

RESERVOIR SEDIMENTATION MONASAVU HYDRO LAKE

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SUMMARY

Six profiles first surveyed in 1991 were resurveyed to assess reservoir sedimentation processes and likely impacts on the lake's function in generating hydroelectricity. In addition to this a second bathymetric survey to complement the 1993 bathymetry survey for the Department of Energy was also completed. Data interpretation generated bathymetry models to assess change in the lake bathymetry with respect to reservoir and river sediment processes. During the survey period the lake remained below the 745 meter spill level.

Reservoir sedimentation is a very complicated and difficult problem, owing to the number of parameters involving both reservoir and river sedimentation processes. The survey found that slope failure appears to be the primary source of sedimentation and change in the lake morphology. Based on the completed work, indicative figures for sedimentation rates have been deduced to range from 0.22 m yr^{-1} to 0.57 m yr^{-1} or an average of 0.37 m yr^{-1} . Based on these estimates, sedimentation levels may reach the low pressure intake level of 701 m within eight years.

Volume calculations at the minimum operating level computed volume for the 1998 model to within 1% of the figure derived from the existing equation. However, at near full supply level, computed volume was within 10 %, reflecting the problem in delineating the upper boundary of the lake, and mapping in areas with restricted access such as intervening tributary arms and embayments which appear to significantly affect computational accuracy. This indicates a need for aerial photography with good ground control for image rectification.

All data relating to the three surveys is available digitally and can be transferred into a GIS format for developing an integrated information system for reservoir management and monitoring.

As a number of hazards associated with slope failure have been identified, further work is required to fully assess their potential impacts on the function of the lake for generating hydro-electricity. This is highlighted in the conclusions and recommendations.

The major conclusions of the study are:

- Slope failure appears to be the primary source of the sedimentation in the lake.
- Significant changes occurred in profiles 1 through 4 due to slope failure.

- No evidence for sedimentation was found in profiles 5 and 6.
- Lack of sediment appearing in profiles 5 and 6 suggested that the sediment seen in the other profiles is locally derived and principally a result of slope failure.
- That slope failure is most apparent on the right flank of the lake between profile locations 1 and 3.
- That slope failure varies considerably in size from small features, no more than a couple of metres wide, to slide scars over 100 m wide. The larger slides appear to have resulted in lake shoreline retreat in the order of 10 m to 30 m.
- The potential for large blocks to be displaced and fall into the lake as a result of slope failure cannot be fully realised with the existing data on the local geology.
- Changes in the order 10-20 m have occurred in the lake bathymetry as a result of slope failure.
- Sedimentation to date has not reached levels which could impact on the live storage volume.
- The lack of baseline data in the vicinity of the low-pressure tunnel intake to assess change is a concern.
- The lack of detailed geology maps for the lake reservoir area and catchment area to better assess the impact of slope failure is a concern.

The major recommendations of the study are:

1. Aerial photography with good ground control for image rectification to delineate the full supply level boundary and areas of slope failure should be completed.
2. Detailed geological mapping to assess the full impact of slope failure and the risk due to large boulders being displaced and generating a wave climate that may affect dam structure integrity, should be conducted.
3. All ground control points to be relocated with respect to the Fiji Map Grid.
4. Missing ground control points for profiles 1 and 3 to be relocated.
5. A new profile be inserted to monitor change on the southern side of profile 2.

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- The potential for large blocks to be displaced and fall into the lake as a result of slope failure cannot be fully realised with the existing data on the local geology.
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4. Missing ground control points for profiles 1 and 3 to be relocated.
5. A new profile be inserted to monitor change on the southern side of profile 2.

6. To measure the current regime associated with the low pressure intake tunnel to assess the sediment transport regime. This is best done using an acoustic doppler current profiling technology to measure current fields.
7. Consideration be given to the use of swath mapping techniques to define lake-bed morphology and conditions, particularly for areas below the dam minimum operating level prior to 2003. Swath mapping can also be used to monitor and map the conditions of the dam face and low-pressure tunnel intake area.
8. Consider implementing a GIS such as MAPINFO for an intergrated reservoir management and monitoring system, incorporating digital datasets from the 1991, 1993 and 1998 surveys.
9. Future consideration be given to numerical modelling to assess hazard potentials associated with sedimentation, slope failure, wave setup due to wind and boulder impact.

OBJECTIVES

The terms of reference or objectives for this survey are:

- to undertake a bathymetric survey based on the datum of the 1993 survey;
- to estimate changes due to siltation (if any); and
- prepare models based on bathymetry measurements

INTRODUCTION

The Monasavu Dam is one of Fiji's more important public assets. In 1991 a geophysical survey was carried out between 7 and 9 May at the Monasavu Reservoir (Smith 1991) to establish six baseline profiles to monitor possible siltation effects resulting from agriculture, logging activities and landslips within the catchment area. A second survey commissioned by the Energy Department of the Fiji Government was carried out between 16 and 21 of March 1993 to produce a detailed model (Smith and Saphore 1993) of the reservoir for an accurate reservoir height-volume relationship that could be used for energy planning. In addition to a resurvey of the six profiles, a second bathymetry data set was collected. An added result to having the two bathymetry datasets from the 1993 and 1998 surveys, is that

information on profile changes in the lake-bed morphology between profiles can be interpolated from the existing model.

