-electric power generation under an agreed, gazetted set of guidelines that specify lake levels, durations of levels and rates of water level change that are followed as closely as practicable. In this situation beach erosion, especially erosion involving net loss of beach sediment from the upper, visible, usable parts of the shore is of most concern.

The present report can be taken in conjunction with Kirk (1985) which discusses planning and management related matters for the urban foreshore of Lake Te Anau, and with a letter by the writer dated September 2, 1987 to the Guardians of Lakes Te Anau and Manapouri discussing aspects of the operating lake level guidelines.

A considerable period of time has elapsed since the guidelines were agreed (December 1977) so that to some extent the present investigation arises naturally as part of the ongoing review functions and acquired experience of the Guardians but it has a particular background in earlier actions of the Guardians in respect of scientific research and the translation of it into operational practices. The present study is possible

partly because considerable scientific research was commissioned and co-ordinated by the Guardians as a basis for formulating the guidelines (Mark and Johnson, 1985), and partly because a feature of that research was the establishment, commencing in 1973, of numerous permanently marked sites against which longer term trends in shoreline stability could be monitored. These surveys are reported in Irwin (1974a, 1975) and represent work carried out by New Zealand Oceanographic Institute, now in Division of Marine and Freshwater Sciences, D.S.I.R. Mr. Jack Irwin has made his original survey results available for the present study and his assistance has been invaluable.

These far-sighted survey actions are unusual in New Zealand coastal and lake studies and now enable changes over almost 15 years of hydro-electric generation to be measured where the original survey markers can still be recovered and the sites re-occupied. Irwin (1974a, 1975) details 130 profiles surveyed around the two lakes. Some 89 of these were permanently marked with steel fencing 'waratahs' to which numbered metal tags were wired. It is these sites that are potentially re-measurable and from which meaningful comparisons of shoreline changes might be made. More specifically, the upper, dry portions of the profiles and the nearshore sections accessible by wading were surveyed to high precision by levelling, while the outer, deeper portions were surveyed to much lower levels of accuracy by lead-line and echo-sounder. It is therefore the upper portions of the profiles from which the most precise measurements of change are to be expected so that it is on these reaches that the present study has focussed. For the outer, deeper portions only the most gross changes would be detected by repeat echo-sounding and the accuracy of the measurements would be low. For these reasons and for reasons of survey cost in relation to data achieved no repeat echo-sounding was carried out for the present study.

In a third report Irwin (1974b) presented more than 50 profiles from the southern end of Lake Te Anau including many along the foreshore of the township. None of these were permanently marked so that they are not re-locatable and were not pursued in the present investigation. As mentioned above, shoreline management for the Township is examined at length in Kirk (1985).

Beaches and especially the changing forms of their profiles are the integrated net effect of a host of processes at work both above and below the water line. It is characteristic that the processes causing change act at a range of time scales so that it is desirable to distinguish shorter term adjustments from longer term trends. Short term changes of form and shape can be very dramatic, for example in response to variations in the weather (particularly to the incidence of storms with high winds and large waves) and to seasonal cycles of weather and water level. Longer term changes, frequently having importance for management, are often less obvious and may be partly concealed by the 'noise' of more dramatic short term changes that are often without management significance. Such longer term changes may relate to changes in the patterns of water levels or to overall shoreline sediment supply and loss relationships. For these reasons it is usual in coastal work to distinguish between a short term 'envelope' of beach changes (defined by several surveys made under a variety of weather and wave conditions) and the location of the envelope, relative to fixed co-ordinates. In this view erosion is defined as net landward movement of the envelope and/or as net lakeward transport of the sediments within the envelope of change. It commonly occurs that beaches undergoing long term erosion also display small envelopes of short term change. These considerations establish important evaluative criteria for the re-survey of the two lakes.

A distinction between envelope and longer term changes for the

lakes is possible again because of prior research. In 1973-1976 the Guardians supported a detailed study of beach processes as a Ph.D. study by Pickrill (1976). The investigations were carried out under the writer's supervision and involved wave measurements, sediment particle tracer experiments and very detailed, intensive monitoring (over an 18 month period in 1974/1975) of several of Irwin's marked sites. The objectives were to establish site-specific processes of beach change, the short term envelopes of change, and cyclic or sequential elements of behaviour in response to lake level variations. Dr. Pickrill has published extensively on this work and is now also at N.Z.O.I., Division of Marine and Freshwater Sciences where he contributed to discussion and planning for the re-survey work reported here.

The aims of the present study were thus to contribute to review of the guidelines by the Guardians through a concentration of re-survey effort on as many of the profiles studied by both Irwin and Pickrill as could be re-occupied within the available survey resources and constraints posed by weather and the like. Specifically, the aims were:-

(1) To assess longer term (ca. 15 year) trends towards beach and nearshore erosion and/or deposition related to changes in the water level regimes of the lakes, and;

(2) To isolate longer term changes from shorter term, possibly cyclic or sequential changes as represented by Pickrill's (1976) detailed monitoring. A specific assumption is that Pickrill's findings are typical of short term changes occuring over longer periods.

2. HISTORICAL ASPECTS AND THE OPERATING GUIDELINES

While good prospects exist for examining shoreline change since 1973 it is important to realise that the record is incomplete in significant

aspects. Here it is convenient to separate the shoreline history into three phases; one - a 'natural' phase prior to hydro-electric development, secondly - a phase of construction related water level variations, and thirdly, operating phase conditions since construction.

Mark and Johnson (1985) have reviewed the history of events at Lakes Manapouri and Te Anau particularly as they relate to the establishment of the present set of operating guidelines for water levels. They note that a 37 year record of daily water levels was available from the pre-development phase and upon which to found the operating guidelines. It is significant that there is no corresponding data on beach changes so that we have no quantitative information on how beaches were evolving prior to construction activities. Thus there is no 'standard' available for the assessment of beach change and it is necessary to bear this in mind through what follows.

Similarly, there are no measurements of shoreline change from the construction phase when water levels on Manapouri were sometimes lowered very considerably. Mark and Johnson (1985, p.359) report collapse and slumping of appreciable sections of the shore in Surprise Bay when the lake was lowered 54 cm. below its natural minimum in August 1972. The extent of changes to beaches is unknown. Given that beaches tend to be self-stabilising systems (and setting aside irreversible damage such as slumping for the moment) an important notion that arises here is that of relaxation time, or the time taken for a beach to fully adjust and come to equilibrium with a change of regime. These times are unknown for the natural record on the two lakes and are also unknown for the construction phases. Response to extreme water levels during construction is likely to be long term so that effects created during that time are likely to extend well into the operating phase. It is therefore difficult to discriminate among these contributions to shoreline change except where

regular surveys are made over a long period of time.

In general, Mark and Johnson (1985) draw attention to separate problems attending high and low lake levels. High lake levels pose a predominately ecological management hazard to vegetation though, as will be shown later, erosion of beaches occurs to the highest shore levels. On the other hand, low lake levels result in 'combing down' of beaches sediments and their loss to the deeper waters of the lake by transport over the narrow submerged shelf edges that border the beaches. Accordingly, three categories of lake level operation were recognised to retain ecological stability of the shorelines. These were high, main and low operating ranges, each occupying about one third of the natural range of each lake.

In the low operating range rates of drawdown, absolute minimum water levels and maximum duration at particular water levels have all been found to be important. These features are all incorporated in the low range guidelines to minimise slumping and beach erosion. Pickrill's (1976) finding was that the narrow nearshore shelf to lakeward of most beaches was in many ways the key to conserving the often very limited resources of beach sand, or more correctly it held the key to maintaining shoreline changes within natural bounds. He described the shelf as a "wave worked deposit formed during storm conditions at low lake levels exceeded greater than 87% of the time in the natural record" (Pickrill, 1976 p.3). In the pre-construction phase he argues that waves were ineffective in disturbing the outer shelf (and thus incapable of delivering sand to deep waters) for 94.1% of he time. During the time of his study (1974/1975) this was reduced to 84.6% of the time. Changes to the outer, lower parts of surveyed beach profiles are thus of crucial importance to evaluation of the operating guidelines.

Mark and Johnson (1985) and Pickrill (1976) also note that wave action from boat wakes can be a potent source of beach change especially

for beaches that are exposed to short fetches and thus to low energy levels of wind generated waves, the more so where such beaches have very narrow shelves adjacent to deep water.

Finally in this section Mark and Johnson note that the operating guidelines rest upon a great deal of experience and scientific research. They report that at the time of their approval in December 1977 the procedures were described in a joint statement by the Minister of Energy and the Minister of Environment as "a satisfactory compromise between protecting the unique environmental and ecological features of the lakes' system and maximising the energy output of the Manapouri power station". The results to be reported here measure the success of that compromise in respect of beach health and the low operating range in particular.

3. SURVEY PROCEDURES AND METHODS

The first step in the re-survey work necessitated discussion at New Zealand Oceanographic Institute in Wellington with Mr. Jack Irwin and with Dr. Pickrill on February 1, 1988. It transpired that no original survey data is extant from Pickrill's work so that short term envelope shapes and calculations of sediment volumes involved in them were recovered and re-plotted from his Ph.D. thesis (Pickrill, 1976). In contrast, Mr. Irwin made available large volumes of original data including the locations, orientations, datums and tag numbers for the marked profile sites. In addition to the listings provided in his published reports all of this information is annotated and held on large scale air photographs. Following correlation of Pickrill's work with that of Irwin it was then possible to make Xerox copies of the portions of the photographs containing profiles used in both sets of studies. These prints proved to be very useful in field recognition of the approximate locations of the steel pegs marking the profiles. Mr. Irwin also provided the complete set of his original profile

plots. These have proven invaluable in scaling the original data for comparison with the re-surveyed profiles.

Allowing one week for fieldwork and concentrating on profiles surveyed by both previous workers, enough location and form data was prepared to enable re-survey of up to 20 sites on each of the lakes. In addition, a number of sites surveyed only by Irwin were prepared to allow for the probability of being unable to re-locate some percentage of the preferred sites. Here it should be noted that no attempt was made to secure general coverage of the lake shorelines. Rather the re-survey was guided by the original site selections that had been made so as to represent the most popular, the most affected and the most sensitive shores. These are generally to be found in the eastern portions of both lakes.

Site locations were transferred to large scale maps for navigation to the sites. Once in the vincinity the Xerox air photograph prints were used and finally a shore search was made on foot to locate the tags and the site peg. Lake Manapouri has about 170km of shoreline and Lake Te Anau about 320 km. Together with the fact that the sites had not been visited for survey purposes for many years this meant that high proportions of field time were spent in travelling between sites and in attempts to locate the pegs.

In addition to the steps already detailed an extensive series of colour slides and photographs dating from 1974 and held by the writer were taken into the field and used for on-site comparison. Most sites were re-photographed and a number of areas were given visual inspections and photograph comparisons (eg: Surprise Bay, Lake Manapouri) though no re-locatable profiles were available for them.

Fieldwork was planned for the week of 15-19 February inclusive, the aim being to spend two days per lake working from a 16' radio-equipped jet-boat provided by Electricorp. In the event the weather

was bad for much of the week. On 16 February three profiles were re-located and re-surveyed in the rain working from a Landrover along Fraser's beach, Lake Manapouri. On 16 February in difficult boating conditions a further 12 profiles were re-surveyed to acceptable levels of accuracy on Lake Manapouri. Another 10 sites could not be re-surveyed because the pegs had either been removed or were unrecoverable (buried in sediment perhaps or undetectable in the vegetation). A curious feature of several sites was that though the peg was still in place the tags had been removed. It is doubtful if such interference can be referred to as vandalism within a National Park!

Problems of site peg removal are especially severe on lake Te Anau. Re-surveys there were attempted in difficult and at times dangerous boating conditions on February 17th. Only 8 profiles could be re-occupied and measured, 6 of these being used previously by both Pickrill and Irwin. Popular beaches closer to Te Anau were completely devoid of pegs. As will be seen later, loss of tags has also created some uncertainty in correlating the surveys at two sites.

The total of 23 profiles re-measured is a little more than half of the work planned but it is felt that the results are acceptable given the difficulties of relocation after such a long period, the evident extent of interference with sites, especially on Lake Te Anau and the difficult working conditions encountered.

Profiles were re-surveyed using a Sokkisha DT 20E digital theodolite and a staff graduated to 5mm intervals. For each break of slope on a profile, the peg and the water level, three stadia and the vertical angle were read and recorded. Irwin (1974a, 1975) gives reduced height data for each peg and surveying the elevation of the water level gave an added height control for each profile. Once a site was re-located the theodolite was set up on the profile line and locked to the original orientation angle

given by Irwin. Breaks of slope were surveyed across the beach from the backshore to the offshore limit of wading by one of the party in a 7mm wetsuit. Wetsuits were worn for the duration of the fieldwork by both members of the party as protection against the weather, particularly when on the water.

Ashore each day the raw survey data were tabulated and reduced to datum heights and distances by programmable calculator. Error checks were carried out as part of this process. In Christchurch all data were transferred to a 'spreadsheet' on a microcomputer for collation, reduction and presentation for profile plotting. Irwin's original profiles and the 1988 re-surveys were plotted to common scales at a vertical exaggeration of 5 times and then overlaid for computer digitisation. This procedure allowed accurate determination of the sediment volume changes over the 15 years between surveys. Finally, Pickrill's short term envelope changes were scaled from the diagrams in his thesis and re-plotted over the re-surveys. Values for envelope volume change were abstracted from the Appendices to the thesis (Pickrill, 1976).

Lake levels during the re-surveys were 177.28 metres for Lake Manapouri (in the main operating range) and 201.9 metres for Lake Te Anau (also in the main range though near the lower end). For Lake Manapouri this level was remarkably close to that obtaining during the original survey by Irwin (177.24 to 177.4 metres). For Lake Te Anau the water levels during Irwin's surveys were more than 40cm higher than for the re-survey.

Sediment volume changes and other aspects of shoreline behaviour are reported here generally above 175.85 metres for Lake Manapouri and above 200.75 metres for Lake Te Anau. These elevations are close to the shelf breaks of slope for most of the sites re-located.

4. BEACH PROCESSES AND LAKE BEACH PROFILE CHANGES

Before proceeding to detailed consideration of the re-survey results it is worth recalling some features of lake beach profile behaviour established at Lakes Manapouri and Te Anau by Pickrill (1976).

Sand and gravel beaches around both lakes respond to variations in wave energy and to fluctuations in still water level. Because of the grain sizes available, the relatively low wave energies and the steep lakeside slopes, the beaches are typically steep and narrow and they accumulate slowly except immediately adjacent to active rivers. The short, steep waves generated by winds blowing over short fetches are generally highly erosive in character, if limited in energy. Sediment eroded from the foreshore can be readily lost to deeper parts of the lakes, especially where storms coincide with low lake levels.

Pickrill (1976) showed that short term profile envelope changes are generally small. He distinguished three types of beach, each with a distinctive pattern of behaviour. Pavement beaches are erosional in character and have a thin veneer of pebbles, cobbles and boulders, often a single layer thick, embedded in a matrix of poorly sorted glacial moraine. These 'lag' surfaces act as transport surfaces on which more mobile materials can be transported to the downdrift ends of embayments. Short term profile envelope changes for this type of beach averaged 0.40 m^3 of sediment per linear metre of shore on Manapouri and 0.37 $m^3 . m^{-1}$ on Te Anau.

Mixed sand and gravel beaches are more mobile and often have one or more depositional berms on the foreshore. Short term profile envelope changes averaged 0.41 $m^3 . m^{-1}$ for Manapouri and 0.44 $m^3 . m^{-1}$ for Te Anau.

Sandy beaches are even more mobile and they display the most complex array of forms. For these beaches the largest changes are induced

by fluctuations in lake water levels. Average volumetric changes were 0.48 $m^3 . m^{-1}$ for Lake Manapouri and 1.43 $m^3 . m^{-1}$ for Lake Te Anau.

As distinct from the relationship between beach type and profile change, it is evident from the figures presented above that beach changes are generally larger on Lake Te Anau than they are on Lake Manapouri.

Further, Pickrill noted important variations in profile behaviour with what is best described as beach context (exposure to wind, geometry of the embayment, proximity to sediment resources etc.). Here it was evident that the largest changes to beach form occured where there was strongly directed longshore transport of sediments. Thus, on both high and low energy beaches with a narrow wave approach window and minimal or uni-directional drift, the envelopes of profile change were narrow. The area contained by the envelopes was no larger than necessary to account for shifts of sediment up and down the profile in response to varying wave energy and fluctuating lake levels. On pocket beaches there were no measurable exchanges of sediment along the beach.

At the other extreme, long beaches with indistinct boundaries (such as headlands with adjacent shallow water and wide shelves along which sand can drift) may sustain substantial longshore sediment transport with little measurable effect on the profiles.

By contrast, pocket beaches with a wide wave approach window and bi-directional drift displayed the widest envelopes of short term profile change. Waves from one direction can can erode the updrift end of such a beach and deposit it at the downdrift end while the centre undergoes little change. A shift in wave approach direction can reverse the transport direction and the sequence of profile changes. The net result is constant re-adjustment of both the profile forms and the orientation of the beach in response to varying wave conditions.

In a later paper Pickrill (1985) notes that no correlations could be

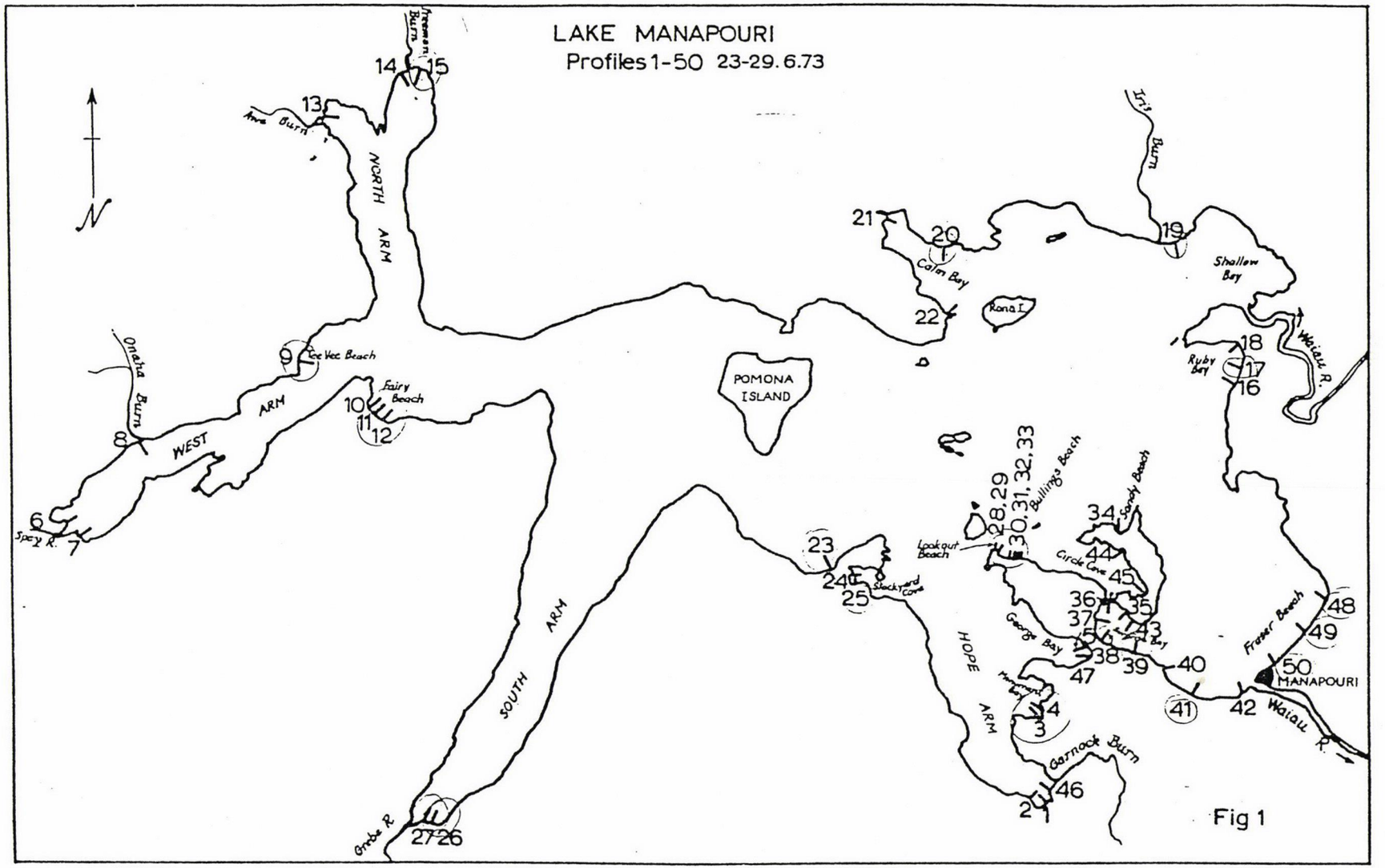


Fig. 1. Lake Manapouri showing positions of beach and underwater profile lines 1-50, June 1973.

(source: Irwin 1974a Figure1).

established between profile volumetric changes in the short term and either the water level range in the inter-survey periods of his study or the rising/falling trends in water level that occured. However, the volume of mobile sediment within the envelopes of profile change (ie: gross volumetric changes) increases as a positive function of the lake level range between the surveys. This was interpreted to mean that the profiles were more extensively reworked under fluctuating levels.

The objective of the low operating ranges of lake levels is thus to minimise shore-normal transports of sediments and to confine the envelope patterns described above to the zone above and landward of the nearshore shelf break of slope.

5. SURVEY RESULTS - LAKE MANAPOURI

5.1 Profile forms and Inspections

Figure 1 shows locations discussed in the text, Irwin's profile numbers and the overall geometry of the shoreline on Lake Manapouri. Tables to be presented later list the original metal tag numbers on the pegs as well as both Irwin and Pickrill's profile numbers. On the surveyed profile plots both location descriptors and Irwin's tag numbers are given.

Figures 2 to 16 present the overlay plots of the 1973 Irwin profiles, Rickrill's 1974/75 short term envelope, and the February 1988 re-survey.

Figure 2 (Profile 50) occurs at the southern (updrift) end of Fraser's Beach. The foreshore is comprised of mixed sand and gravel and it carries small berms related to episodes of wave action at varying lake levels. To landward, a small erosion scarp occurs inland of the bench mark (the reference for the profile) within a stand of Manuka. Figure 2 shows that erosion has occurred across the entire profile and that the 1988 profile

occurs close to the position of Pickrill's 1974/1975 envelope. Thus, most of the erosion evident occurred between 1973 and 1975.

Figure 3 presents profile 49 on central Fraser's Beach, a site that is in a zone of through-transport under longshore drift. The profile is a broad, flat one composed of a mixture of lag boulders and gravel high on the foreshore with finer sediments offshore. There is marked erosion of the turf beds to landward of the peg, a consequence of strong waves at high lake levels. It can be seen from the diagram that the profile form in 1988 is similar to that in 1973 with net retreat at most levels on the foreshore. In agreement with Pickrill's conclusions concerning longer beaches subject to longshore drift, the short term envelope form from 1974/75 shows that considerable variations of beach form are possible.

Figure 4 presents Profile 48 further north (downdrift) on Fraser's Beach. In this case there is also evidence of strong erosion of turf and reed beds high on the shore. There is also strong rilling of the beach from effluent groundwater. The upper foreshore comprises lag gravels though net accretion has occurred there and the nearshore bed is finer and very soft despite net erosion there.

To the southwest, the shoreline in Surprise Bay was inspected and subject to photographic comparison. No profiles are available for re-survey. It is evident that large areas of turf shore developed in the Damsite Formation have slumped completely since 1974, so that a system of gently sloping flats have become very narrow, limited pockets of turf beach. Between these pockets small headlands have been eroded back into coarse gravels and boulders. In areal terms and possibly in habitat and ecological terms the loss of these turf shores represents the largest changes sustained anywhere on the two lakes.

Figure 5 presents Profile 34 to the west at Sandy Bay. This beach is in a very healthy condition and appears to be well adjusted to both wave

action and the range of lake levels, there having been small net gains to sand volume since 1983. Once again, Pickrill's short term envelope indicates greater short term erosion than the net change for the whole period since 1973. There are few traces of erosion high on the profile in 1988.

Figure 6 presents Profile 44 in Circle Cove. A number of small pocket beaches between Sandy Bay and here appear to be in well nourished condition but it is evident from the diagram that the higher, landward portions of Circle Cove have sustained quite severe erosion. This is represented both as landward retreat by scarping and as appreciable sand volume loss. Over most of the remainder of the beach there is close correspondence between the 1973, the 1988 and the 1974/75 profiles. It is thus most probable that the losses from the upper beach have occured mainly by longshore displacement under strong wave action at high lake levels.

Figure 7 presents Profile 31 on Bullings Beach. This beach is very steep and narrow and in 1974 it had a considerable longshore extent. In 1988 it is reduced to discontinuous pockets. The diagram shows strong erosion over the whole profile and there are prominent signs of erosional encroachment on the upper backshore. This is exposing tree roots and leading to tree death. Net losses of sediment from this profile are permanent in that they occur to deep water on steep nearshore slopes.

During the re-survey work the beach was strongly disturbed by boat wake waves up to 40cm high.

At Lookout Beach, another steep, narrow shore adjacent to deep water, it proved impossible to re-locate the profile. The site is now difficult to recognise even from photographs and what remains of the beach is a thin, patchy cover on peats and Damsite Formation or a similarly 'spongey' substratum.

It thus appears that Lookout and Bullings Beaches along with the turf shores of Surprise Bay have suffered substantial erosional degradation.

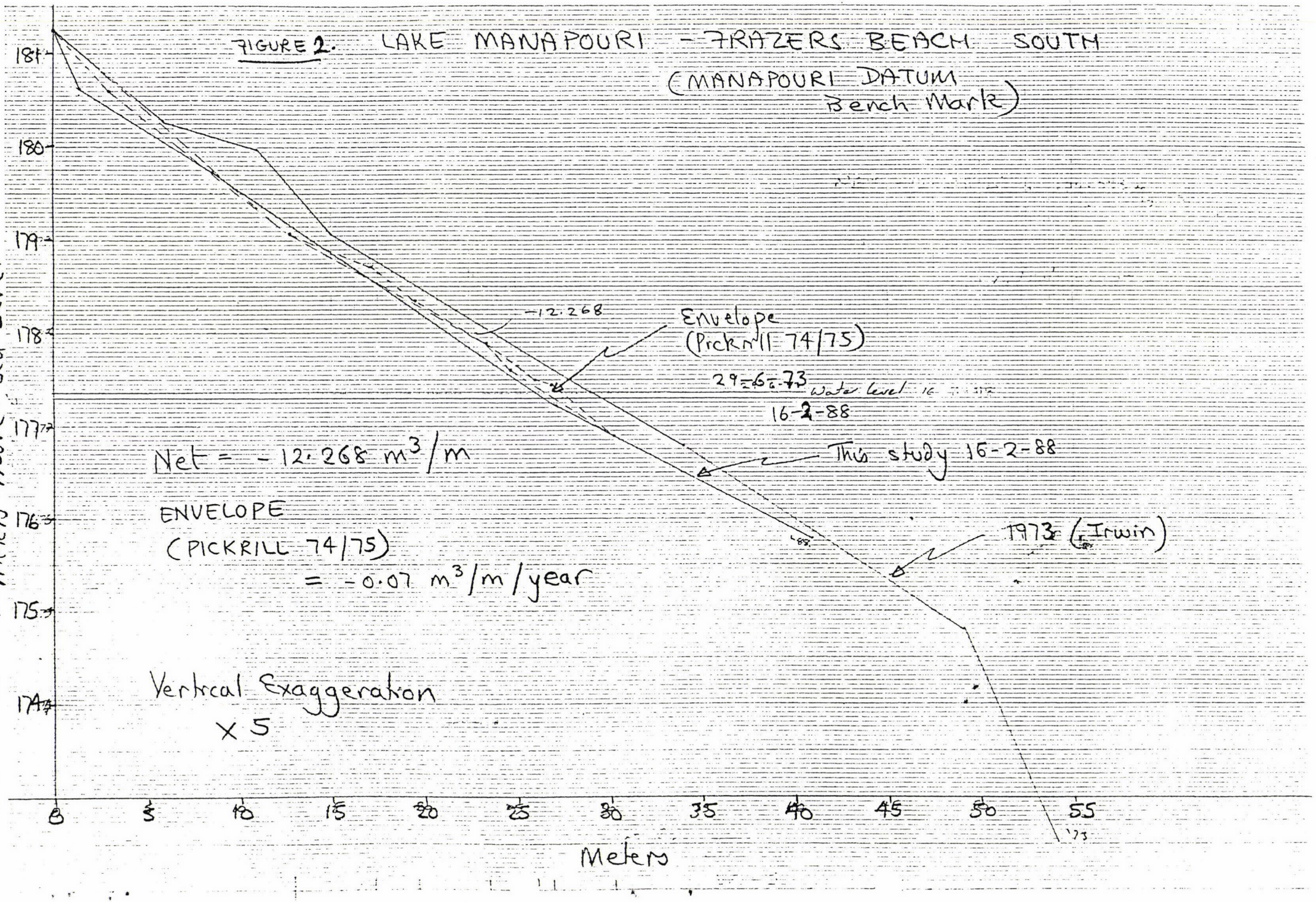
Figure 8 presents Profile 47 in George Bay, Hope Arm. The diagram shows overall accretion of the profile since 1973, especially at the upper levels and considerable envelope changes, particularly in the middle portions of the profile. The net gains notwithstanding the beach displays evidence of erosional encroachment to landward. Again, this is a high lake level phenomenon and is associated with vegetation death. In 1988 the foreshore displayed two prominent accretional berms, a firm, weakly eroded foreshore near the water level and an offshore sandy, flat bed.

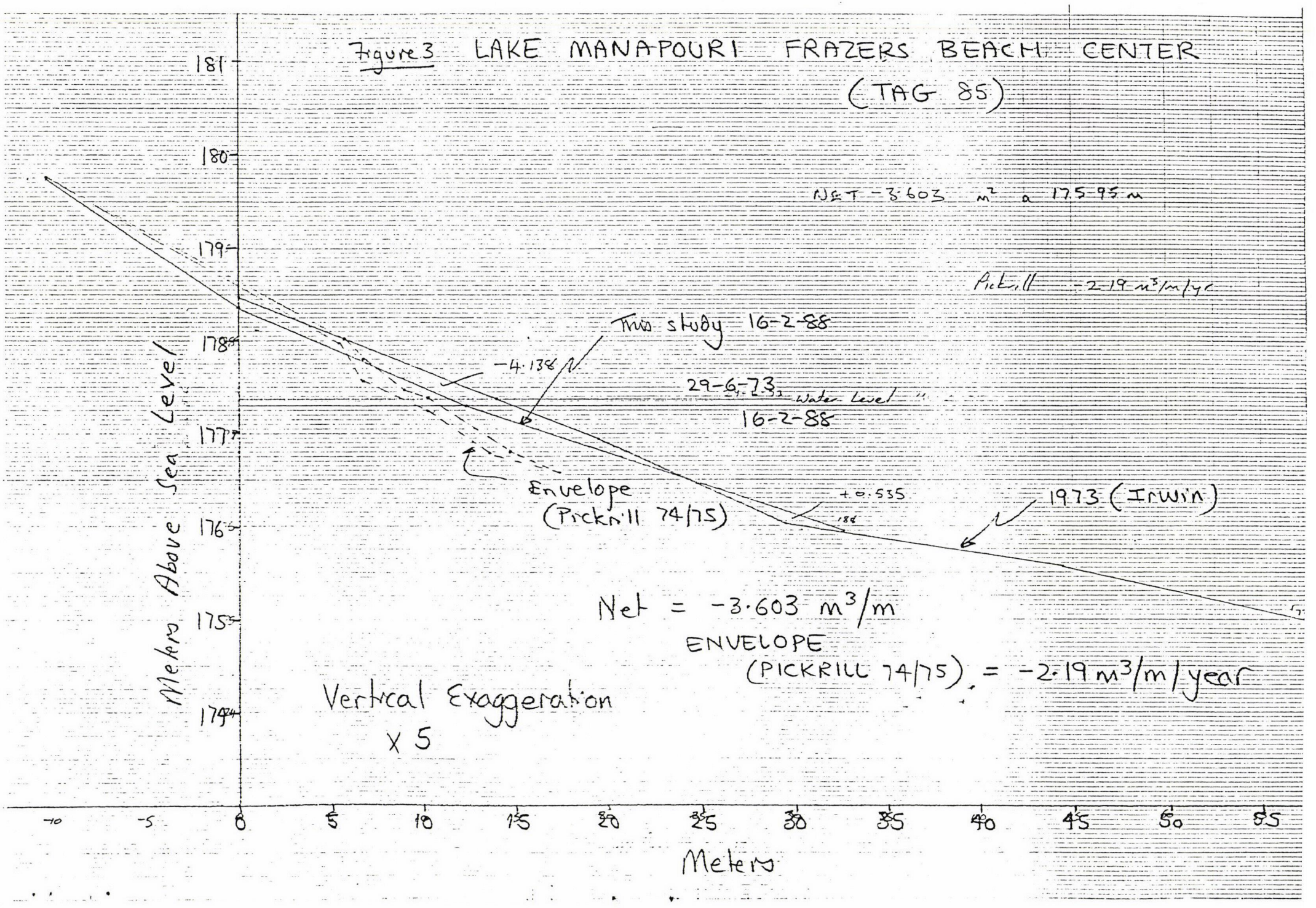
Figure 9 displays Profile 3 in Monument Bay toward the head of Hope Arm. In 1988 the profile was very steep and displayed moderate erosional encroachment to landward. The profile overlays show quite dramatic net erosion across the whole profile since 1973. It is also evident that much of this has occurred since Pickrill's short term envelope measurements in 1974/1975.

Figure 10 shows Profile 24 in Stockyard Cove. It is clear that the beach continues to maintain its steep, gravel form with an abrupt drop to deep water offshore. It is also apparent that moderate erosion has occured over the whole profile since 1973, though the short term envelope shows that accretion is possible, most likely by longshore transfers, and there has been a small net gain of sediment at the deepest part of the profile. As with several of th other sites discussed to date the landward margins of the profile display erosional encroachment into vegetation.

Profile 23 at West Beach could not be re-surveyed but inspection showed a high, wide foreshore fed mainly by longshore drift and with little sign of erosion to landward.

Furthest to the west Profile 11 was re-surveyed at Fairy Beach near the entrance to West Arm. The results are shown in Figure 11. This


FIGURE 2. LAKE MANAPOURI - FRAZERS BEACH SOUTH
(MANAPOURI DATUM
Bench Mark)
Meters Above Sea Level
181
180
179
178
177
176
175
174
0
5
10
15
20
25
30
35
40
45
50
55
Meters
-12.268
Envelope
(Pickrill 74/75)
29-6-73 Water level
16-2-88
This study 16-2-88
1973 (Irwin)
Net = -12.268 m³/m
ENVELOPE
(PICKRILL 74/75)
= -0.07 m³/m/year
Vertical Exaggeration
X 5


Figure 3 LAKE MANAPOURI FRAZERS BEACH CENTER
(TAG 85)
NET -3.603 m² a 175.95 m
Pickrill -2.19 m³/m/yr
This study 16-2-88
-4.138
29-6-73 Water Level
16-2-88
Envelope
(Pickrill 74/75)
+0.535
1973 (Irwin)
Net = -3.603 m³/m
ENVELOPE
(PICKRILL 74/75) = -2.19 m³/m/year
Vertical Exaggeration
X 5
Metres Above Sea Level
181
180
179
178
177
176
175
174
-10
-5
0
5
10
15
20
25
30
35
40
45
50
55
Metres