PERSONNEL INVOLVED

- Peni Musunamasi Electronics Technician (SOPAC)
- Simon Young Electronics Engineer (SOPAC)
- Edward Saphore Consultant (ISLANDTRONICS)
- Robert Smith Marine Geologist (SOPAC)
- Graeme Frost Technical Support Assistant (SOPAC)

EQUIPMENT & METHOD

Navigation Control

Navigation control utilised the GPS system using a Del Norte 1009+ Differential GPS. Position was logged with a Del Norte 1009+ in Latitude and Longitude format with respect to the WGS84 datum. Bathymetry lines were surveyed at 50 m intervals along the length of the lake. A 6 second fix period was used to log location and associated depth to lake bed. The six baseline profiles originally established by Westfield Surveyors were run across the width of the reservoir between survey markers for the profiles 1 through 6. In contrast to the 1991 survey of the profiles no positioning control was used, but the 1998 traverse position was logged by real-time differential GPS. An important point to note for navigation is relating WGS 84 position data with the 1993 data which is based on a Cassini projection using the Clarke 1880 spheroid as the geodetic datum on which the original base maps for the Monasavu area are based .

In the 1993 bathymetric study, lake navigation was accomplished with the use of range range equipment “*Delnorte Trisponder*” from two known shore control stations calculating coordinates of the position by means of triangulation. The shore-based control was based on the Cassini Soldner system, hence position on the water was therefore calculated based on the same system. The 1998 resurvey of the lake used real-time DGPS for positioning control. A reference station based on WGS84 had to be established for the real-time DGPS

to function. This is not a problem in itself, but comparisons between the two data sets when projection parameters differ was not a straightforward exercise. As an objective of the study was to compare the two data sets, the problems transcribing data from one datum to another had to be overcome.

Presently, conversion of Fiji Cassini Soldner coordinates to Fiji Map Grid (FMG) is difficult particularly where little to no geodetic control work has been completed for converting to FMG in remote areas such as Monasavu. A number of options were looked at, including repeating the survey along similar lines using range range based on the same control or converting all existing data to Fiji Map Grid coordinates. Using DGPS was the preferred method for control both for time constraints and ease of operation knowing that at least two programs were currently available that could will allow for conversion from Cassini Soldner to FMG not with standing filed verification of the accuracy of conversion. The first is available from the Fiji Forestry Department written by Mike Poidevin. A second is commercially available software from Bluemarble called Geographic Calculator. The version used for conversion was Ver 3.01. Within the Geographic Calculator library of systems and datums available there is a “*Viti Levu 1916*“. This datum is based on Clarke 1880 spheroid. In setting up a customised system for conversion such as the Cassini Soldner for Viti Levu to FMG the values are as follows:

- False Northing : 141621.0010 m
- False Easting : 109434.4700
- Central Meridian : 178 0 0 East
- Latitude of True Scale : 18 0 0 South

Using the Geographic Calculator it is a single step converting Cassini Soldner coordinates to Fiji Map Grid coordinates. However in using the Forestry program “*Fijitrans*” it was necessary to convert the grid coordinates to Clarke 1880 geographicals. This was done independent of the Geographic Calculator using hydrographic software to remove any potential bias or introduce additional error in the calculation. Results of computations from the Geographic Calculator and the Forestry program are tabulated below.

From Geographic Calculator			From Fijitran		Difference in Co-ordinate values		
Station	Easting	Northing	Easting	Northing	Delta-East	Delta Northing	
mom7	1925462.35	3916120.97	1925463	3916120	-0.87	1.32	
mom8	1926012.21	3916153.00	1926013	3916152	-0.86	1.47	

L1	1925985.88	3917227.51	1925987	3917226	-1.11	1.62
R1	1925644.00	3916736.21	1925645	3916735	-1.09	1.66
RS 35	1924382.37	3918160.44	1924383	3918159	-1.04	1.65
RS15	1924069.94	3917346.62	1924071	3917345	-0.97	1.63
L2	1924742.20	3917968.49	1924743	3917967	-0.97	1.65

To verify the accuracy of the computed conversions, the Del Norte GPS was used in ESTABLISH POSITION mode was located at the dam monument *MOM 7* for a period of 24 hours. The measured WGS 84 geographical co-ordinates were converted to FMG, and the result was 2.7 metres difference on the easting co-ordinate and 5.4 metres on the Northing co-ordinate, compared to the original Cassini co-ordinated computed to FMG using the same software. Noting the difference, rather than use the *establish position* co-ordinates for the reference station control for consistency in conversions for all data sets, all the reference station co-ordinates were computed using the Geographic Calculator. However all navigation data for the 1998 survey were logged in WGS 84 geographical and later converted to FMG for this study. At a later date more accurate parameters for the Cassini to WGS 84 can be derived, so the data sets can be recalculated. The GPS reference locations computed and used for line control are listed in Appendix 1.