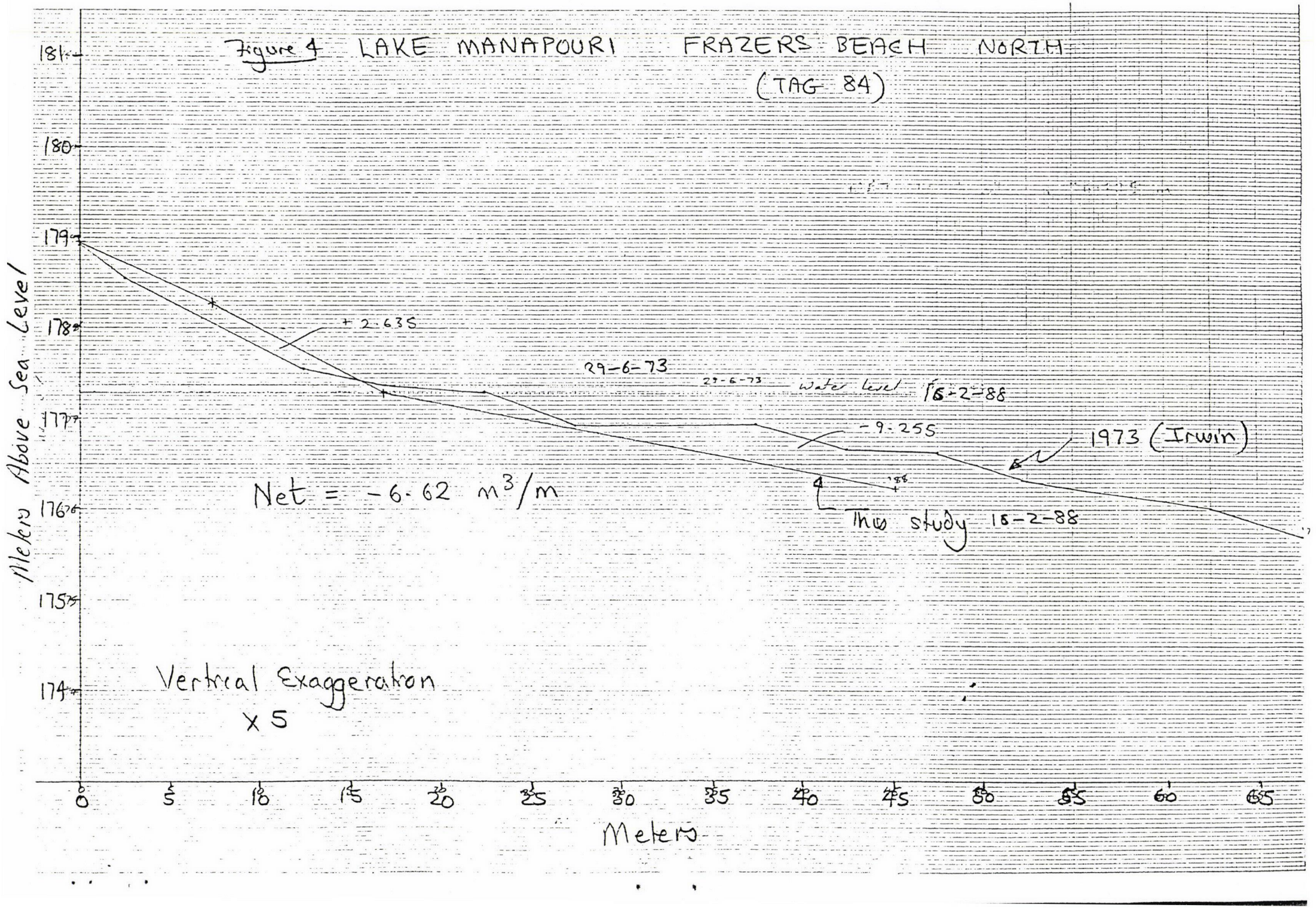
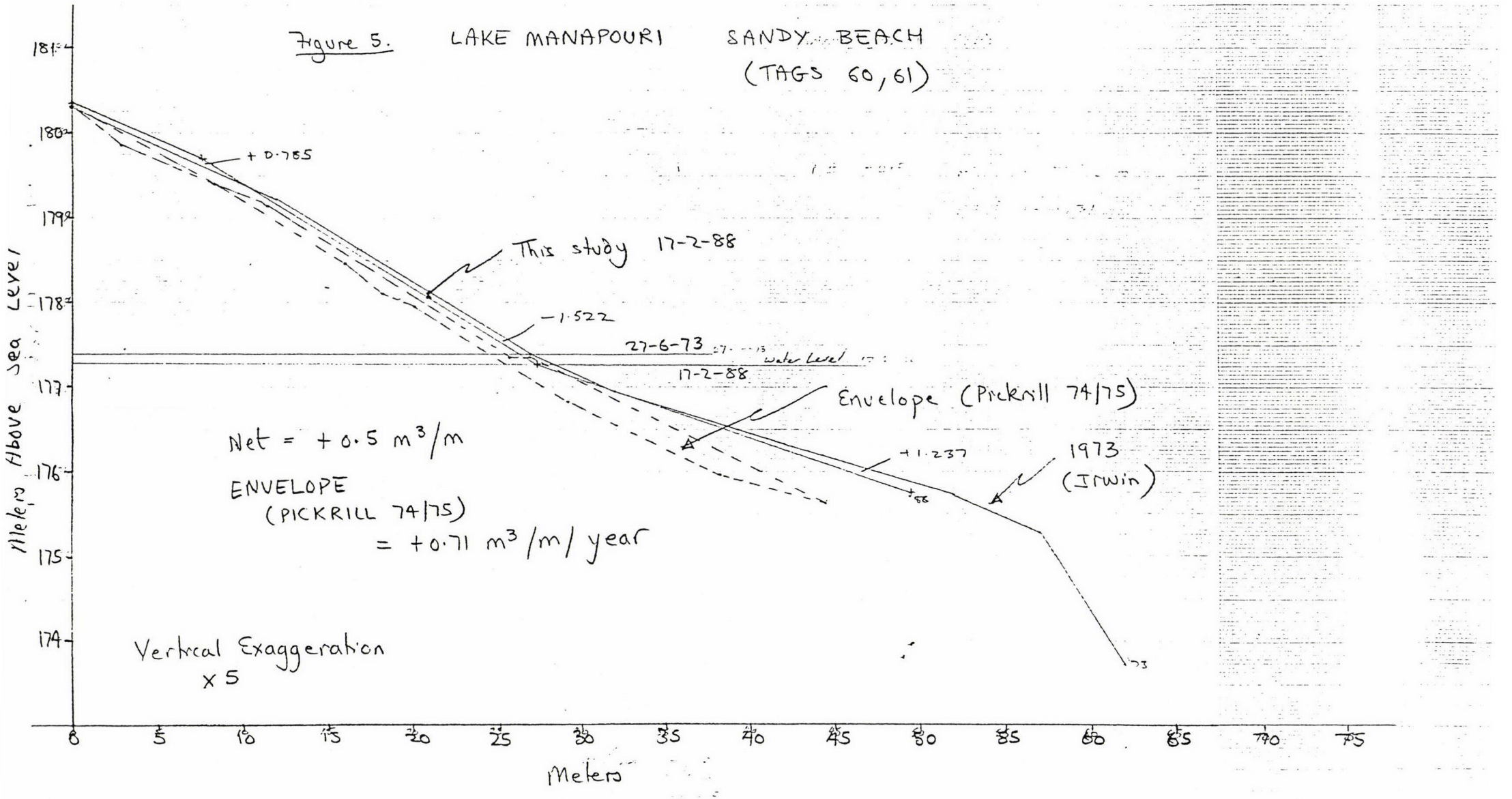
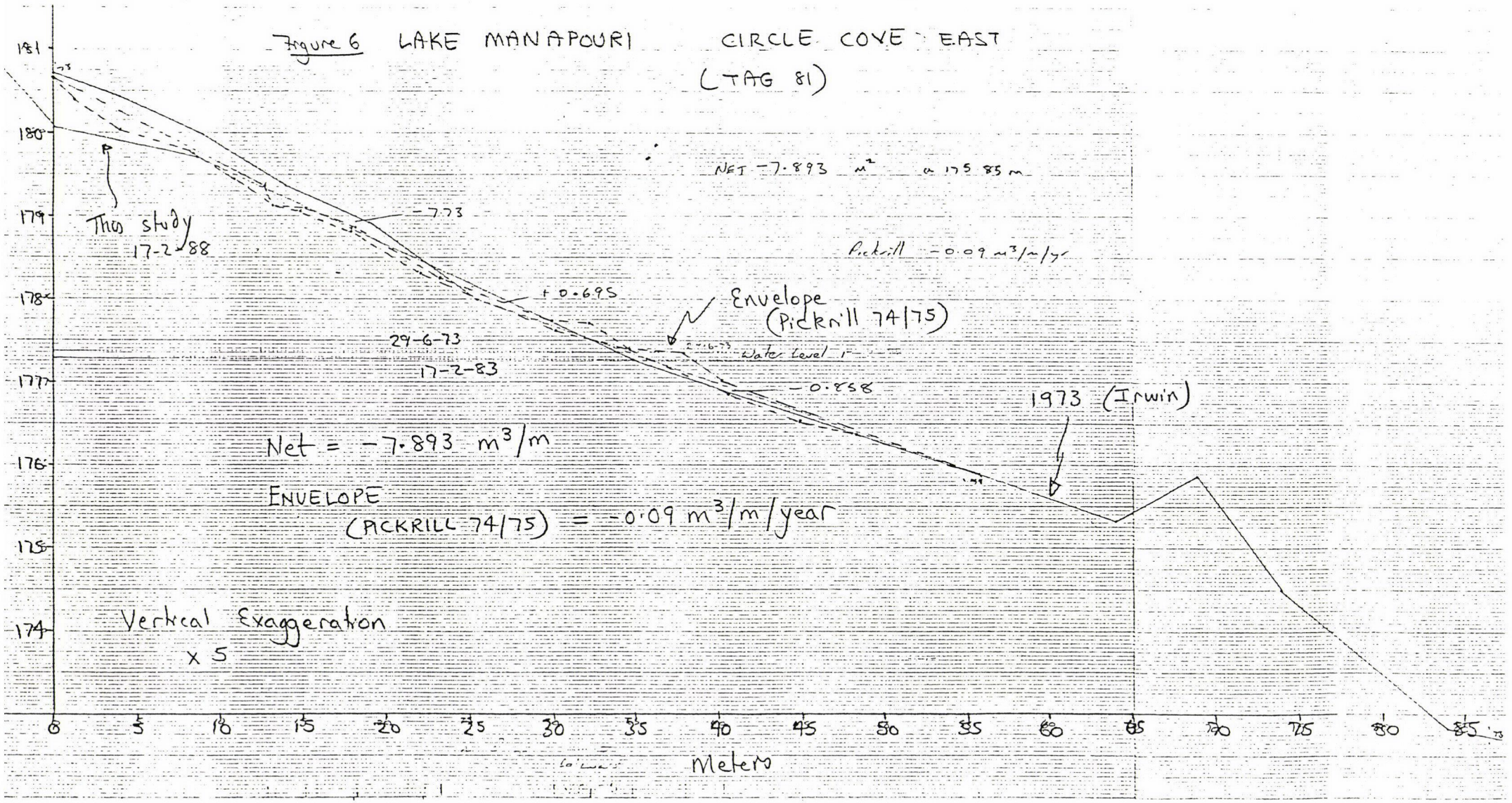
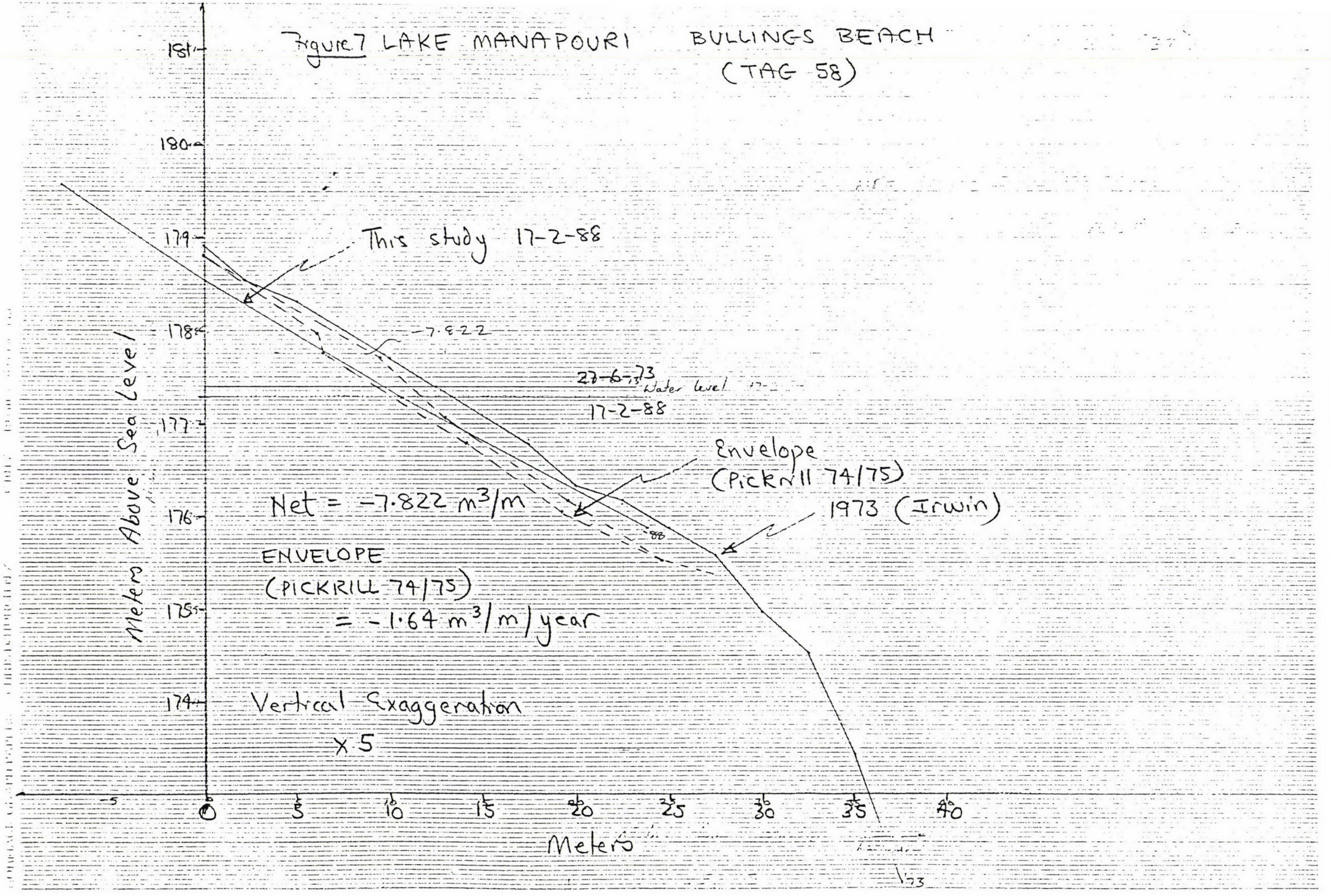

Figure 4 LAKE MANAPOURI FRAZERS BEACH NORTH
(TAG 84)
Meters Above Sea Level
181
180
179
178
177
176
175
174
+2.635
29-6-73
29-6-73 water level 16-2-88
-9.255
1973 (Irwin)
Net = -6.62 m³/m
This study 16-2-88
Vertical Exaggeration
x 5
0
5
10
15
20
25
30
35
40
45
50
55
60
65
Meters

Figure 5. LAKE MANAPOURI SANDY BEACH (TAGS 60, 61)




Figure 6 LAKE MANAPOURI CIRCLE COVE EAST
(TAG 81)
181
180
179
178
177
176
175
174
This study
17-2-88
-7.73
NET -7.893 m²
@ 175.85 m
Pickrill -0.09 m³/m/yr
+0.695
Envelope
(Pickrill 74/75)
29-6-73
17-2-83
-0.858
1973 (Irwin)
Net = -7.893 m³/m
ENVELOPE
(PICKRILL 74/75) = -0.09 m³/m/year
Vertical Exaggeration
x 5
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
Meters


Figure 7 LAKE MANAPOURI BULLINGS BEACH (TAG 58)
181
180
179
178
177
176
175
174
Meters Above Sea Level
This study 17-2-88
-7.822
27-6-73 Water level
17-2-88
Envelope (Pickrill 74/75)
1973 (Irwin)
Net = -7.822 m³/m
ENVELOPE (PICKRILL 74/75) = -1.64 m³/m/year
Vertical Exaggeration x 5
-5
0
5
10
15
20
25
30
35
40
Meters
173

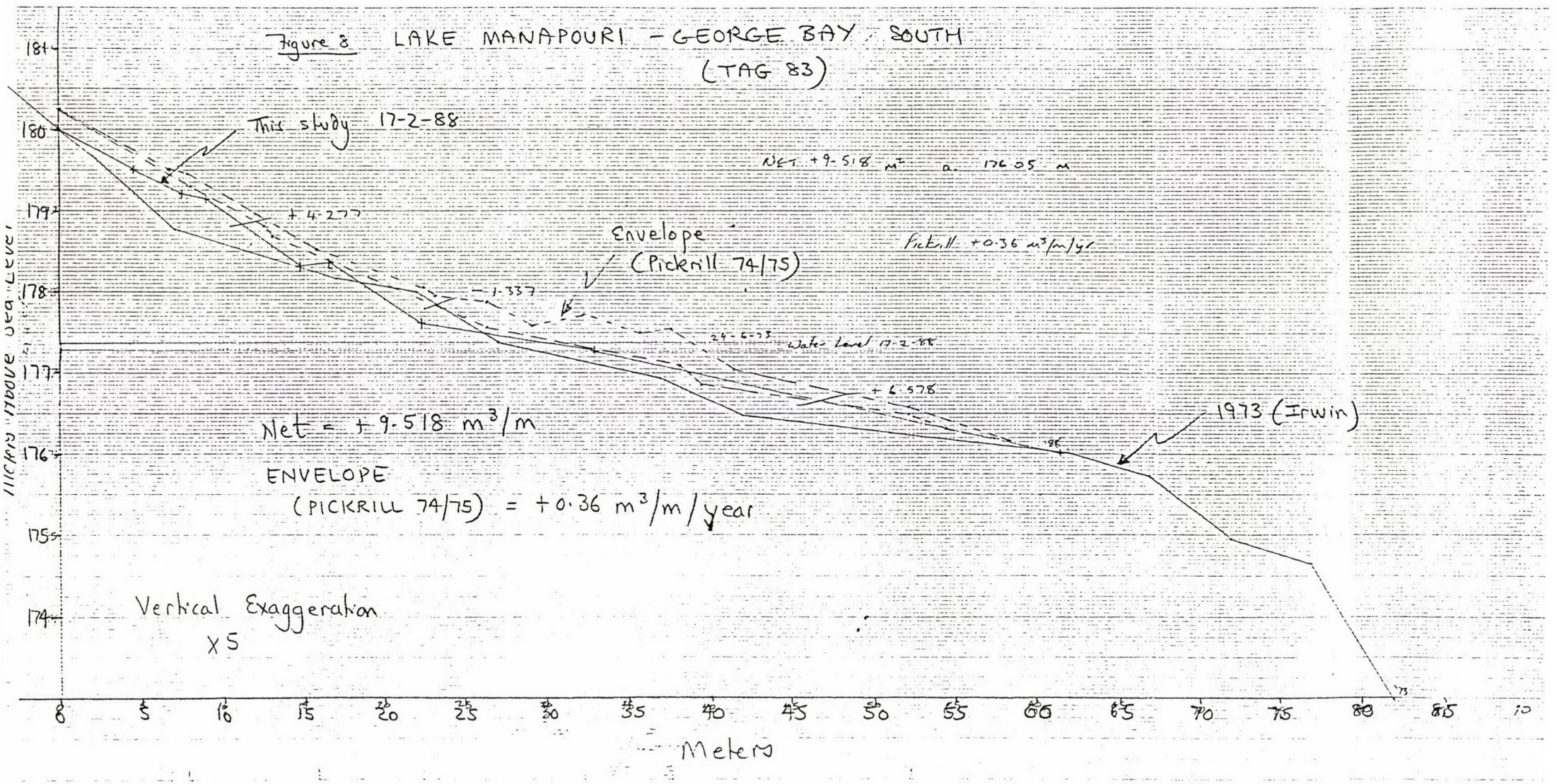

Figure 8 LAKE MANAPOURI - GEORGE BAY SOUTH
(TAG 83)
This study 17-2-88
Net +9.518 m² a. 176.05 m
+4.277
Envelope
(Picknill 74/75)
Picknill +0.36 m³/m/yr
-1.337
24-6-75 Water Level 17-2-88
+6.578
1973 (Irwin)
Net = +9.518 m³/m
ENVELOPE
(PICKRILL 74/75) = +0.36 m³/m/year
Vertical Exaggeration
X5
Metres
Height above sea level
180
179
178
177
176
175
174
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90

Figure 9 LAKE MANAPOURI MONUMENT BAY
(TAGS 5, 6)

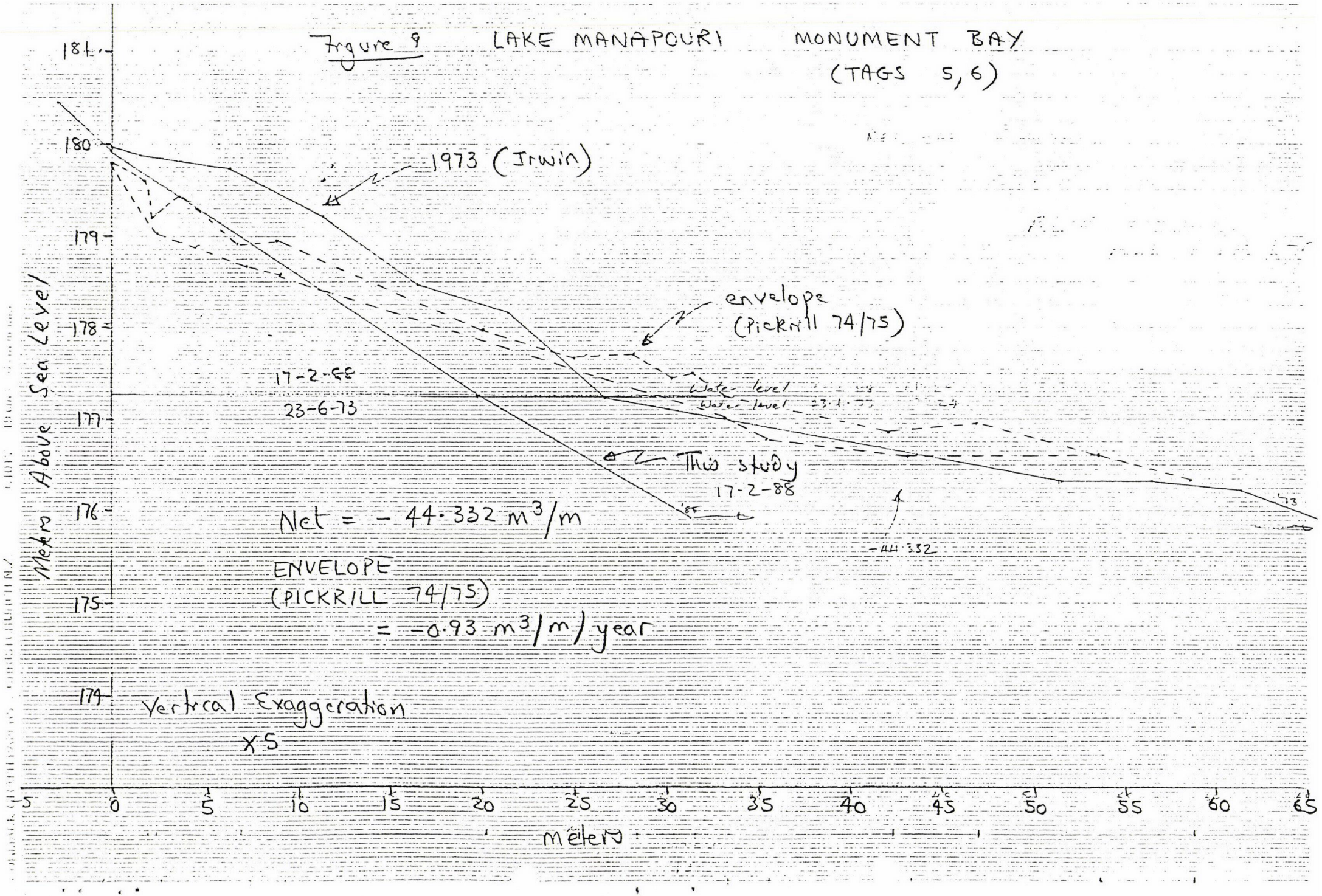
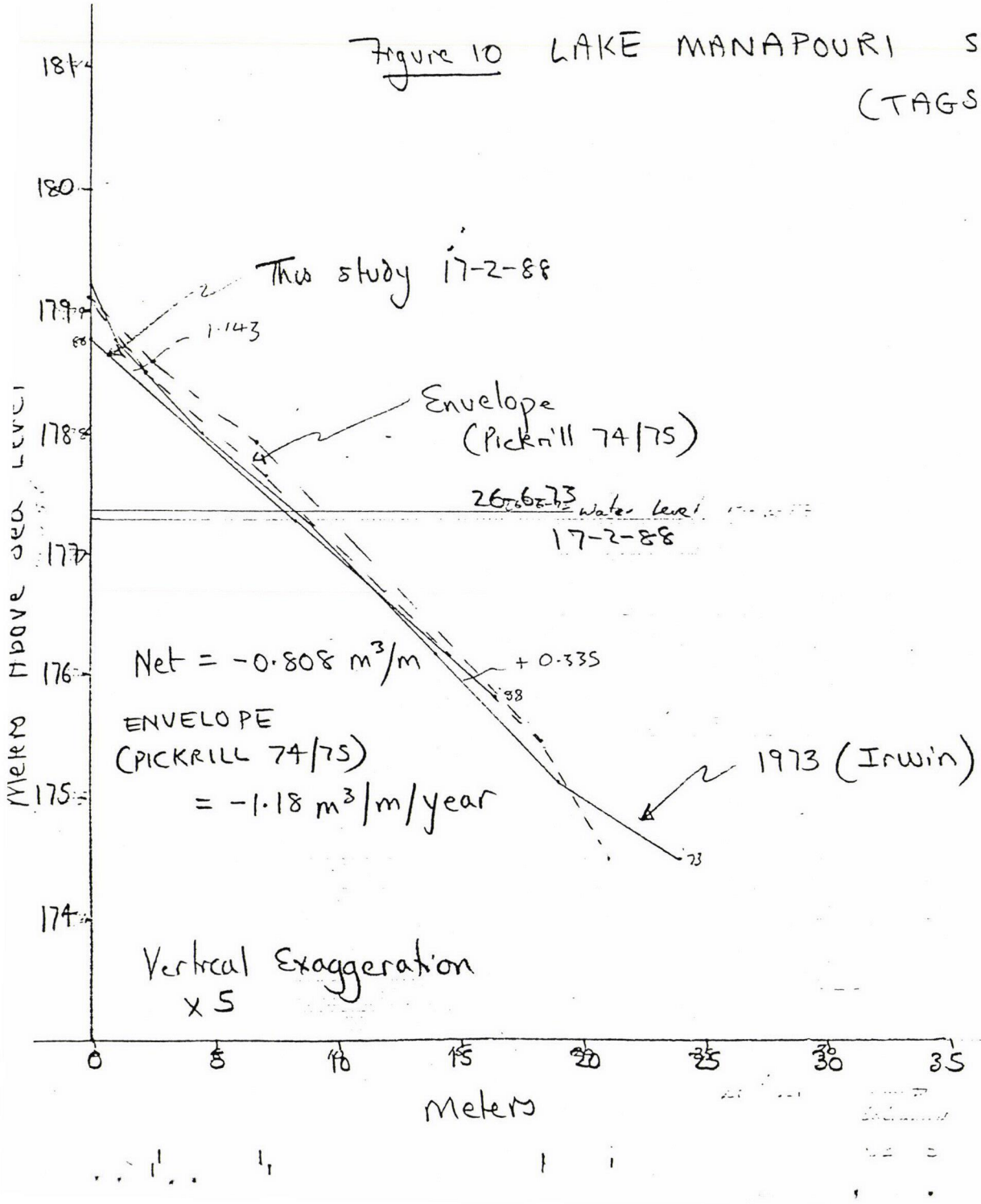
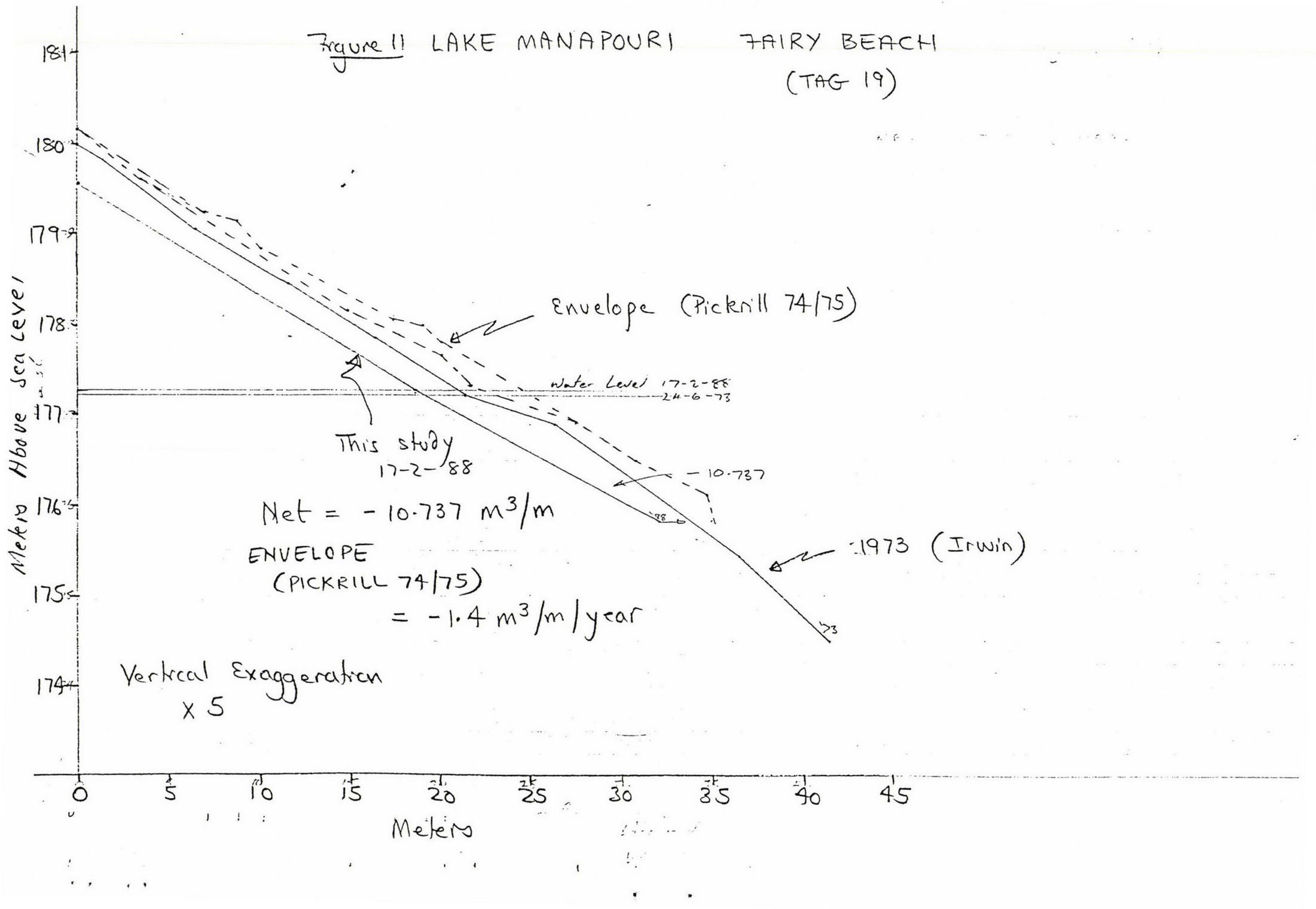


Figure 10 LAKE MANAPOURI STOCKYARD COVE WEST
(TAGS 44, 45)




Figure 11 LAKE MANAPOURI FAIRY BEACH
(TAG 19)
Metres Above Sea Level
181
180
179
178
177
176
175
174
Envelope (Picknill 74/75)
Water Level 17-2-88
24-6-73
This study
17-2-88
- 10.737
Net = - 10.737 m³/m
ENVELOPE
(PICKRILL 74/75)
= - 1.4 m³/m/year
1973 (Irwin)
Vertical Exaggeration
X 5
0
5
10
15
20
25
30
35
40
45
Metres

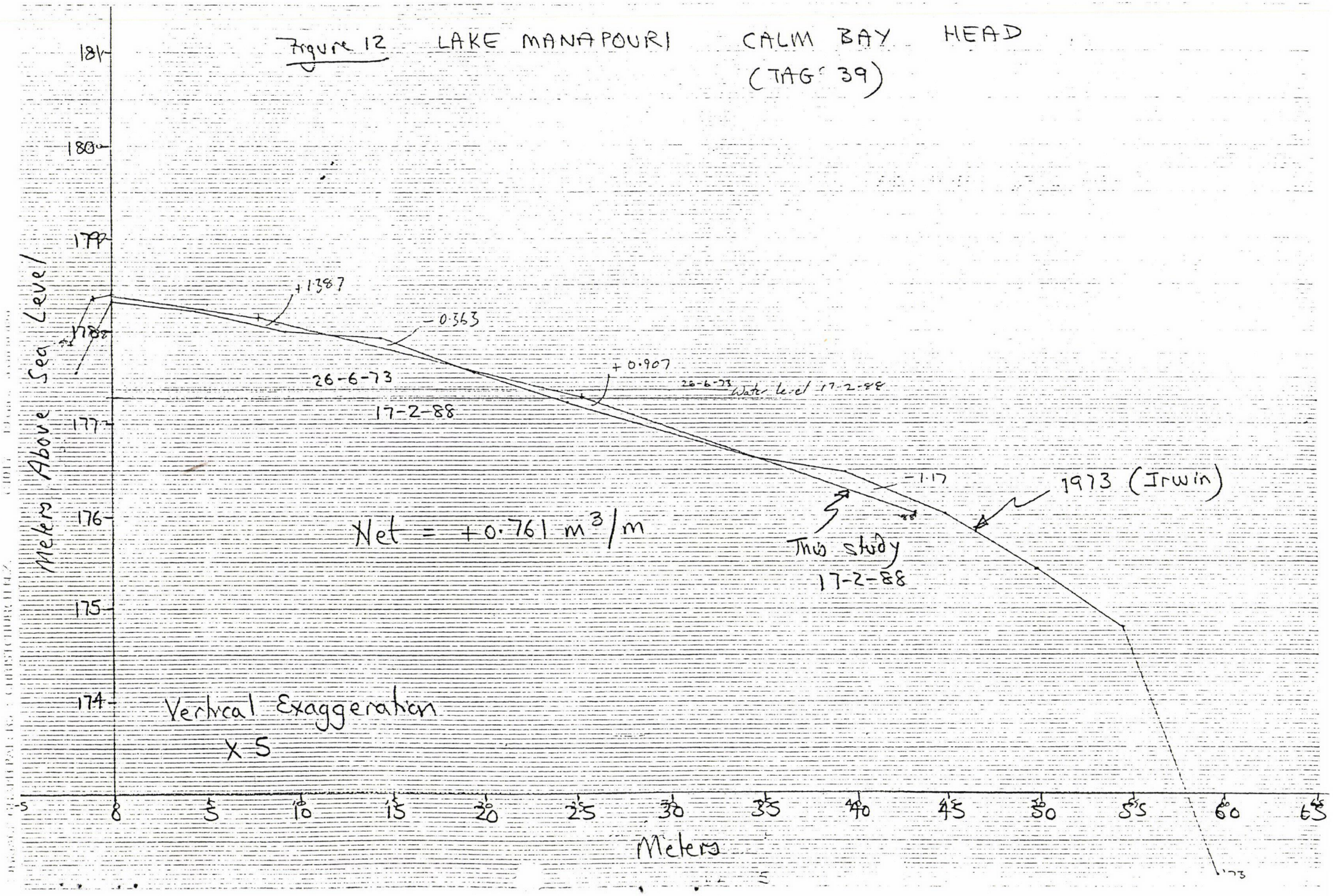
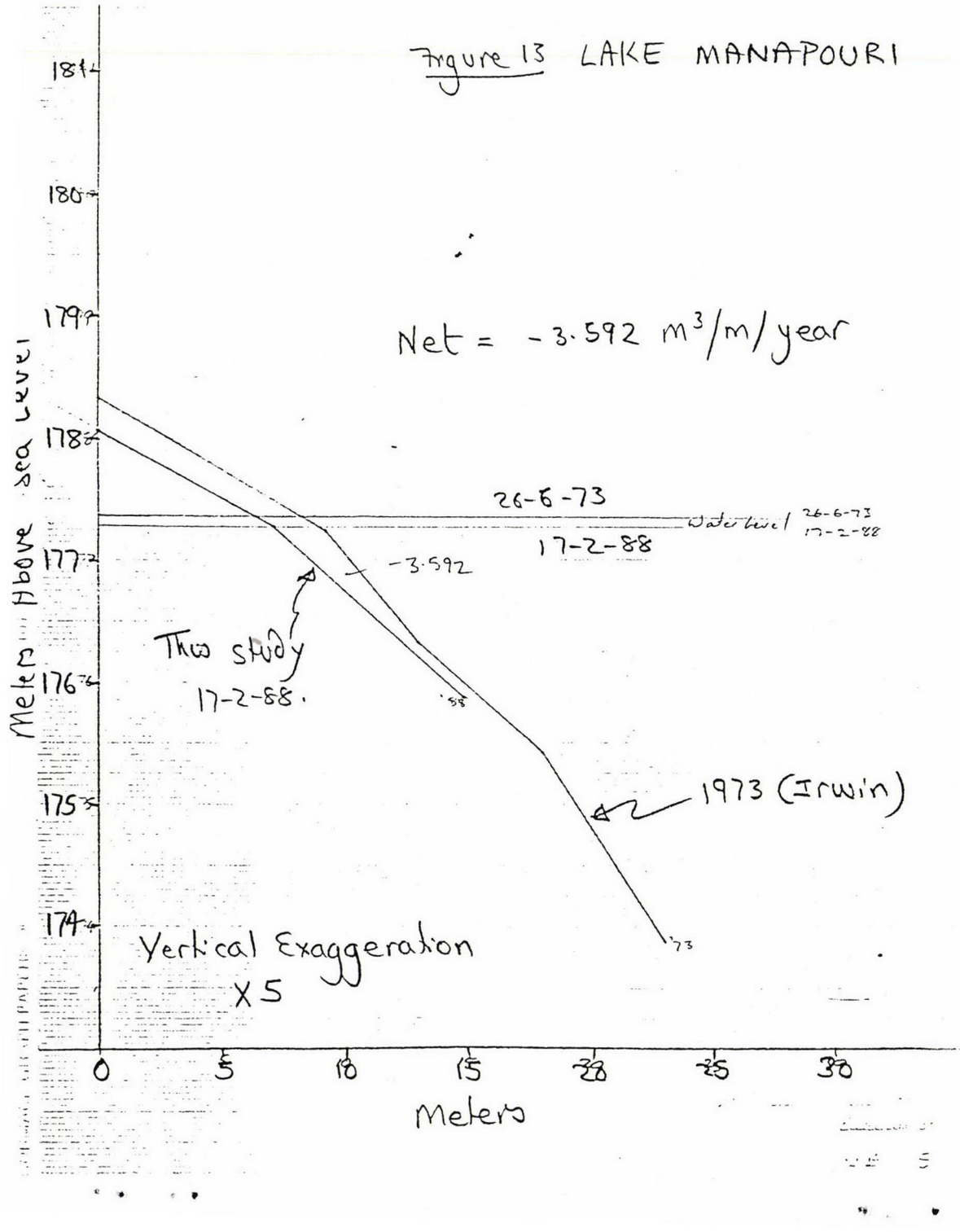
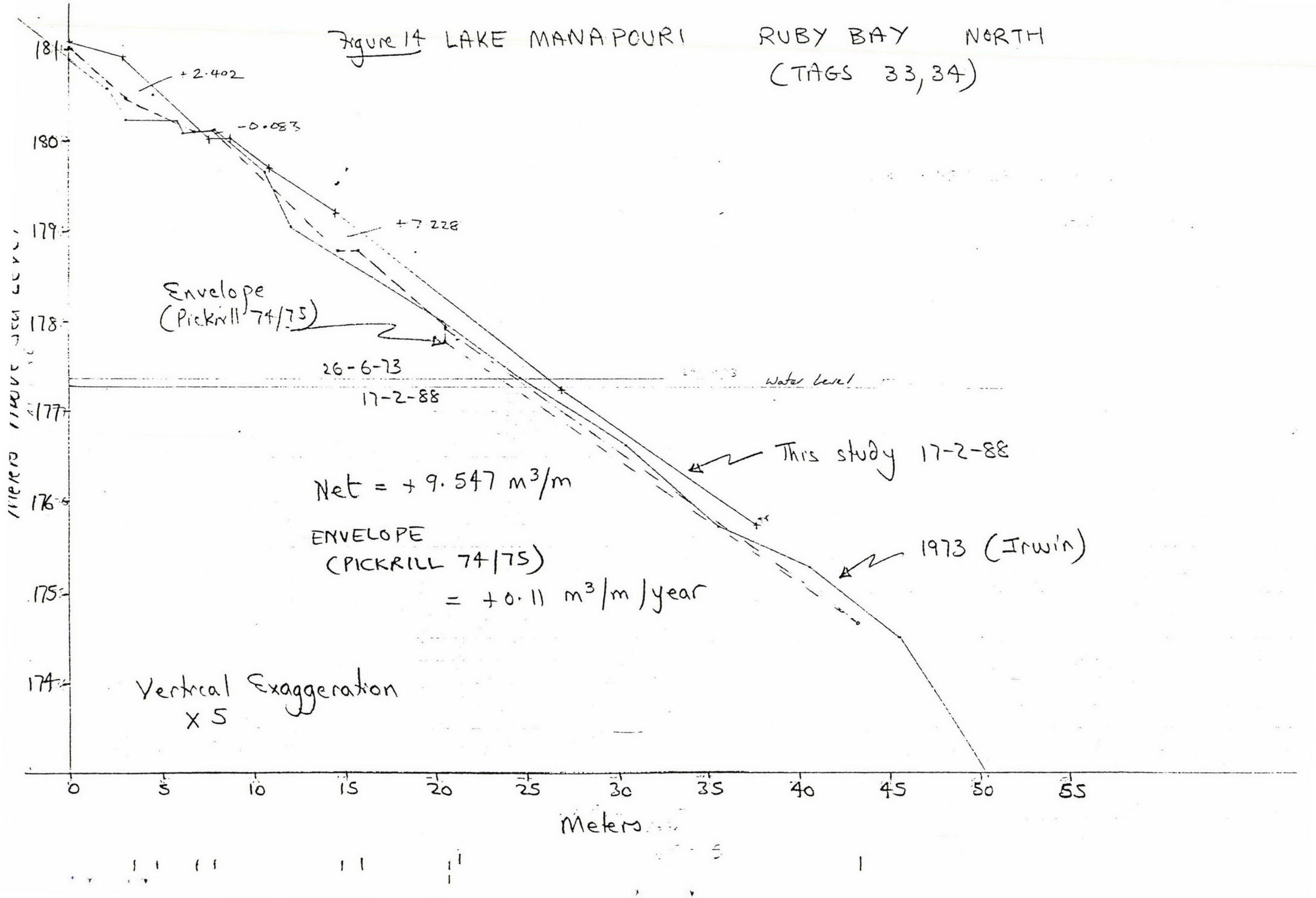
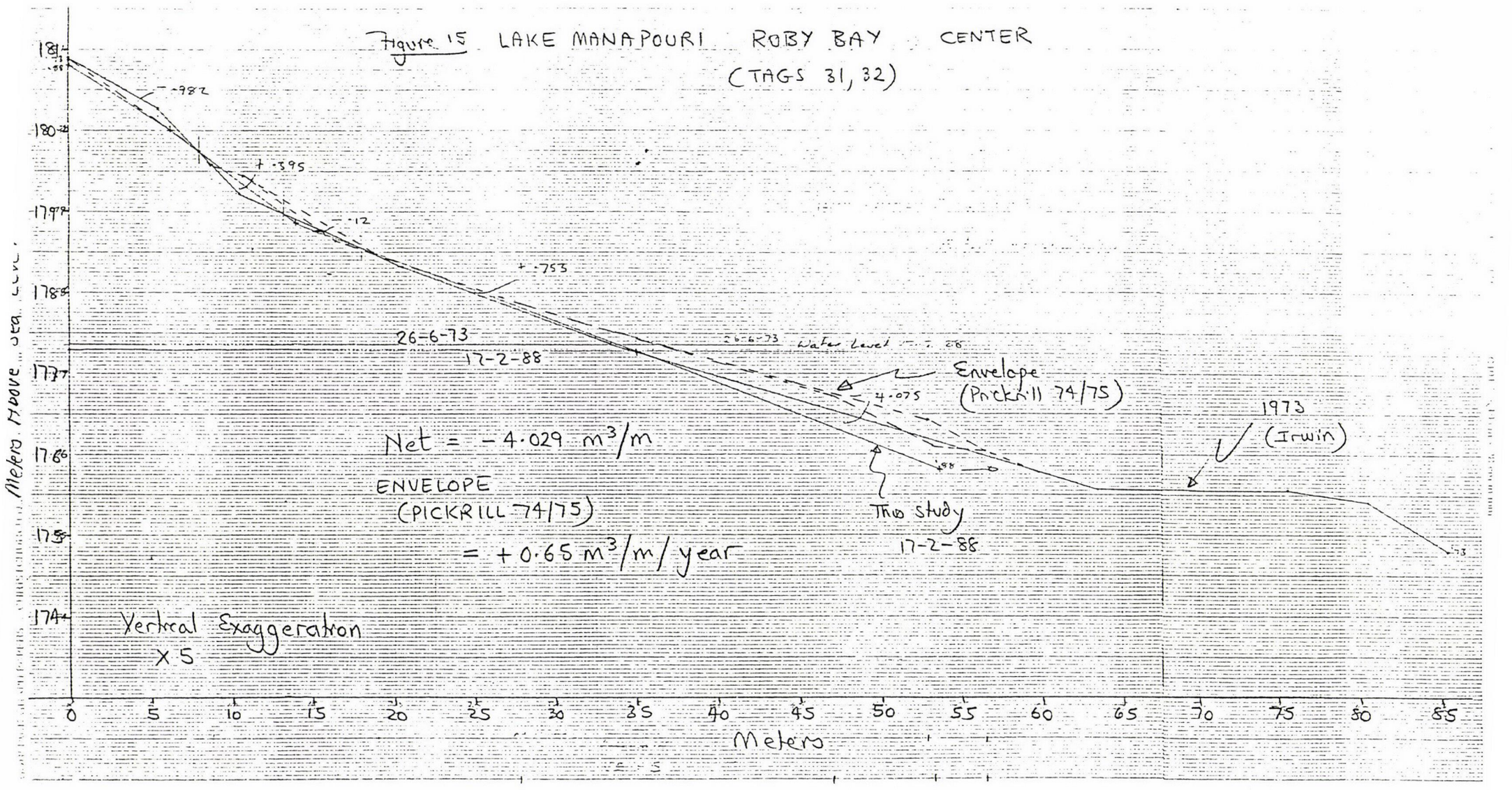
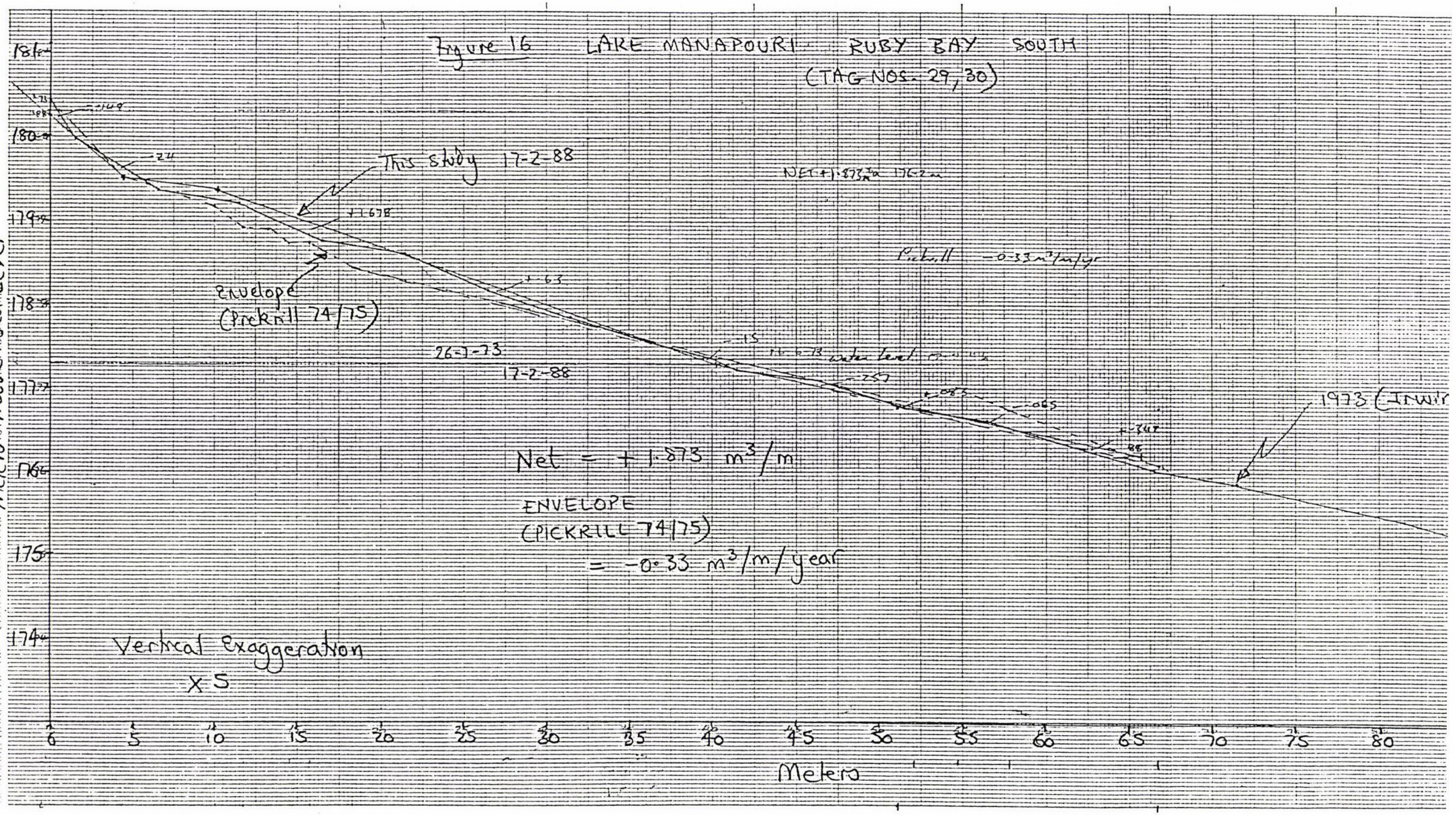