Bathymetry

A Echotrac Mk1 precision echo sounder was used for profiling the lake bed. The resulting profiles were recorded as hardcopy by the Echotrac and digitally by the Del Norte 1009+ GPS unit. Bathymetry readings are synchronised to the Del Norte 1009+ clock. The calibration of the sounder was accomplished using an ODEM digibar check that averaged speed of sound measurements taken with the probe placed near the surface and at calibrated intervals at depth. An average velocity of 1493 m/sec was used throughout the survey. All bathymetric data collected are to be reduced to the Monasavu datum at 745.0 m above mean sea level. Dam water levels were recorded daily and these are shown in Table 1

3.5 kHz Seismic Profiles

Seismic profiles were taken at six locations using a Datasonics 3.5 kHz acoustic profiling system with a floating transducer array that was towed along the starboard side of the survey boat. EPC 650 and EPC 4800 line scan recorders recorded the seismic data on hard copy. Bottom and possible sub-bottom information, sediment thickness, lake-bed texture i.e. (hard versus soft terrain) can be interpreted. The profiling unit consisted of an array of 4

transducers in parallel mounted on a small catamaran and towed by a vessel. A transceiver unit transmits a 3.5 kHz signal, which is interpreted by a receiver and graphically annotated on an EPC 1650 graphic recorder. Typical minimum bed thickness resolvable by this unit, depending on sediment type and pulse width, can be as little as 10 cm. Bathymetry (200 kHz) and 3.5 kHz profile data were obtained simultaneously. Annotation for start of line (SOL) and end of line (EOL) are marked on both records. Reference position fix marks (numbered on profile) annotated during the profile traverse have also been added to each of the profiles to allow for easy cross reference between the two sets of profile data.

Table 1

Date	Water level for lake WRT to Monasavu Datum 745 m
15-4-98	743.27 meters
16-4-98	743.15 meters
17-4-98	743.04 meters
18-4-98	742.96 meters
19-4-98	742.82 meters
20-4-98	742.72 meters
21-4-98	742.60 meters
22-4-98	742.46 meters

Water Samples and Grab Samples

- Two water samples, WS1 and WS2, were taken at location near R2.
- Three grab samples were collected. GS1 was taken in the middle of the R2–L2 channel, GS2 was collected in the channel of R1–L1, and GS3 was obtained from the main dam area. A split of the grab samples was given to FEA.