Figure 12 LAKE MANAPOURI CALM BAY HEAD
(TAG 39)
Meters Above Sea Level
181
180
179
178
177
176
175
174
+1.387
-0.363
+0.907
26-6-73
17-2-88
26-6-73 Water level 17-2-88
-1.17
1973 (Irwin)
Net = +0.761 m³/m
This study
17-2-88
Vertical Exaggeration
X 5
-5
0
5
10
15
20
25
30
35
40
45
50
55
60
65
Meters

Figure 13 LAKE MANAPOURI CALM BAY NORTH
(TAGS 37, 38)




Figure 14 LAKE MANAPOURI RUBY BAY NORTH
(TAGS 33, 34)
181
180
179
178
177
176
175
174
+2.402
-0.083
+7.228
Envelope
(Pickrill 74/75)
26-6-73
17-2-88
water level
This study 17-2-88
Net = + 9.547 m³/m
ENVELOPE
(PICKRILL 74/75)
= +0.11 m³/m/year
1973 (Irwin)
Vertical Exaggeration
X 5
0
5
10
15
20
25
30
35
40
45
50
55
Metres


Figure 15 LAKE MANAPOURI ROBY BAY CENTER
(TAGS 31, 32)
Metres above sea level
-.982
+.595
-.12
+.753
26-6-73
17-2-88
26-6-73 Water Level
Envelope
(Pickrill 74/75)
4.075
1973
(Irwin)
Net = -4.029 m³/m
ENVELOPE
(PICKRILL 74/75)
= +0.65 m³/m/year
This study
17-2-88
Vertical Exaggeration
x 5
Metres


Figure 16 LAKE MANAPOURI RUBY BAY SOUTH
(TAG NOS. 29, 30)
This study 17-2-88
Envelope
(Pickrill 74/75)
NET +1·873 m²/m 17-2-88
Pick. 11 −0·33 m³/m/yr
26-1-73
17-2-88
Net = +1·873 m³/m
ENVELOPE
(PICKRILL 74/75)
= −0·33 m³/m/year
1973 (Inwin
Vertical Exaggeration
X 5
Metres
Metres above Sea Level

is a very exposed beach, subject to higher wave energies and to variable longshore drifts. The profiles reveal substantial net erosion since 1973 over the whole beach. Again, there has been erosional encroachment to landward at high lake levels. Pickrill's short term envelope shows that appreciable accretion is possible and the fact that this lies above both the 1973 and 1988 profiles suggests that it is a short-term longshore drift-related phenomenon, one that masks an underlying trend toward erosion.

The remaining profiles represent the northern and eastern shores of the lake. Figure 12 is profile 21 at the head of Calm Bay. The site is adjacent to an active river source of coarse sediments and displays net accretion since 1973 within a generally constant form. The diagram shows that the washover berm at the crest of the beach is growing landward over turf and meadow. No short term envelope data are available for this site but it is likely that short term changes are appreciable.

Figure 13 presents profiles for a pavement beach along the eastern margin of Calm Bay (Profile 20). As noted by Pickrill and discussed earlier, these beaches are generally of an erosional aspect and comprise a lag of relatively immobile materials over moraine or other deposits. The diagram shows that the Calm Bay site is erosional and that there is encroachment into backshore vegetation for this type of beach as well. The sediment losses occur offshore to deep water. At Profile 20 the remaining beach sediments are a thin veneer over very soft Damsite Formation and the nearshore bed is treacherous to walk on. It is likely that slumping of parts of this shore will occur as the beach sediment cover is thinned.

No profiles could be located along the shore in Iris bay.

A final set of three profiles showing longshore drift relationships were re-surveyed in Ruby Bay. Profile 18 (Figure 14) occurs at the northern, downdrift end of the system. The diagram shows that there has

been net gain of sediment over almost the whole profile. The beach is high and steep with a similarly steep nearshore. There are few signs of erosion to landward.

Profile 17 (Figure 15) lies near the centre of the beach and is thus in a zone of through transport. It displays moderate erosion since 1973, particularly in the nearshore and the foreshore has extensive veneers of coarser, lag gravels. The envelope of short term changes lies close to the other two surveys, the greatest departure being in the nearshore. This suggests that the nearshore is the principal zone of the longshore transport. This situation contrasts with that at Profile 18 (Figure 14) where the short term envelope lies below both the 1973 and the 1988 surveys for the nearshore zone.

Profile 16 (Figure 16) occurs at the southern, updrift end of the beach system. There, mild accretion has occured since 1973, mainly on the upper part of the beach. Profile forms are similar in 1973 and 1988 and considerable short term changes are possible, particularly in the nearshore.

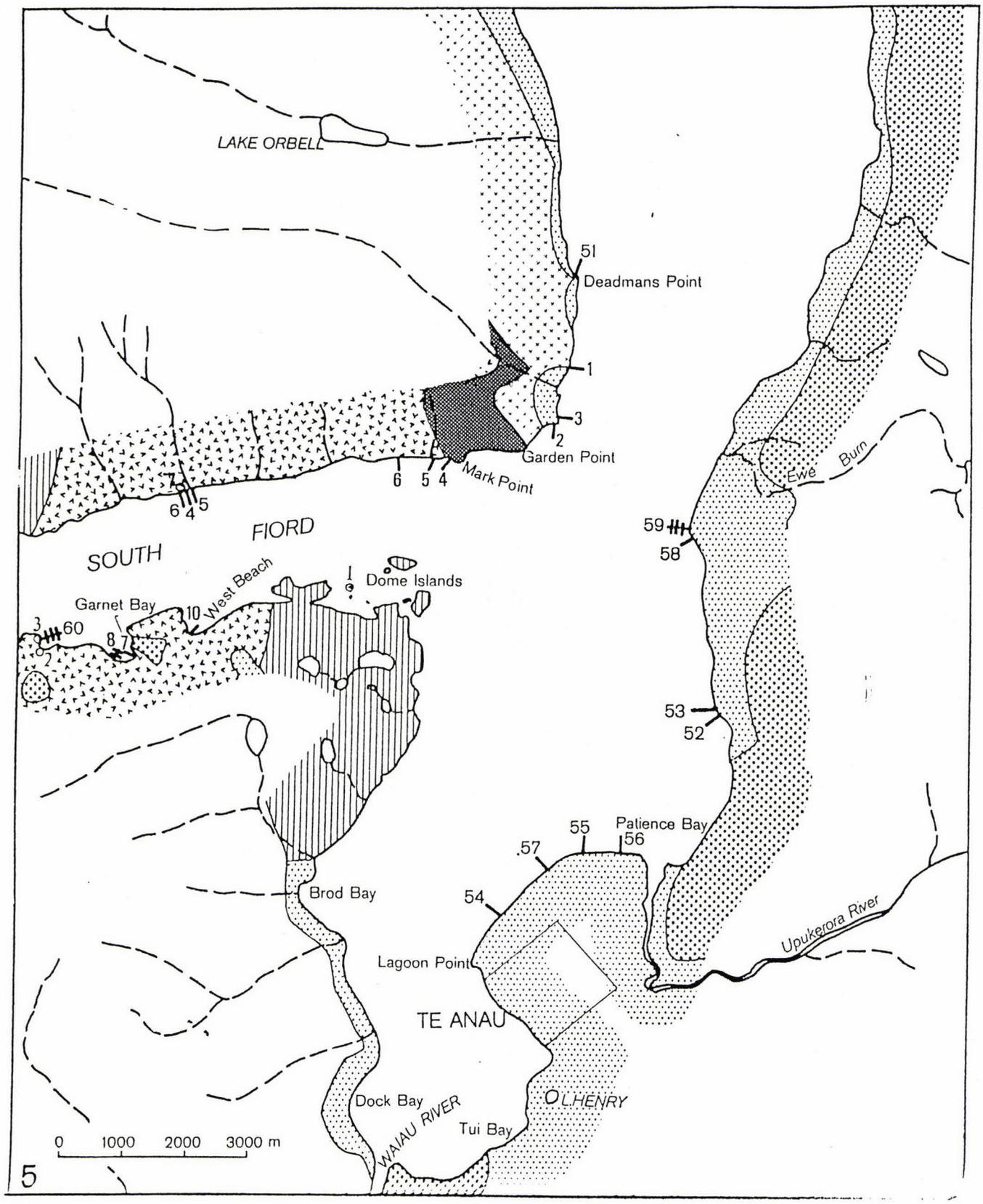
5.2 Rates of Beach Profile Change

Figures 2 to 16 list calculated values for both the short term envelope changes and for the total (net) change from 1973 to 1988. These data have been collated, along with the various profile numbers and metal location tag numbers in Table 1. The table also gives a summary of the type of profile change that has occured at each site over the whole survey period.

As mentioned at the outset, one of the problems of interpretation in such beach survey data is to distinguish changes initiated in the construction phase of low water levels from those in the operating phase, especially if construction-phase changes have long adjustment times. It must also be borne in mind that the beaches of Lake Manapouri display

TABLE 1. Lake Manapouri - Beach Volume Change above 175.85m approx.

	A	B	C	D	E	F	G
1	Profile	Irwin Tag	Irwin	Pickrill	Volume Change	Envelope Change	Profile Form
2	Location	Numbers	Profile	Profile	-full period	74/75	Change
3			Number	Number	73/74 to 1988	(Pickrill 1976)	
4					(m3/m)	(m3/m)	
5							
6	Fraser's Beach - south	Bench Mk	50	23	-12.268	-0.07	Parallel retreat
7	Fraser's Beach - centre	85	49	24	-3.603	-2.19	Parallel retreat
8	Fraser's Beach - north	84	48	34	-6.62	-5.46	Steepening (upper accretion,
9							lower erosion)
10	Sandy Beach	60 & 61	34	3	0.5	0.71	Accretion; similar form
11							
12	Circle Cove - east	81	45	5	-7.893	-0.09	Flattening; erosion of upper
13							
14	Bullings Beach - east	58	32	8	-7.822	-1.64	Strong parallel retreat
15							
16	George Bay - south	83	47	17	9.518	0.36	Steepening; upper accretion
17							
18	Monument Bay - south	5 & 6	3	16	-44.332	-0.93	Steepening; strong retreat
19							
20	Stockyard Cove - west	44 & 45	24	19	-0.808	-1.18	Parallel retreat
21							
22	Fairy Beach	19	11	27	-10.737	-1.4	Parallel retreat
23							
24	Calm Bay - head	39	21	-	0.761	No data	Stable/accreting
25	Calm Bay - north	37 & 38	20	-	-3.592	No data	Parallel retreat
26							
27	Ruby Bay - north	33 & 34	18	33	9.547	0.14	Accretion over whole profile
28	Ruby Bay - centre	31 & 32	17	32	-4.029	0.65	Erosion of berms
29	Ruby Bay - south	29 & 30	16	31	1.873	-0.33	Accretion to upper berms
30							
31	Notes:						
32	(i) positive values indicate accretion						
33	(ii) negative values indicate erosion						


LAKE ORBELL
51
Deadmans Point
1
3
2
Garden Point
6 5 4
Mark Point
7
6 4 5
FIORD
SOUTH
Dome Islands
West Beach
Garnet Bay
10
3
60
8 7
2
59
58
Ewe Burn
53
52
55
Patience Bay
56
57
54
Brod Bay
Upukerora River
Lagoon Point
TE ANAU
Dock Bay
WAIAU RIVER
Tui Bay
OLHENRY
0 1000 2000 3000 m
5

great ranges of behaviour depending upon their type and their context.