RESULTS

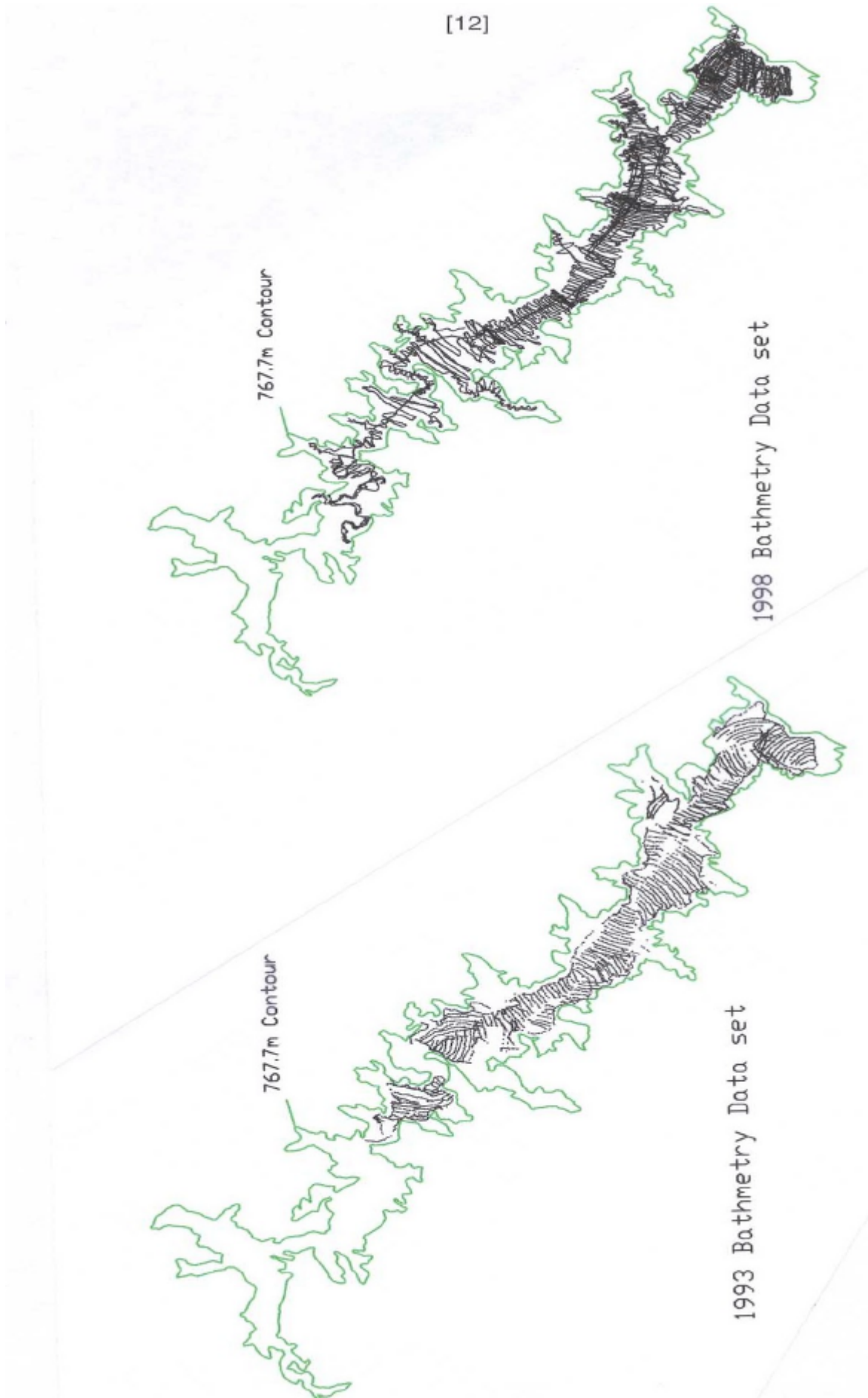
Navigation

Conversion of all data sets from WGS 84 geographical to Easting and Northing values based on the Fiji Map Grid (FMG) were done using Geographic Calculator. Thirteen data sets comprising 14460 data points were post processed. Figure 1 illustrates the track plot of these profiles drawn to scale. Post processing of the bathymetry and navigation data was required to check for erroneous depth and control values. All of the digital data files were saved in directories labelled by the Date on which the data was collected. The original data files were used to create a final DAT file that is saved in the space delimited format of EASTING (FMG) NORTHING (FMG) DEPTH (corrected to 745 m Monasavu Dam datum). Detailed descriptions of the various data files can be found in Digital Data File Listings with Track Plots at Appendix 2.

The base map on which the track data were plotted was digitised from two map sets (references 1, 2) at 1:5000 scale using AutoCAD. The lake at its full service volume would be defined by the 745 m contour. For this work a reservoir boundary (RL 747.7 + 20 m) was digitised from drawing number 1001 prepared by Westfield surveyors. As this data was originally digitised based on the Cassini projection, conversion of the base map to FMG was again accomplished using the Geographic calculator to maintain consistency in all the data sets converted. Figure 1 illustrates the relationship between the reservoir boundary, which has been used as a reference for showing the morphology of the lake, with respect to the final track plots of data collected to date.

Profile Analysis and Interpretation of Change

Of the 12 permanent markers put in place in 1991 for the six profiles, locations all were relocated except for L1 which has since disappeared due to a large landslide. Also under threat to further landslides are L2 and R3 the latter being the more vulnerable. R3 is considered to have a remaining life span of 12 months before it is lost in a landslide.



Changes in the profiles were initially assessed through a visual comparison of the seismic profiles. Accurate overlays of the 1991 and 1998 seismic profiles was not possible due to scale differences, variations in boat speed, and photo-reduction effects. Also the 1991 profiles were completed without precise navigation control, but the 1998 profile transects were located with DGPS/GPS with position Easting, Northing and depth logged every 10 seconds.

Also used to assess change in the lake bed morphology at the four transects were cross section profiles based on 3D models of the lake computed from 1993, and 1998 bathymetry data sets. From these data a number of cross section plots were computed. A transect profile which represents a cross section between the "R and L" control points at each transect and a *vessel track profile* representing the actual path or vessel track plot based on the 1998 seismic and bathymetry profiles taken using DGPS/GPS for position.

In all, thirty-six cross section profiles were computed to assess the changes seen in the seismic sections. Of the six profiles surveyed significant changes were noted only in profiles 1 through 4. Profiles 5, and 6 show no change.