This complexity and the uncertainties notwithstanding, it is clear from the survey information that consistent patterns of change having implications for water level regime are in evidence.

First, Table 1 shows that both erosion and accretion are occurring but that significant erosion is a feature even of profiles that display net sediment gain since 1973. As indicated previously this is primarily related to high wave energies when the lake is in the high operating range.

Secondly, there are a number of beaches (Circle Cove, Bullings, Monument Bay, Stockyard Cove) that are substantially affected by erosion in generally steepshore situations. Lookout beach is also in this group and it is almost completely denuded.

Thirdly, a few sites that are well endowed with sediments (eg: Sandy Bay and the head of Calm Bay) appear to be in approximate equilibrium.

Fourthly, high energy sandy beaches like Fairy Beach are eroding.

Finally, longshore drift dominated shores with wide wave approach windows are very active. Fraser's Beach is generally erosional within such a drift regime, as is much of Ruby Bay, only the northern, downdrift end being accretional.

A quite different aspect of Table 1 concerns the comparison of the total changes with the short term envelope data of Pickrill. It is evident that with only two exceptions the sign of the short term change has been sustained over the full survey period. Thus, beaches with generally erosive changes in the short term have continued to be erosional in the longer term. Similarly, accreting beaches have mostly maintained the type of behaviour displayed in 1974/1975. The exceptions occur for the updrift end and centre zones of Ruby Bay and the reversals of behaviour can be readily accounted for by variable longshore drift in the manner proposed

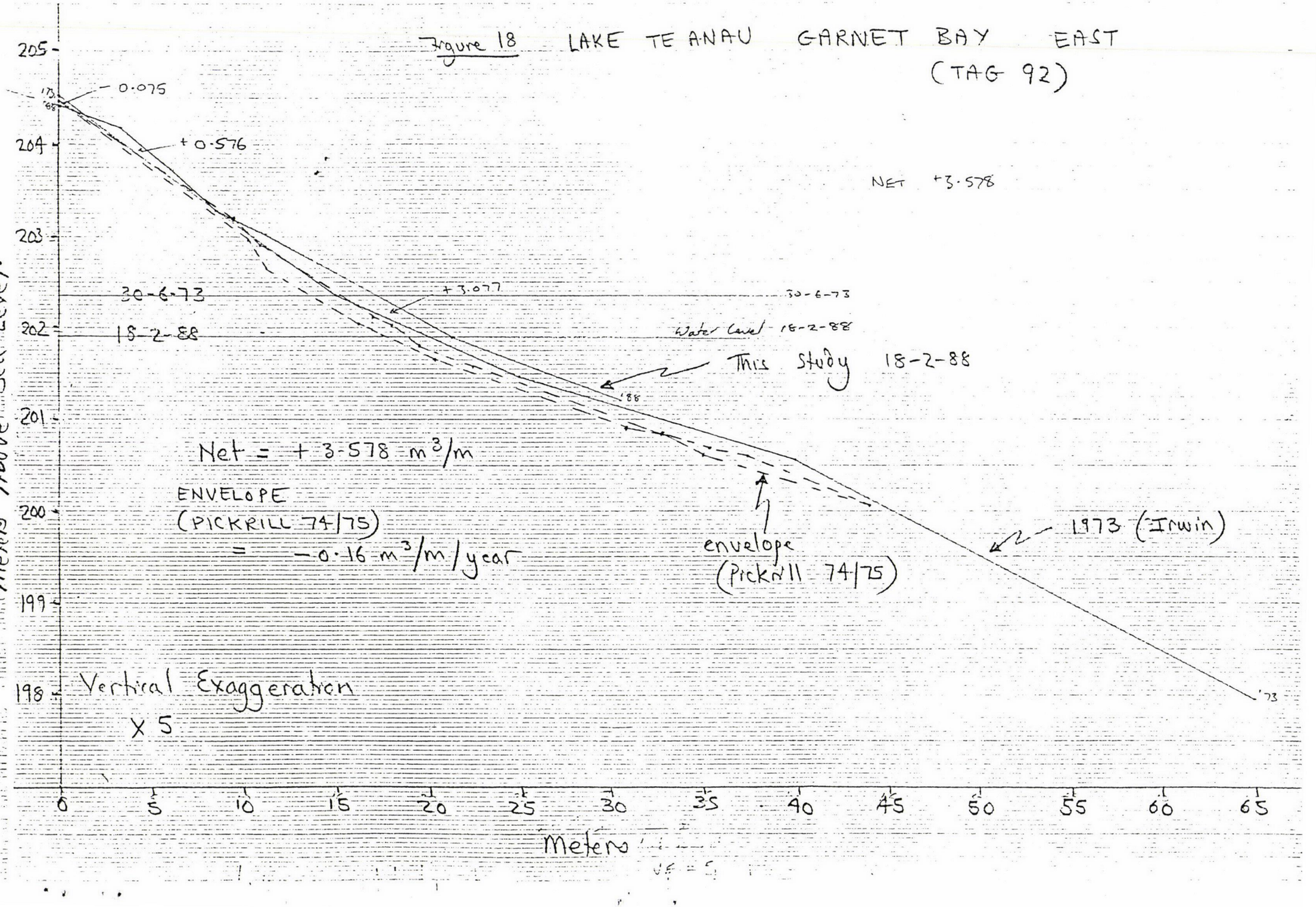
by Pickrill.

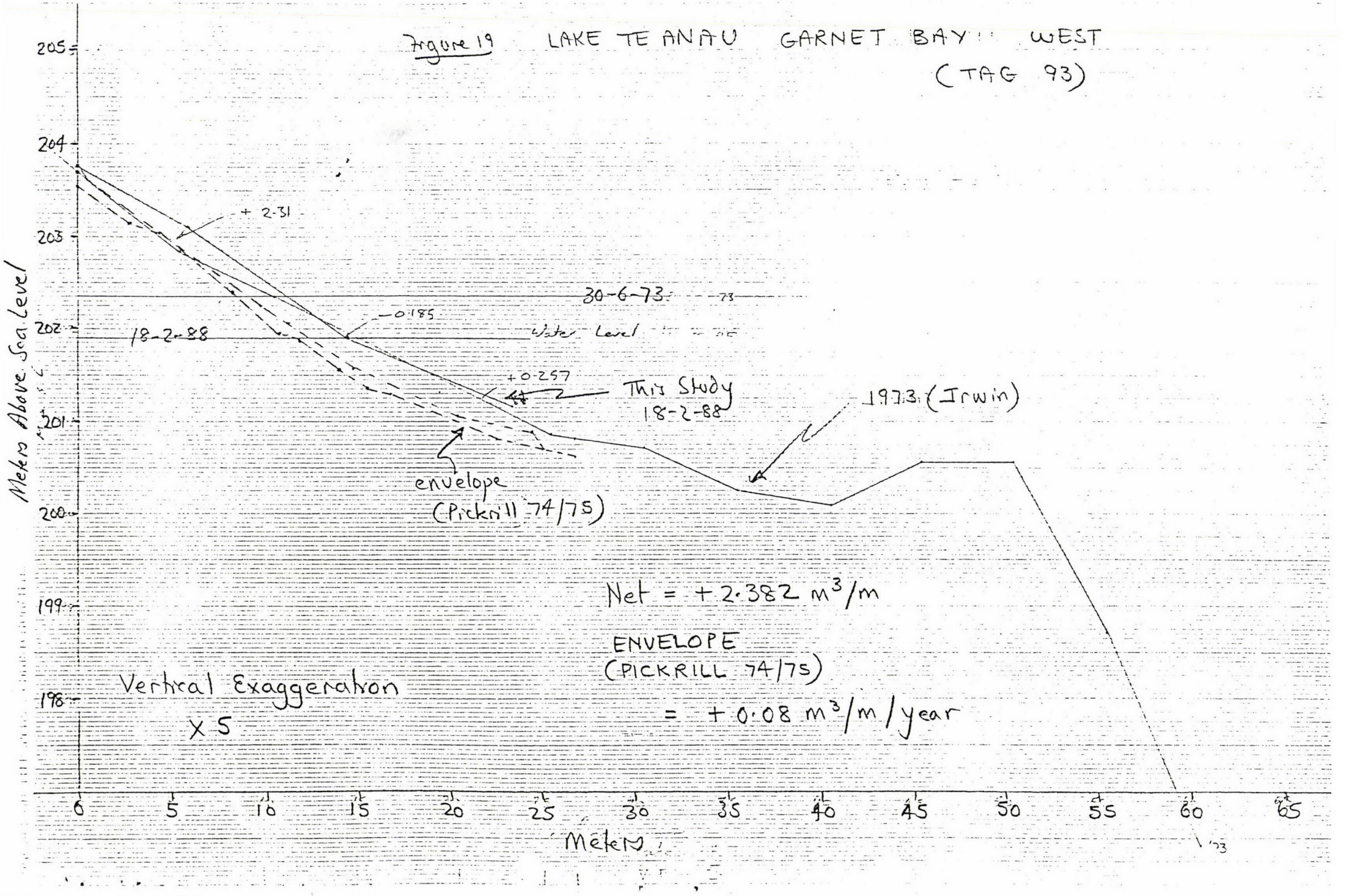
More generally, these findings suggest considerable support for Pickrill's (1976) and subsequent conclusions as to the process controlling beach behaviour on Lake Manapouri, and for management decisions based upon his findings. Pickrill's findings from intensive, short term monitoring and from sediment particle tracer studies can now be shown to have been good 'predictors' of the type of shoreline change to be expected for a given beach type and/or a given beach context. However, rates of change are not well specified by the short term envelopes.

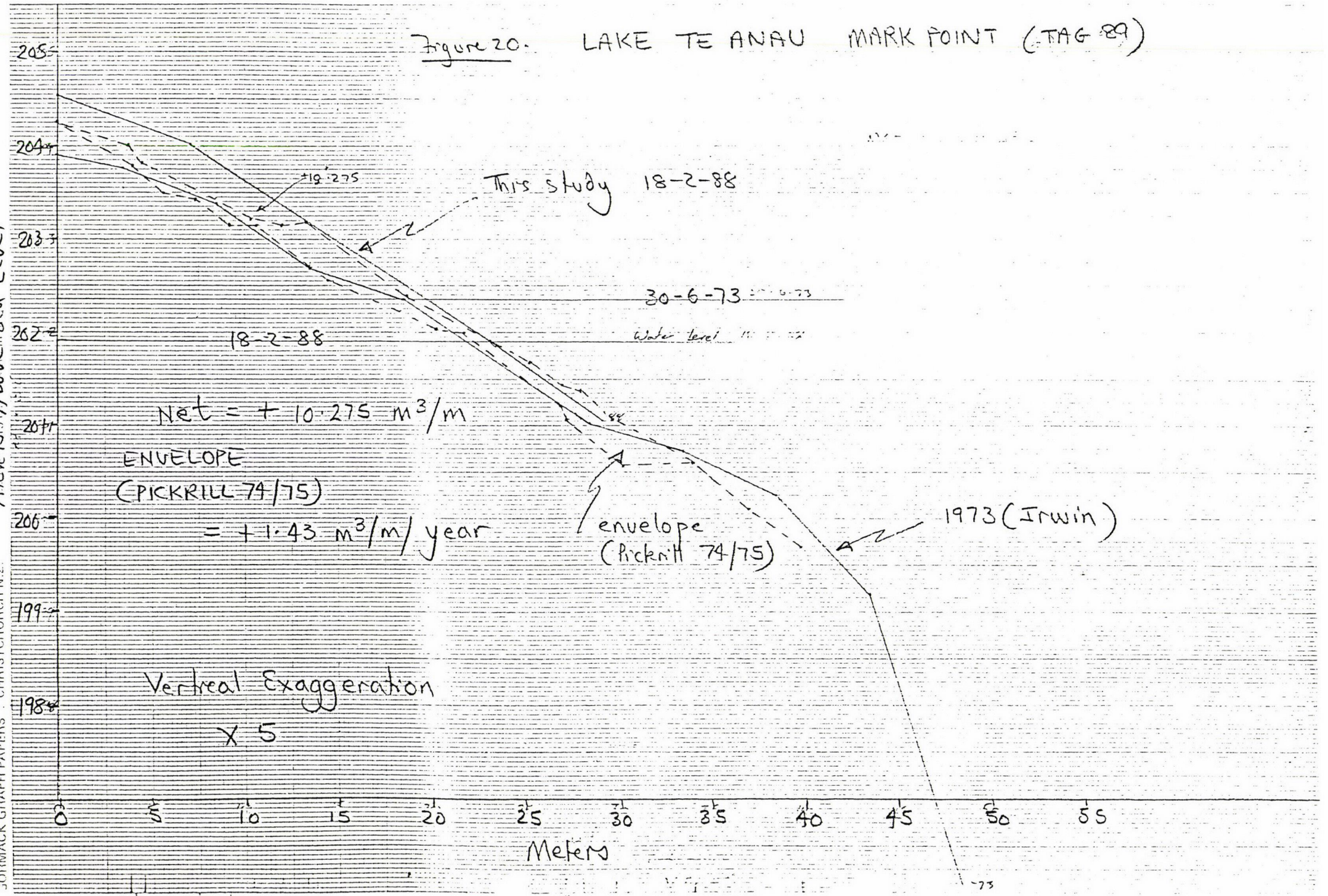
Table 2 presents measurements of erosional retreat (horizontal distances) at the survey pegs over the period 1973-1988, average rates of erosional retreat, average rates of beach volume change for the full period and the percentage relationships between short term envelope changes and total change since 1973. Positive percentages relate to accretion, negative values to erosion and no determination has been made for the two cases where the behaviour is different between the short and the longer terms.

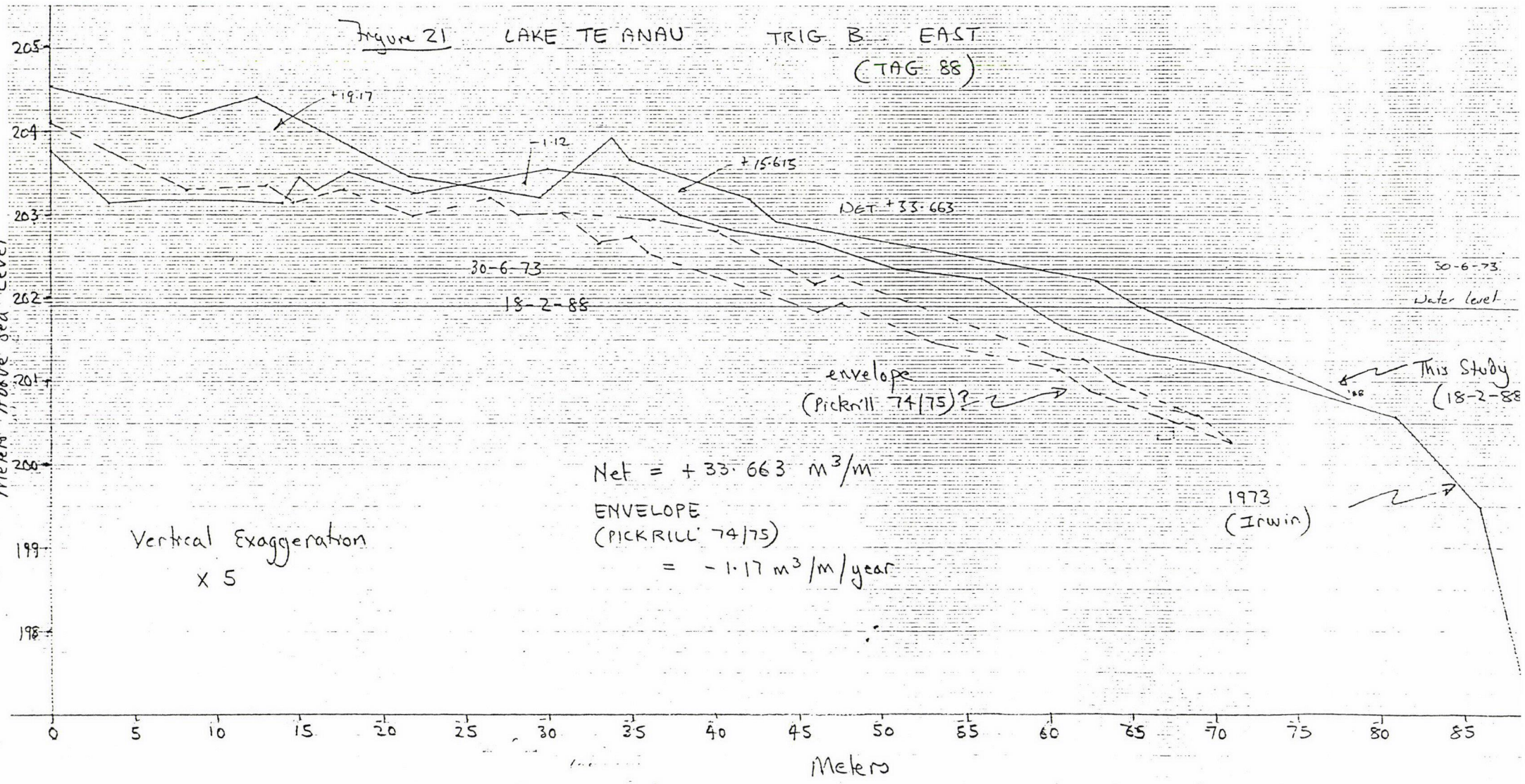
It can be seen from the table that both erosion and accretion have occurred at generally more rapid rates than indicated by the envelope data. Horizontal retreat at the pegs, the rates of encroachment of the beach on to the vegetated hinterlands, have varied from a few centimetres per year to as much as -29 cm/year at Fairy Beach. The mean erosion rate for the data in the table is -12.7 cm/year.