For interpretation and reporting the seismic profiles (both the 1991 and 1993 were photo reduced to A3 paper size scanned and the resultant images imported into AutoCAD. To convert the recorded two-way time to depth, a conversion of 10 msec = 7.45 m was used for a water velocity of 1496 msec⁻¹. Interpretation and analysis of the profiles are dealt with separately in the following section

Profile R1–L1

Figure 2 a, b show the 1991 and 1998 seismic profiles as surveyed from R1 to L1. For both the 1991 and 1998 seismic profiles the data was recorded in a traverse from R1 to L1 at a scale of 100 msec. In comparing the profiles it can be seen in the 1998 profile that the original Nanuku creek bed has infilled with some 2 m plus of sediment. In the 1991 profile, where the original creek bed is, Figure 2b, sediment accumulation is not evident. Between 1993 and 1998 upper slope failure has occurred at R1 resulting in shoreline retreat at lake level taking the R1 marker with it. Below lake level there is also strong supporting evidence for slope failure to have occurred at the 8 msec, 12 msec and 30 msec time levels as shown by the concave inflections in the slope profile. Around 20 msec sediment accumulation seen in the slope profile is also attributed to failure up slope. This sediment is

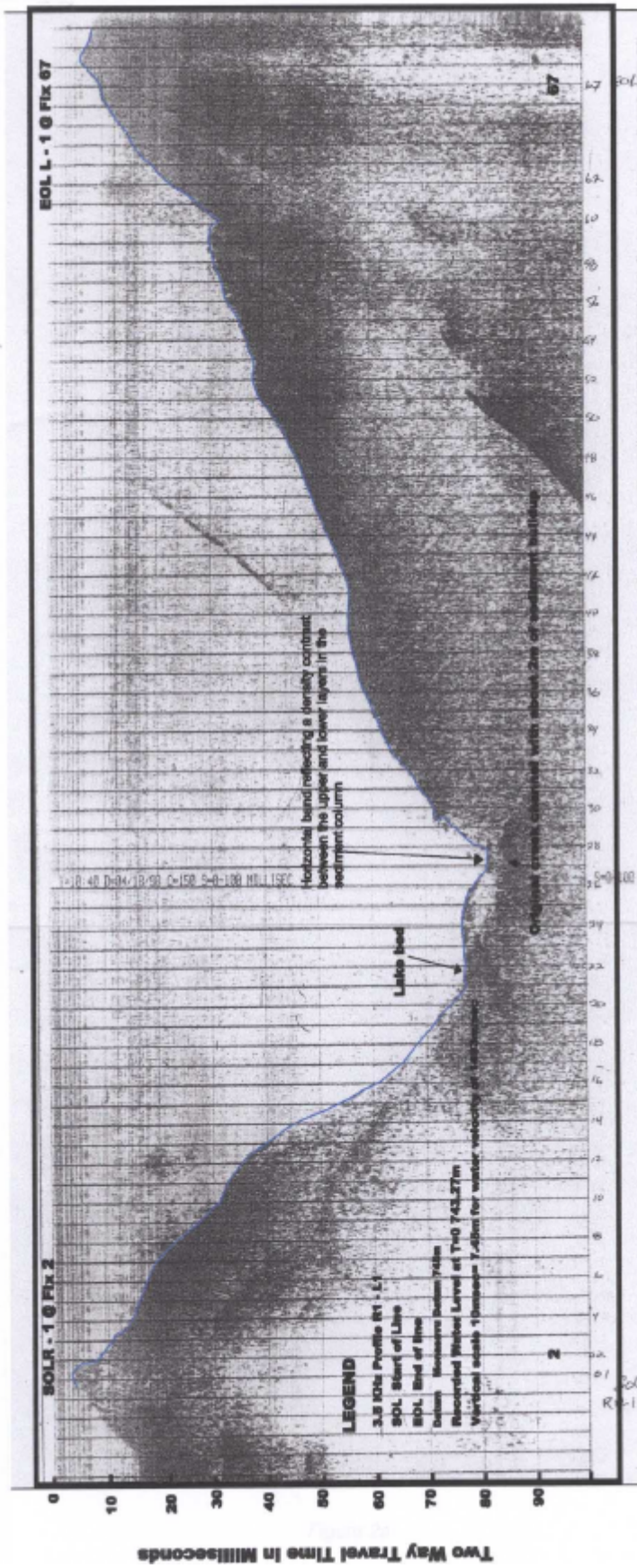


Figure 2a,b: 1991, 1998 seismic profiles as surveyed from R1 to L1

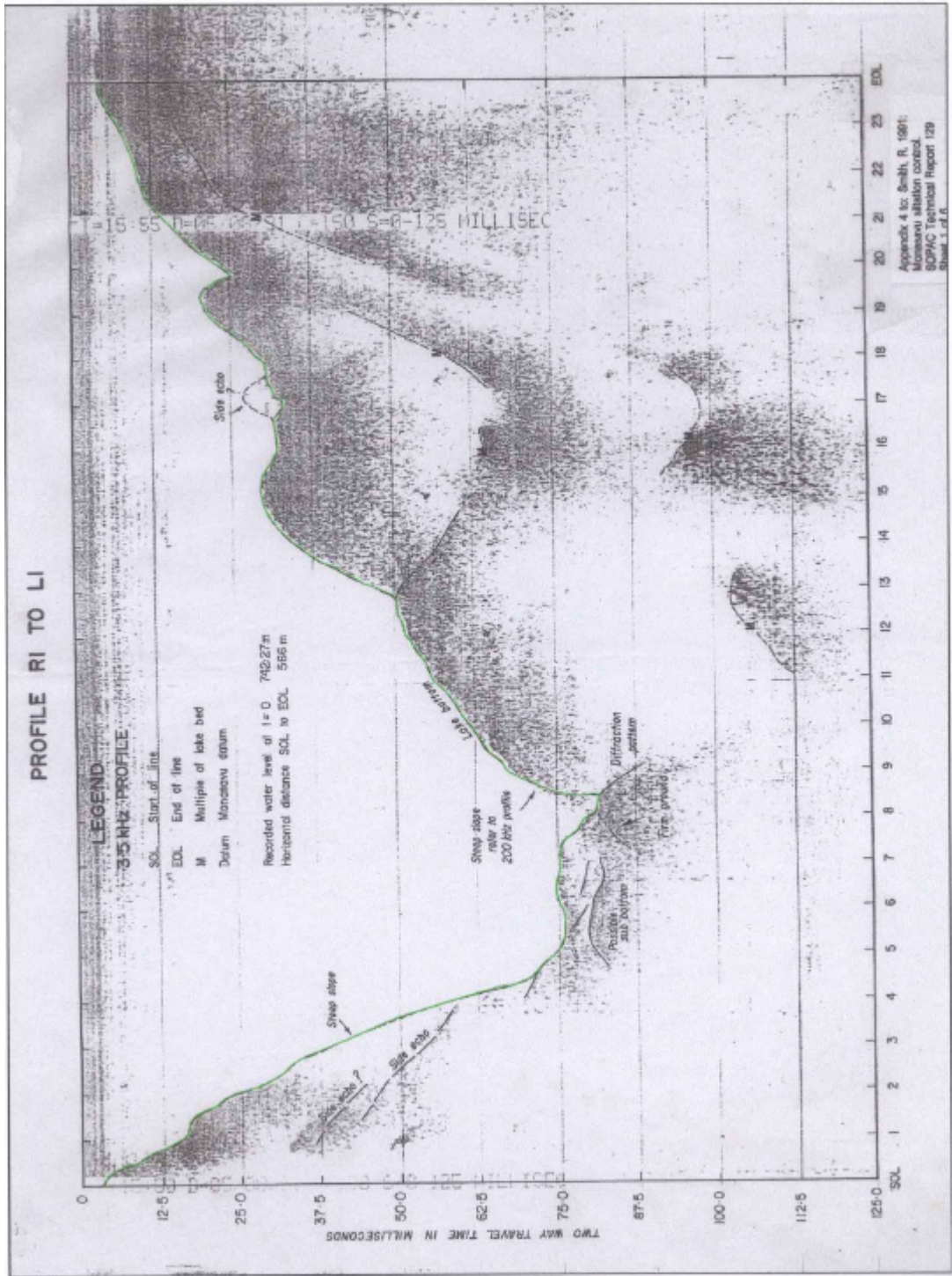


Figure 2b

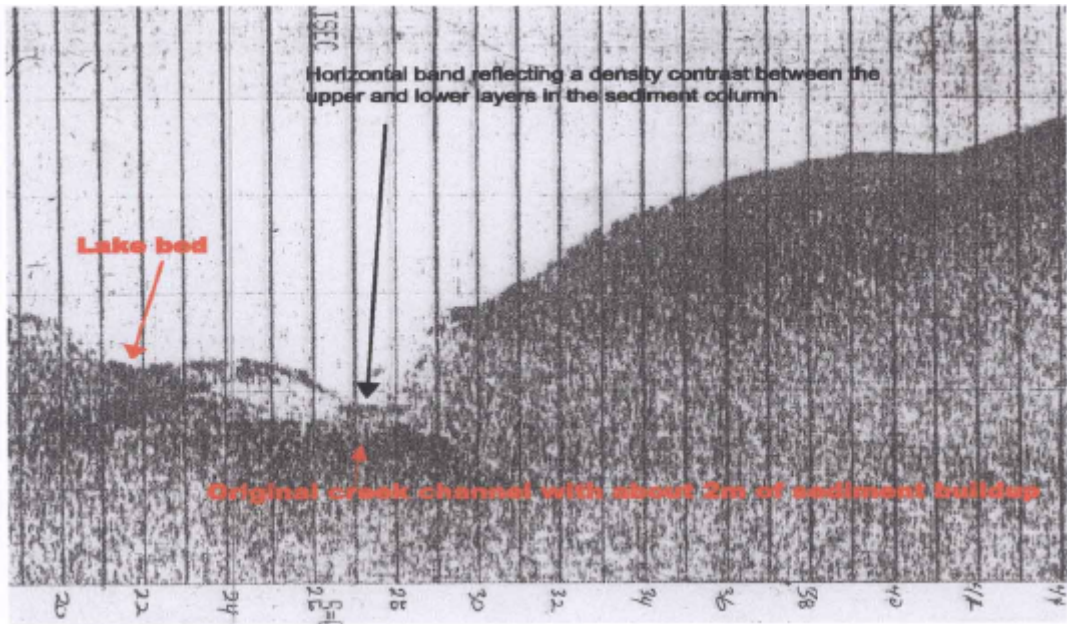


Figure 3. Sediment accumulation in Nanuku creek as seen in seismic profile 1.

quite distinct and can be seen as a horizontal band reflecting a density contrast between the upper and lower layers in the sediment column. This is shown in Figure 3.

Examining the cross section plots computed from the lake bathymetry models, evidence of similar changes can be discerned and are measurable. These are shown in Figure 4 a, b and are computed from the model for the transverse R1 to L1. Three cross section plots are presented.

The red line represents the computed cross section from the 1993 bathymetry data set which is also the control profile in which to assess quantitative changes in the lake-bed profile. The green line represents the computed cross section from the 1998 bathymetry data set with the 3D model computed from DGPS xyz values only. A third line black, also representing the cross section computed from the 1998 bathymetry data set except that the model in which this cross section has been taken includes both DGPS and GPS xyz values. With the GPS position, xyz values are not as accurate as the DGPS xyz values thus the inclusion of them in computing a 3D model of the lake can influence the computed grid resulting in anomalous depth

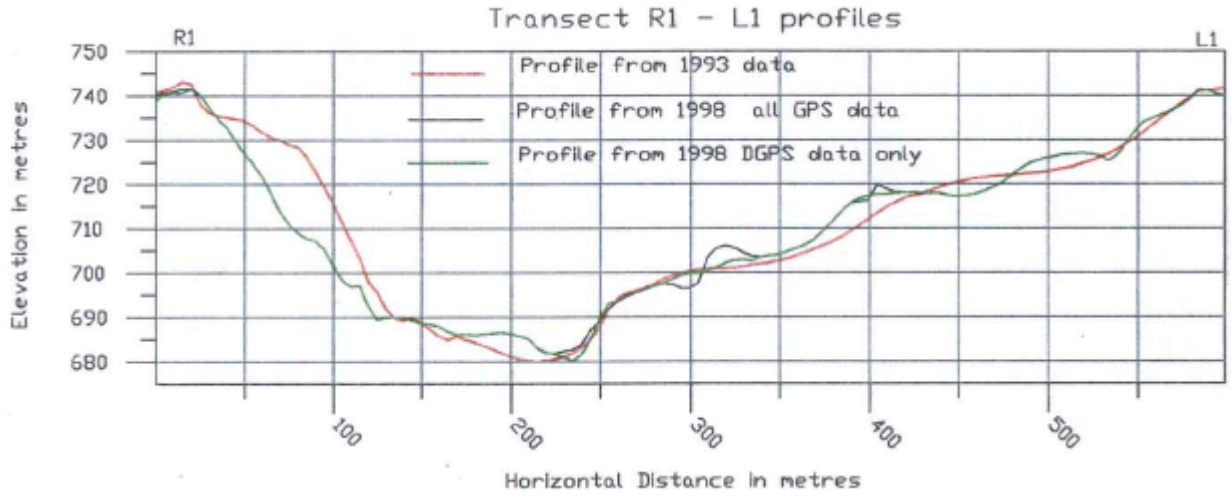


Figure 4 a, b. Computed cross section profiles R1 to L1 from 1993 and 1998 models.