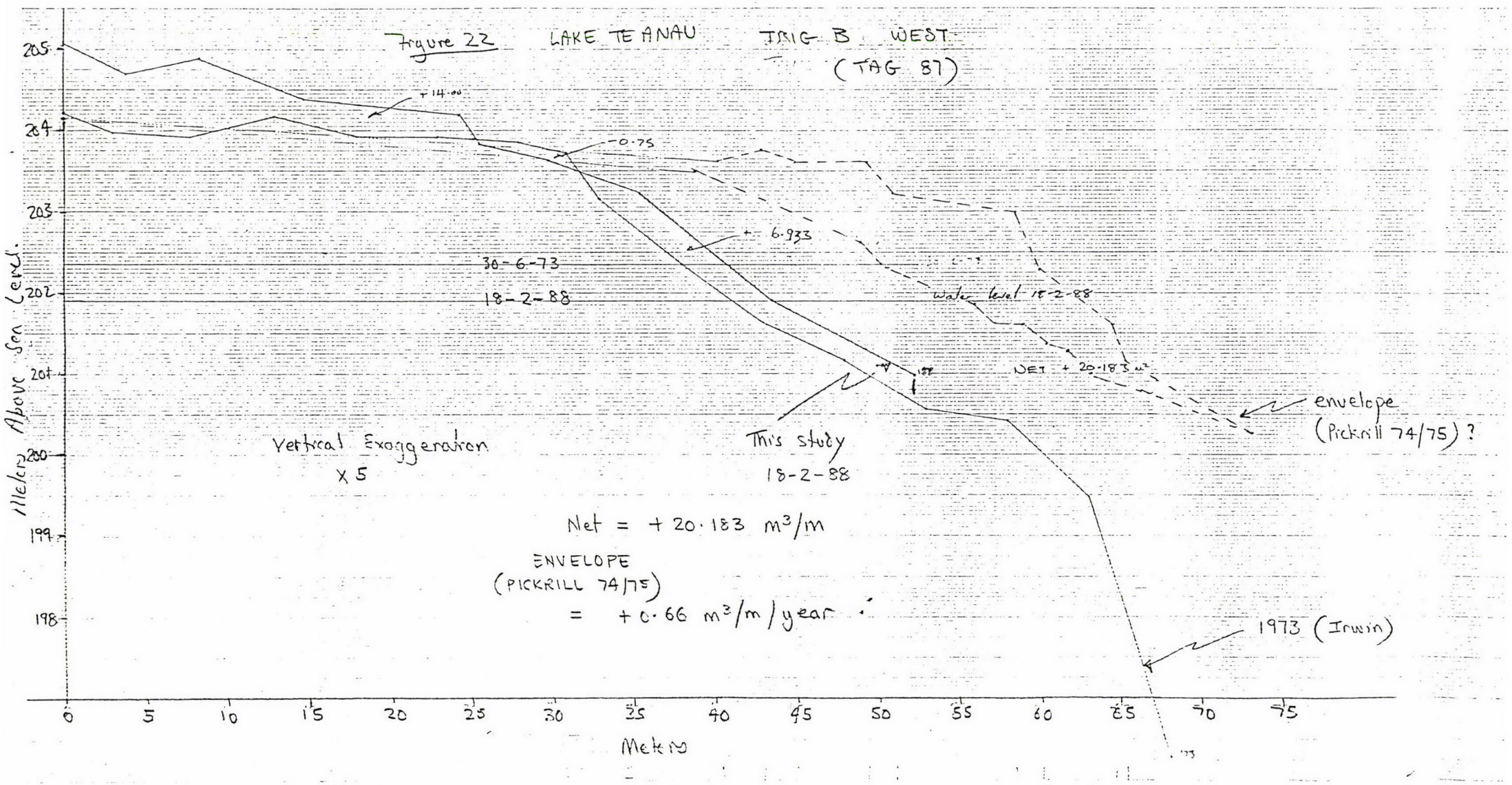
Rates of volume change range from -3.02 m^3 of sediment per metre of shore (erosion) at Monument Bay to +0.65 m^3/m at George Bay and the downdrift end of Ruby Bay (accretion) when expressed as annual averages. Few beaches are eroding more slowly than the volume change rates determined in 1974/1975 by Pickrill. Amongst this group are Bullings Beach (already substantially depleted), Stockyard Cove and Fairy Beach. For the larger, higher energy, longshore drift dominated shores

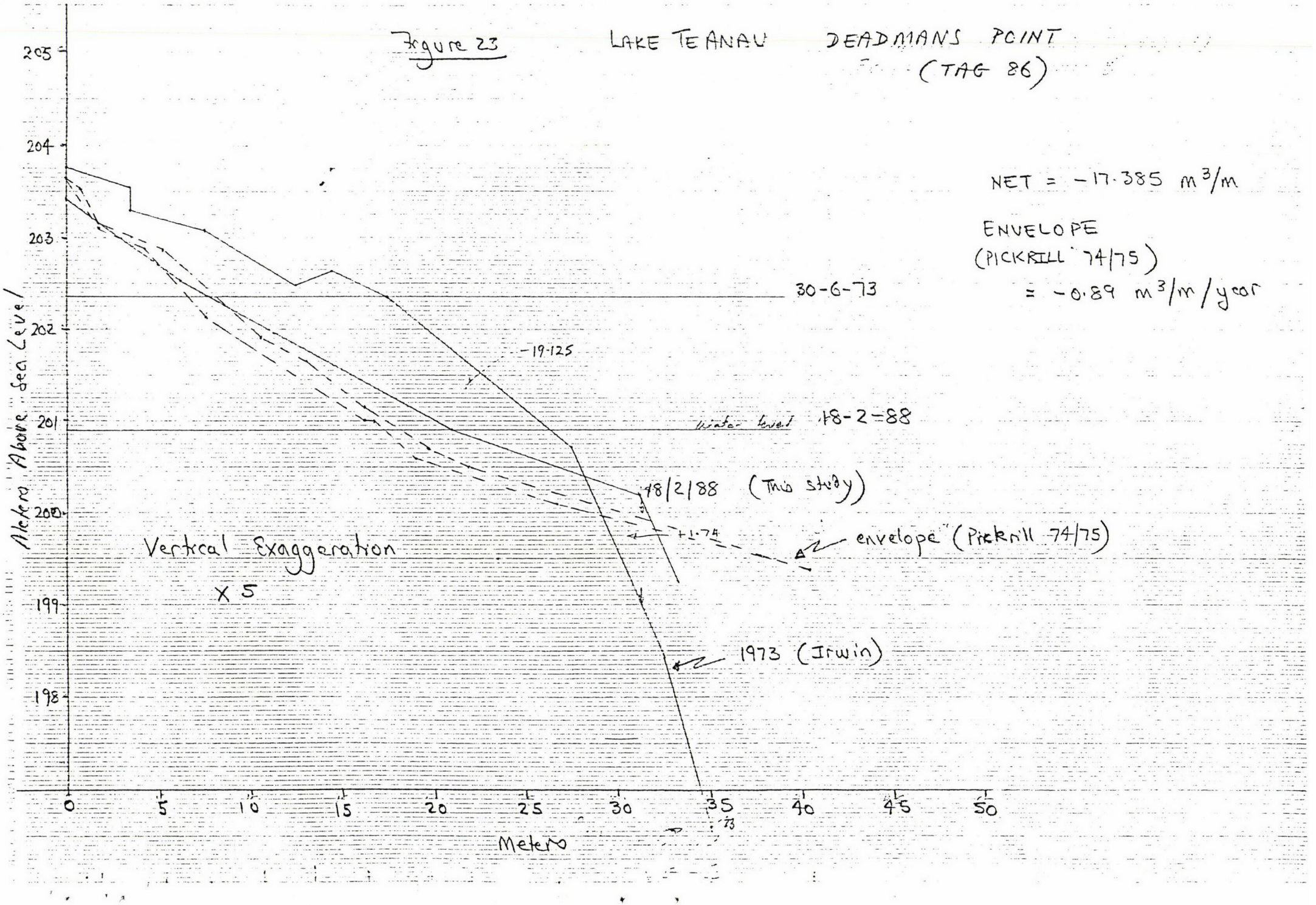

Figure 18 LAKE TE ANAU GARNET BAY EAST
(TAG 92)
205
204
203
202
201
200
199
198
Metres Above Sea Level
- 0.075
+ 0.576
NET +3.578
30-6-73
18-2-88
+ 3.077
30-6-73
Water Level 18-2-88
This Study 18-2-88
'88
Net = + 3.578 m³/m
ENVELOPE
(PICKRILL 74/75)
= -0.16 m³/m/year
envelope
(Pickrill 74/75)
1973 (Irwin)
'73
Vertical Exaggeration
X 5
0
5
10
15
20
25
30
35
40
45
50
55
60
65
Metres
VE = 5

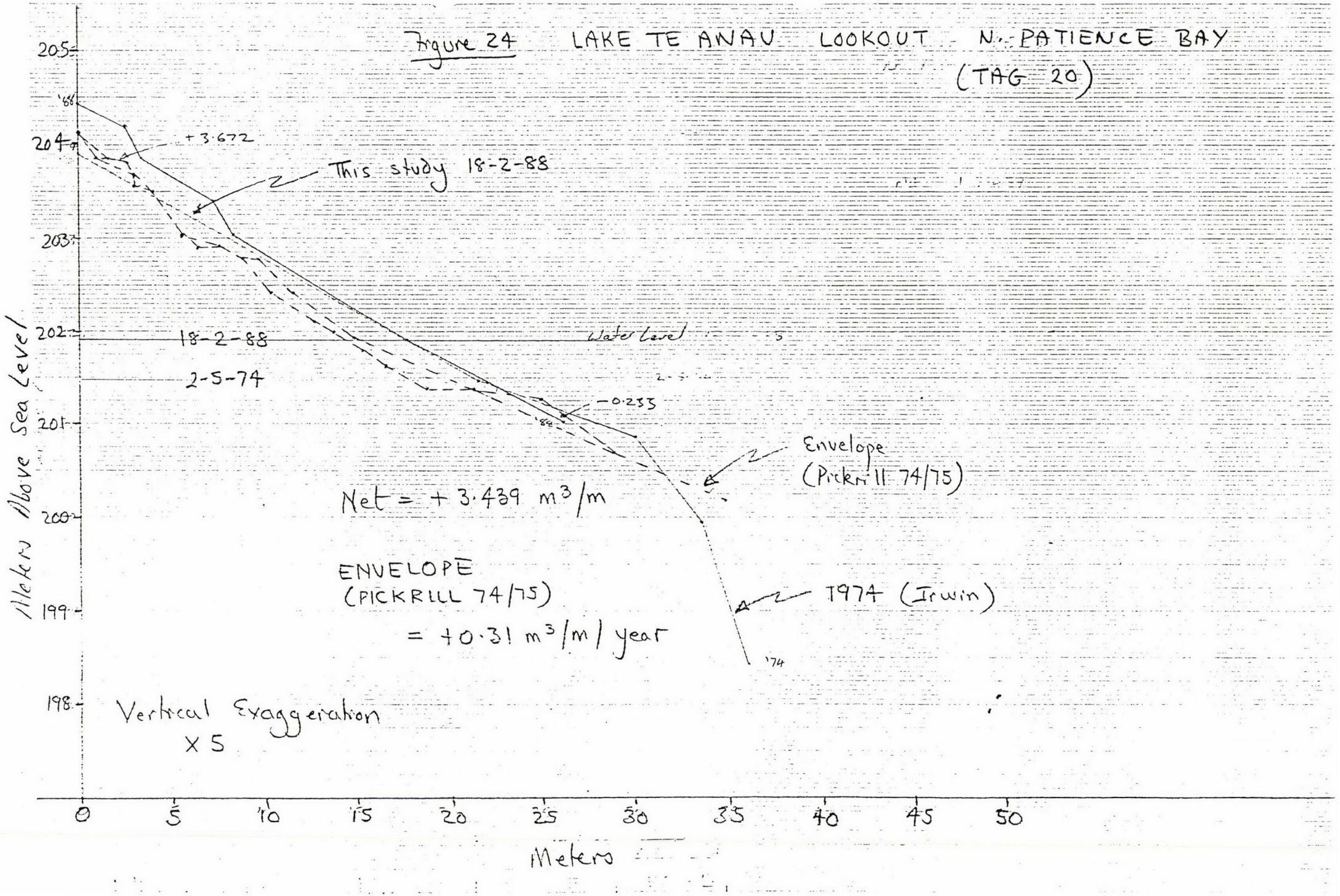

Figure 19 LAKE TE ANAU GARNET BAY : WEST
(TAG 93)
Metres Above Sea Level
205
204
203
202
201
200
199
198
+ 2·31
30-6-73
73
-0·185
18-2-88
Water Level
+0·257
This Study
18-2-88
1973 (Irwin)
envelope
(Pickrill 74/75)
Net = + 2·382 m³/m
ENVELOPE
(PICKRILL 74/75)
= + 0·08 m³/m/year
Vertical Exaggeration
X 5
0
5
10
15
20
25
30
35
40
45
50
55
60
65
Metres
'73


Figure 20. LAKE TE ANAU MARK POINT (TAG 89)
205
204
203
202
201
200
199
198
Metres Above Sea Level
+19.275
This study 18-2-88
30-6-73
18-2-88
Water level
Net = + 10·275 m³/m
ENVELOPE
(PICKRILL 74/75)
= + 1·43 m³/m/ year
envelope
(Pickrill 74/75)
1973 (Irwin)
Vertical Exaggeration
X 5
0
5
10
15
20
25
30
35
40
45
50
55
Meters
-73
GORMACK GRAPH PAPERS : CHRISTCHURCH N.Z.


Figure 21 LAKE TE ANAU TRIG B EAST
(TAG 88)
+19.17
-1.12
+15.615
DET +33.663
30-6-73
18-2-88
30-6-73
Water level
envelope
(Pickrill 74/75)?
This Study
(18-2-88)
Net = +33.663 m³/m
ENVELOPE
(PICKRILL 74/75)
= -1.17 m³/m/year
1973
(Irwin)
Vertical Exaggeration
X 5
Meters Above Sea Level
205
204
203
202
201
200
199
198
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
Meters


Figure 22
LAKE TE ANAU
TRIG B WEST
(TAG 87)
+14.00
-0.75
+ 6.933
30-6-73
18-2-88
water level 18-2-88
NET + 20.183 m²
envelope
(Pickrill 74/75)?
This study
18-2-88
Vertical Exaggeration
X 5
Net = + 20.183 m³/m
ENVELOPE
(PICKRILL 74/75)
= + 0.66 m³/m/year
1973 (Irwin)
Above Sea Level
Metres
205
204
203
202
201
200
199
198
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75


Figure 23
LAKE TEANAU DEADMANS POINT (TAG 86)
NET = −17.385 m³/m
ENVELOPE (PICKRILL 74/75) = −0.89 m³/m/year
30-6-73
−19.125
Water level 18-2=88
18/2/88 (This study)
+1.74
envelope (Pickrill 74/75)
Vertical Exaggeration X 5
1973 (Irwin)
Metres Above Sea Level
205
204
203
202
201
200
199
198
0
5
10
15
20
25
30
35
40
45
50
Metres


Figure 24 LAKE TE ANAU LOOKOUT N. PATIENCE BAY
(TAG 20)
205
204
203
202
201
200
199
198
Meters Above Sea Level
'68
+3.672
This study 18-2-88
18-2-88
2-5-74
Water level
-0.233
'68
Envelope
(Pickrill 74/75)
Net = + 3.439 m³/m
ENVELOPE
(PICKRILL 74/75)
= +0.31 m³/m/year
1974 (Irwin)
'74
Vertical Exaggeration
X 5
0
5
10
15
20
25
30
35
40
45
50
Meters

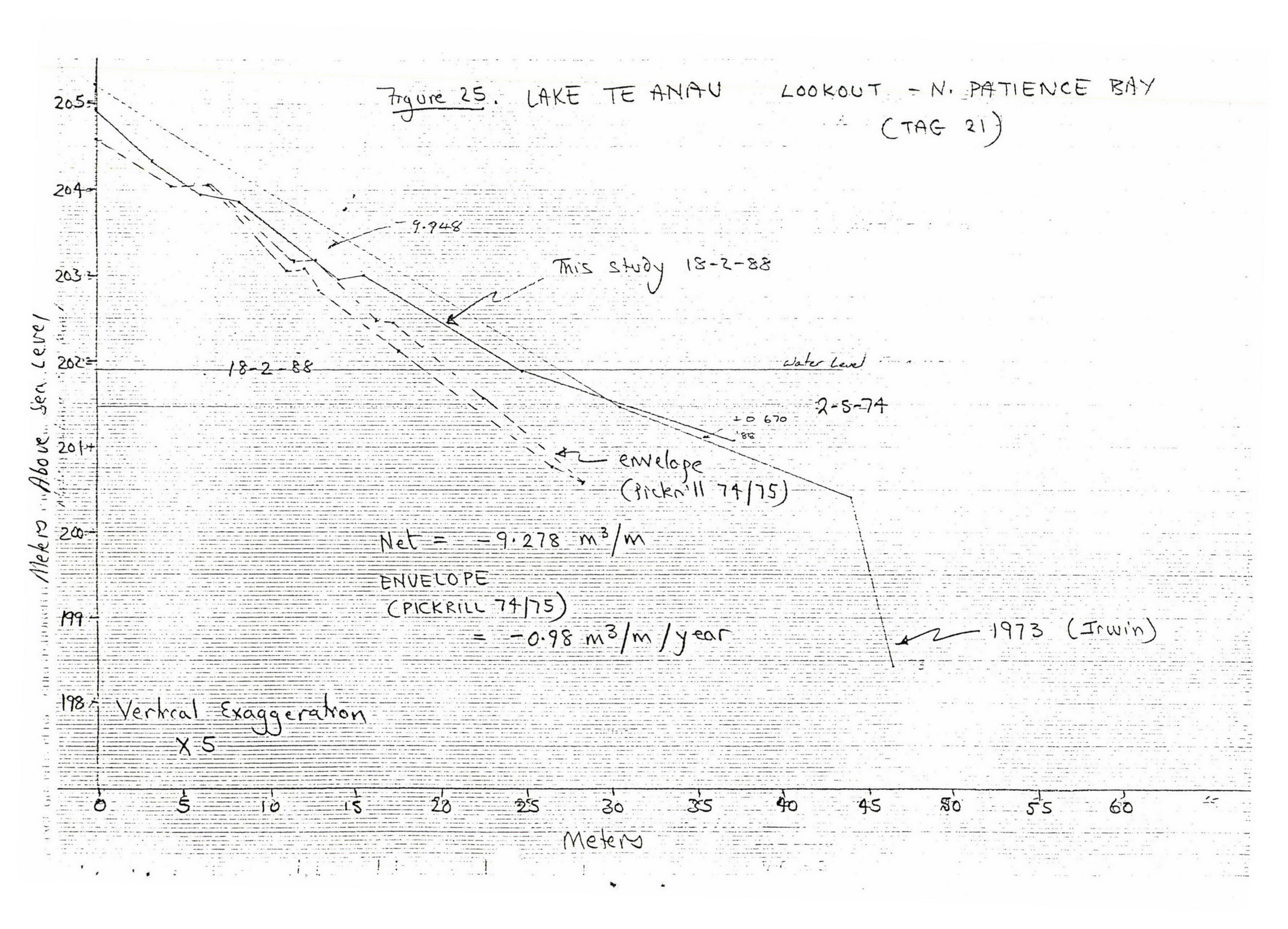

Figure 25. LAKE TE ANAU LOOKOUT - N. PATIENCE BAY (TAG 21)
205
204
203
202
201
200
199
198
Meters Above Sea Level
-9.948
This study 18-2-88
18-2-88
Water Level
2-5-74
+0.670
'88
envelope (Pickn'll 74/75)
Net = -9.278 m³/m
ENVELOPE (PICKRILL 74/75) = -0.98 m³/m/year
1973 (Irwin)
Vertical Exaggeration X5
0
5
10
15
20
25
30
35
40
45
50
55
60
Meters

TABLE 2. Lake Manapouri - Rates of Beach Change 1973/74 to 1988

	A	B	C	D	E	F
1	Profile	Accretion/	Average rate of	Av. rate of	% faster or	Notes
2	Location	Erosion at peg	accretion or erosion	Volume change	slower than	
3		-full period	-full period	-full period	envelope	
4		(m)	(m/year)	(m3/m/year)	74/75	
5						
6	Fraser's Beach - south	negligible	0	-0.84	-1200	Faster erosion
7	Fraser's Beach - centre	-1.5	-0.1	-0.25	-11.42	Slower erosion
8	Fraser's Beach - north	-1	-0.07	-0.45	-8.24	Slower erosion
9						
10	Sandy Beach	-1.5	-0.1	0.03	233	Faster accretion
11						
12	Circle Cove - east	-3	-0.2	-0.54	-598	Faster erosion
13						
14	Bullings Beach - east	-2.5	-0.17	-0.53	-32.5	Slower erosion
15						
16	George Bay - south	-1.75	-0.12	0.65	180	Faster accretion
17						
18	Monument Bay - south	-0.25	-0.02	-3.02	-325	Faster erosion
19						
20	Stockyard Cove - west	-2.5	-0.17	-0.06	-4.7	Slower erosion
21						
22	Fairy Beach	-4.25	-0.29	-0.73	-52.3	Slower erosion
23						
24	Calm Bay - head	Accretion	-	0.05	-	Mild accretion
25	Calm Bay - north	-2.25	-0.15	-0.24	-	Moderate accretion
26						
27	Ruby Bay - north	-1.2	-0.08	0.65	592	Faster accretion
28	Ruby Bay - centre	-1.25	-0.09	-0.27	-	Change from acc. to er.
29	Ruby Bay - south	-1.25	-0.09	0.13	-	Change from er. to acc.
30						
31	Notes:					
32	(i) Positive values					
33	indicate accretion					
34	(ii) negative values					
35	indicate erosion					

(Fraser's Beach and Ruby Bay) both considerably accelerated erosion and accretion are evident.

On these results, and mindful that neither natural nor construction-phase rates or signs (erosion/accretion) are known, it is concluded that shoreline change on Lake Manapouri has been occurring at generally accelerated, disequilibrium rates. Under equilibrium or near equilibrium conditions it would be expected that short term envelope changes would be substantially greater than long term net changes. While the rates of natural change are unknown it is also evident that changes since 1973 are related to lake level regime since a high proportion of the changes involve erosional encroachment at the upper limits of the beaches and/or net loss across the whole beach profile. In this respect it is noteworthy that the low operating range was structured particularly in respect of beach conservation and the volume change results presented here show that that has met with limited success (with the notable exception of steep, exposed pocket beaches). However, the findings presented here also show that a significant component of shoreline change is related to events that occur in the high operating range.

Boat wake continues to influence at least Bullings Beach.

6. SURVEY RESULTS - LAKE TE ANAU

6.1 Profile forms and Inspections

Figure 17 shows the locations and names of profile sites for the southern portions of Lake Te Anau. It should be recalled that numerous profiles installed between Lagoon Point and Tui Bay along the Township foreshore by Irwin (1974b) are not relocatable. Also, this area has been discussed in detail by Kirk (1985). In brief, shoreline stability in this area is affected by a general north to south longshore drift of finer sediment toward Steamer Beach and the erosional status has been markedly

influenced by a range of urban, road alignment and construction practices carried out along the backshore. These works disrupt the longshore transport in a variety of ways thus generating zones of inadequate sediment nourishment and/or they contribute to maintaining an erosional status for the beach profile through effects on freshwater drainage.

Fieldwork on Lake Te Anau proceeded by the same methods and in the same wave and weather conditions as for Lake Manapouri. Re-survey commenced with a search by vehicle and on foot of the long, longshore drift-dominated beach system that feeds the Township beaches. This system extends from Patience Bay across the mouth of the Upukerora River (which is an active source of beach sediments) to Lagoon Point (the downdrift end). No pegs were re-located.

As stated previously, removal of pegs and/or the metal tags that identified sites proved to be particularly common on Lake Te Anau, especially on popular beaches within easy reach of the Township.

Boat work commenced with a visual and photographic comparison survey at Dock Bay. The foreshore comprised coarse sand and gravel and appeared to be well nourished with few signs of erosion anywhere on the profile.

Similarly healthy beaches are evident as far north as Brod Bay where a large, sandy point accumulation displays multiple berms and only slight signs of erosion of turf and other vegetation on the backshore. In the main body of Brod Bay the beach is again well nourished though there are more prominent signs of erosional encroachment into backshore vegetation.

At West Beach (South Fiord) what appeared to be Profile 10 was re-located and resurveyed but subsequent difficulties were encountered in computation of the results so the profile has not been plotted here. The beach at the time of survey comprised a steeply sloping coarse sand and pebble foreshore carrying minor berms (accretional features that are

short-lived). On the backshore there had been considerable erosional retreat of the beach into Manuka, Beech etc. and a number of trees were fallen.

Figure 18 presents Profile 7 at the south end of Garnet Bay (South Arm). As can be seen, the short term envelope in 1974/1975 was erosional but over the full period the beach has displayed moderate accretion. Despite this there is appreciable erosion into vegetation on the backshore.

Figure 19 shows Profile 8 at the head of Garnet Bay. The beach here is much coarser than at Profile 7 and comprises boulders, cobbles and pebbles adjacent to a creek mouth. The accretional trends in profile behaviour are thus to be expected, though there is erosion of the backshore and abundant driftwood high on the beach.

At Mark Point (west) the location peg has been removed. The beach was very steep with a narrow shelf giving way abruptly to deep water and the foreshore displayed a very prominent erosion scarp at the western end.

Figure 20 shows Profile 4 at Mark Point (east). This site is also a steep, narrow, sandy beach which the diagram shows to be in a very healthy state of net accretion. However, short term envelope changes are also large here and a prominent erosion scarp was evident at the east end of this beach. Why this mirror-image pattern of scour should occur on two adjacent beaches having different exposures and orientations is not obvious, but it points to longshore variations in wave attack and thus indicates that these two beaches are among the more active surveyed.

Figures 21 and 22 show a pair of profiles re-located at Trig B north of South Arm on the main body of the lake. Both pegs and tags were intact so that there is no confusion as to correlation with Irwin's data. However, considerable difficulties were encountered in relating the 1973

and 1988 surveys to Pickrill's (1976) data. For this reason the short term envelope positions and volumes shown in these two diagrams should not be relied upon. As is evident from the longer term data the beaches forming this depositional foreland are extremely well nourished. On the east side the shoreline has prograded up to 5 metres and the growth on the west side is almost comparable. There are no signs of backshore erosion.

En route to Trig B a search was made for sites at Garden Point but none were re-located. The sandy beaches here displayed signs of slight to moderate backshore erosion.

At Deadman's Point in the vicinity of the Glow worm Caves Profile 51 was found and resurveyed. The site is at the more exposed, updrift end of the beach system and comprised mainly coarse cobbles and pebbles on the foreshore. These deposits had a lag character and the profile was flattened to a form consistent with erosion. As can be seen from Figure 23 substantial erosion has occurred at the site. The short term envelope was also erosional. On the backshore there has been appreciable erosion into vegetation.

From Deadman's Point the lake was crossed in difficult conditions to the northern portions of Patience Bay where both landings and surveys were complicated by strong wave action. Profile 58 was relocated but could not be resurveyed owing to inability to safely beach the boat.

Figure 24 shows Profile 52 nearer to the head of Patience Bay where the shore is somewhat more sheltered. The beach is broad and comprised of gravel and coarse sand. The diagram shows that moderate accretion has occured and there were no signs of backshore accretion or erosion. This site conforms to Pickrill's characterisation of profiles through which there is abundant longshore transport in predominantly one direction. The shore is very active but there is little change in the envelope.

Figure 25 shows the final profile relocated and resurveyed at site 53 closer to the head of Patience Bay. The diagram shows that this site is erosional in both the short and the longer terms. This is because it occurs at the updrift end of the beach system with respect to strong waves generated in southerly winds. In northwesterly winds this part of the lakeshore is somewhat sheltered from the largest waves.

From site 53 the remainder of the shore in Patience Bay was inspected as far as Lagoon Point to close the traverse of the southern part of the lake. As described before these beaches are subject to transport west toward Lagoon Point and are well nourished.

6.2 Rates of Beach Profile Change

As for the data from Lake Manapouri the available data for Lake Te Anau have been tabulated and expressed as rates of change in both horizontal shoreline positions and foreshore volumes. Also, the various profie designations and tag numbers have been collated.

Table 3 shows that for Lake Te Anau, as for Lake Manapouri, both erosion and accretion are occurring. It is also evident from the descriptions of the sites that once again even sites in longer term accretion are vulnerable to backshore erosion under high energy waves occurring at higher lake levels.

The table also supports a general observation made earlier from the work of Pickrill (1985) that beach changes are generally greater on Lake Te Anau than they are on Lake Manapouri. There are too few data to be confident and sufficient correlation uncertainties that it is not clear whether short term envelope changes are as good a guide to longer term behaviour on Lake Te Anau as they are on Lake Manapouri.

Table 4 presents the information on rates of change. From this it can be seen that erosional encroachment at the pegs (backshore) ranges from an average of -3 cm/year up to -26 cm/year (at the updrift end of

TABLE 3. Lake Te Anau - Beach Volume Change above 200.75m approx.

	A	B	C	D	E	F	G
1	Profile	Irwin Tag	Irwin	Pickrill	Volume change	Envelope change	Profile form change
2	Location	Numbers	Profile	Profile	-full period	74/75	
3			Number	Number	73/74 to 1988	(Pickrill 1976)	
4					(m3/m)	(m3/m/year)	
5							
6	Garnet Bay - east	92	7	8	3.578	-0.16	Parallel accretion + berm
7	Garnet Bay - west	93	8	9	2.382	0.08	Upper profile accretion
8							
9	Mark Point	89	4	12	10.275	1.43	Strong upper profile accretion
10							
11	Trig B - east	88	3	15?	33.663	-1.17?	Strong accretion to upper berms
12	Trig B - west	87	2	16?	20.183	0.66?	Strong accretion, whole profile
13							
14	Deadmans Point	86	1	20	-17.385	-0.89	Upper accretion, lower erosion
15							
16	N. Patience Bay	20	52	18	3.439	0.31	Upper profile accretion
17	N. Patience Bay	21	53	19	-9.278	-0.98	Upper profile erosion
18							
19	Notes						
20	(i) ? - uncertainty as to the						
21	location of Pickrill's profile						
22	(ii) positive values						
23	indicate accretion						
24	(iii) negative values						
25	indicate erosion						

TABLE 4. Lake Te Anau - Rates of Beach Change 1973/74 to 1988

	A	B	C	D	E	F
1	Profile	Accretion/	Average rate of	Av. rate of	% faster or	Notes
2	Location	Erosion at peg	accretion or erosion	Volume change	slower than	
3		-full period	-full period	-full period	envelope	
4		(m)	(m/year)	(m3/m/year)	74/75	
5						
6	Garnet Bay - east	-1.5	-0.1	0.24	-	Change from er. to acc.
7	Garnet Bay - west	-0.5	-0.03	0.16	203	Stronger accretion
8						
9	Mark Point	Marked accretion	-	0.7	48.9	Continued accretion
10						
11	Trig B - east	Marked accretion	-	2.29	-?	Change from er. to acc.
12	Trig B - west	Marked accretion		1.38	2.08?	Very strong accretion
13						
14	Deadmans Point	-2.25	-0.15	-1.18	-133	Faster erosion
15						
16	N. Patience Bay	-3.75	-0.26	0.23	75.6	Slower accretion
17	N. Patience Bay	-1.5	-0.1	-0.63	-64.3	Slower erosion
18						
19	Notes					
20	(i) positive values					
21	indicate accretion					
22	(ii) negative values					
23	indicate erosion					

Patience Bay). The overall average rate is -12.8 cm/year, a value that is closely comparable to that for Lake Manapouri.

Beach volumes are increasing at moderate to rapid rates for all sites surveyed except for two at the updrift (erosional) feeder ends of beaches. When expressed as percentages of the short term envelope values the longer term net changes on Lake Te Anau display a smaller range of values and rather more consistency than was the case for Lake Manapouri. Since the highest relative changes occur for accreting beaches there is little concern for overall beach health except in respect of the backshore encroachment that occurs at high lake levels.

It is therefore concluded that beaches are both better adjusted to and better able to respond to changes of lake level regime on Lake Te Anau than they are on Lake Manapouri. Excepted from this is the Te Anau Township foreshore between Lagoon Point and Steamer Beach where a host of particular local modifications have occurred in response to use of the backshores and foreshores.

7. DISCUSSION

The results of the resurveys show both clear differences in beach behaviour over almost 15 years for the two lakes and some marked similarities, especially in respect of backshore erosion. As well, a number of important processes and patterns of beach change identified by Pickrill from shorter term studies and used as a basis for predicting longer term behaviour have been confirmed. Pickrill's findings were used as input to the process of formulating the operating lake level guidelines, particularly in respect of the low operating range.

Given that there is no available knowledge about the trends of shoreline behaviour on either lake under natural conditions, and a similar absence of data as to trends and corresponding shoreline adjustment times

that were probably initiated during the construction phases of the hydro-electric power scheme, it is impossible to quantify changes of beach behaviour that may have been initiated under the chosen operating regimes. However, the beaches of Lake Manapouri display generally accelerated and manifestly disequilibrium patterns of behaviour in respect of both beach erosion and accretion. In contrast, the beaches of lake Te Anau display a more pronounced tendency toward accretion and a generally closer approximation to equilibrium status when this is measurd as the relationship between short term change and longer term trends. In this context an equilibrium beach is one that displays some characteristic magnitude of beach envelope change in response to changing wave and water level conditions in the short term and these fluctuations occur about either a constant shoreline position or one that changes at only slow rates. Pickrill demonstrated that gross volumetric changes in the beaches were positively correlated with lake level range so that more extensive reworking of beaches occurs under greater ranges of level.

It appears that fluctuations of lake level have had a greater influence, particularly on erosion around Lake Manapouri than they have on Lake Te Anau. Since no analyses of lake levels have been carried out for this investigation it is unknown to what extent this finding reflects differences in water level patterns on the two lakes and/or sediment availabilities at the beaches.

Concerning similarities of bahaviour it is apparent that greatest beach erosion occurs at the updrift ends of beaches on both lakes. Erosion is also more prevalent on steep beaches along the southwestern shores and arms of both lakes. This is expected in light of the processes demonstrated by Pickrill and also in view of the fact that these areas are downwind, and downfetch for the dominant wave generating winds on both lakes. The combinations of small sediment supply, steep shore gradients and high

energy make for rapidly changing and readily denuded beaches. On Lake Manapouri some of these beaches (eg: Bullings and Lookout) have been almost totally removed. There is nothing that can be done to restore these beaches short of artificial nourishment and little that can be done to conserve what remains of them.

Boatwake is still an important influence on steep beaches close to the sailing lines on southern Lake Manapouri.

A surprising degree of uniformity has been demonstrated between backshore erosion rates on the two lakes. It is a major finding of the investigation that significant erosion that is widespread over both generally accreting and generally eroding beaches on both lakes has resulted from episodes of high lake levels.

Again, since no analyses of lake levels were carried out for this investigation the numbers, durations, elevations and recurrence intervals of high lake levels are unknown at the time of writing. It seems that several such events have occurred in the almost 15 years covered by the beach surveys and one event is believed to have carried a 100 year return period, but whatever the distribution of extreme events they have clearly had a significant and widespread effect on the shoreline systems.

In Geomorphology there are well known relationships between the magnitudes and the frequencies of occurrence of significant landforming processes so that the time distribution of events of varying sizes is a major influence on the character and erosional status of the resulting landforms. Here it is pertinent again to draw attention to the relationship between range of water levels and the volumes of beach sediment involved in reworking for the two lakes.

Rare, low frequency, high magnitude events commonly produce substantial changes in landforms and at high rates of change. The effects of these events tend to be long-lived and on beaches the nature of the

response is usually erosional. In contrast, more frequently occuring, lower magnitude events may effect by far the greatest portion of the total work represented by change in a beach (both erosion and accretion). The effects of these events are often in evidence but, may not leave such lasting impacts. It is for this reason that the present investigation focussed on the relationships between the short term beach change envelopes (more frequent lower magnitude events) and the longer term trends in change (the cumulative effects of the work done on the beach), especially landward displacement of the envelopes (resulting from net sediment loss and rare, high magnitude events).

In this context the low operating range of the lake level guidelines can be seen as a management technique to guard against 'combing down' of beach sediments and their net loss to deeper water (ie: envelope loss minimisation). The aim is thus to control the more frequent, lower magnitude events and by constricting the range of levels at the lower end to minimise the volume of beach sediment involved in quasi-constant reworking. No fault has been found with that logic here and no evidence has emerged that would suggest that this aim should be modified. However, nor is there merit in maintaining the lake at low levels for the sake of compliance with the guidelines when circumstances appear to dictate this. Any reduction in lake level range is a positive action in respect of conserving beach sediment volumes.

At the high operating range end of the scales the situation is more problematic. At least two views of the low frequency, high magnitude events that have been shown here to engender widespread backshore erosion are possible. First, it might be considered whether there are implications for the high operating range. In that case once again the management aim should be to reduce levels at acceptable rates of drawdown. In contrast to this, a second view would be that by their

nature low frequency, high magnitude events are poorly predictable so that they cannot be well anticipated in a lake level management scheme. In this view not much more can be done to minimise the erosive effects of an unfortunate occurrence than to reduce lake levels at the fastest acceptable rate. Erosion of the backshores and downcombing of the beaches to lower, more frequently worked levels will be seen to be inevitable from time to time.

Finally in this discussion it is noted that if the eroding beaches were sectioned by boring to determine their remaining sediment volumes it would be possible to calculate acceptable levels of estimates for their remaining 'lifetimes'.

8. CONCLUSIONS

1). Erosion and accretion have occurred on the beaches of both lakes whether these changes are measured as horizontal movements of shoreline contours or as net beach volume changes over almost 15 years since 1973.

2). Beaches on Lake Manapouri are generally changing more rapidly and display stronger disequilibrium characteristics than the beaches on Lake Te Anau. Several important recreational beaches on Lake Te Anau are in robust physical condition and are actively growing.

3). Erosion is most intense at the updrift ends of beaches subject to strong longshore drift of sediment on both lakes. It is also intense on steep, poorly nourished beaches with narrow nearshore shelves sited along the downwind, higher energy southwestern shores and arms of both lakes.

4). A major finding is the widespread occurrence on both lakes of erosional encroachment of the highest levels of beaches into backshore soils and vegetation communities. The average rates of retreat since

1973 are remarkably similar for both lakes at -12 to -13 cm/year. Encroachment has occurred on beaches that are both accreting in the longer term (not an expected result) as well as those that are erosional (an expected result). This shoreline retreat is a function of high energy waves at high lake levels and it may carry significance for the high operating range of the lakes or it may be determined to be the consequence of rare, poorly predictable events that cannot be well anticipated in ongoing lake level management.

5). The investigation has borne out for the longer term many of Pickrill's (1976) conclusions concerning the causes and patterns of beach changes derived from shorter term monitoring and used as input to formulation of the operating guidelines, particularly for the low operating ranges. The positive link between lake level range and the volume of beach sediment involved in active reworking is cardinal among these.

6). Boat wakes are still a significant energy element in shoreline processes for sites in closer proximity to common sailing lines, especially where the beaches are steep and border deep water.

7). The investigation has clearly shown the wisdom and foresight of early establishment of relocatable monitoring sites and the value of the early research that was undertaken. The present investigation would have been impossible without this capability but it has also been curtailed in scope and the overall representativeness of the results (especially for Lake Te Anau) by deterioration of the marker network. At many sites 1.5 metre steel pegs driven into the beach have been removed altogether thereby terminating the data series at that site. At other sites the identifying numbered metal tags have been removed thereby presenting problems in correlating some data sets. Consideration should be given to refurbishing the network and to

restoring some sites particularly for beaches having the highest recreational and ecological values.

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