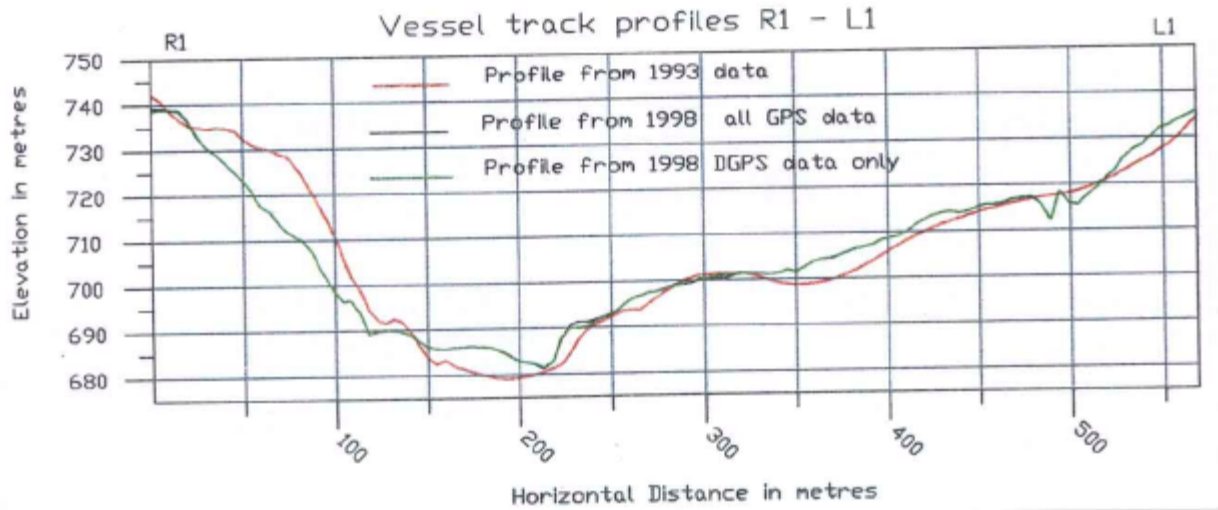


Figure 4 b

representation. Such anomalous results can be seen in the *all data 1998 profile* with the appearance of two small highs at 300 m and 400 m from R1. Change in the cross-section profiles on the red (original profile) and the green cross-section plots are greater at R1. Here it can be seen that a large portion of the left bank has slipped and been deposited at the base of the slope resulting in a 5 m rise in the lake floor.

Figure 4b are cross-section profiles representing the measured vessel position during the traverse R1 to L1. These profiles again show very similar changes. Both cross section profiles confirm the interpretation seen in the seismic section profiles that accumulation of sediment is taking place at the lakebed. From the data it is interpreted that some 2 to 6 metres of deposition has occurred in the old Nanuku creek bed at profile R1–L1.

Profile R2–L2

Figure 5 a, b compares the seismic profiles L2–R2 for 1991 and 1998 respectively. The 1998 profile the data was recorded in a traverse from L2 to R2 at a scale of 100 msec. The 1991 profile was also surveyed from L2–R2 but at a scale of 75 msec.

In comparing the profiles it can be seen in the 1998 traverse that sediment is accumulating in the original Nanuku creek bed. Interpretation of the original creek bed in the 1991 profile has the base of the creek below 75 msec. In the 1998 traverse the profile of the creek bed is no longer distinct, appears broader, and has infilled some 3 to 4 msec (TWTT) representing about 1-2 m of sediment. Again deposition is interpreted to be a result of upper slope failure which is clearly visible at R2. On the R2 side of the 1998 profile, slope infill has also occurred between the 37.5 and 50 msec levels and at the toe of the slope a distinct terrace appears to have formed. From the L2 marker the slope of the lakebed appears to have been modified resulting in a linear slope from the lake top to the bottom. Also noted in the 3.5 kHz records was the presence of gas in the water column that is a result of organic decay. This is apparent in the water column between 10 and 20 msec levels and between 40 and 60 msec on the R2 side of the profile.

For the cross section plots computed from the lake bathymetry models, similar changes are evident and are measurable based on the computed 3D lake models. Figure 6 a, b shows the computed cross section profiles for the vessel track profile and a straight line transect profile from L2 to R2. Three cross section plots are presented for the different data sets.

The red line represents the computed cross section from the 1993 bathymetry data set which is also the control profile from which to assess quantitative changes in the lake-bed profile. The green line represents the computed cross section from the 1998 bathymetry data set with the 3D model computed from DGPS xyz values only. A third line black, also representing the cross section computed from the 1998 bathymetry data set except that the model in which this cross section has been taken includes both DGPS and GPS xyz values. GPS-positioned xyz values are not as accurate as the DGPS xyz values thus the inclusion of these points in computing a 3D model of the lake can influence the computed grid resulting in anomalous depth representation. Changes in the cross-section profiles on the red (original profile) and the green cross-section plots appear to show both erosion, which is due to slope failure and can occur above the profile or below the profile in a lateral sense. Cross-sectional transects would therefore only reflect change along the profile but do not account for changes that have taken place above or below the profile. In either case it is apparent that significant change has occurred in the vicinity of the transects but the geometry of those changes are difficult to interpret without 100 % coverage. With detailed soundings a 3D digital elevation model of the area can be generated to aid interpretation. However with data from the 1998 data set it is possible to generate a preliminary model that reflects the overall morphology of the lake bed at this locality. This is shown in Figure 7 with respect to the Minimum Operating Level (MOL) of 710 m. The interpretation here, shows the lake-bed bathymetry with respect to the MOL of 710 m well illustrates the profile of the original Nanuku creek where it narrows as it meanders around control point R2. Between 690 m and 695 m levels, the channel is only 30 m wide and 15 m below the MOL. A possible implication here is if major slope failure occurred here the existing channel has the potential to at least close off at the 710 m level. Since slope failure was clearly evident at R2 then further slope failure is most probable. During low-water stand an assessment of the geology in this area is recommended to assess the likely impacts of further slope failure here. Failing this, a second monitoring profile should be established at the location shown on Figure 7, to monitor events.

Profile R3–L3

Figure 8 a, b show the seismic profiles R3–L3 for 1991 and 1998 respectively. For the 1998 profile the data was recorded in a traverse from R3 to L3 at a scale of 100 msec. The 1991 profile which was also surveyed from R3–L3 was at the scale 75 msec.

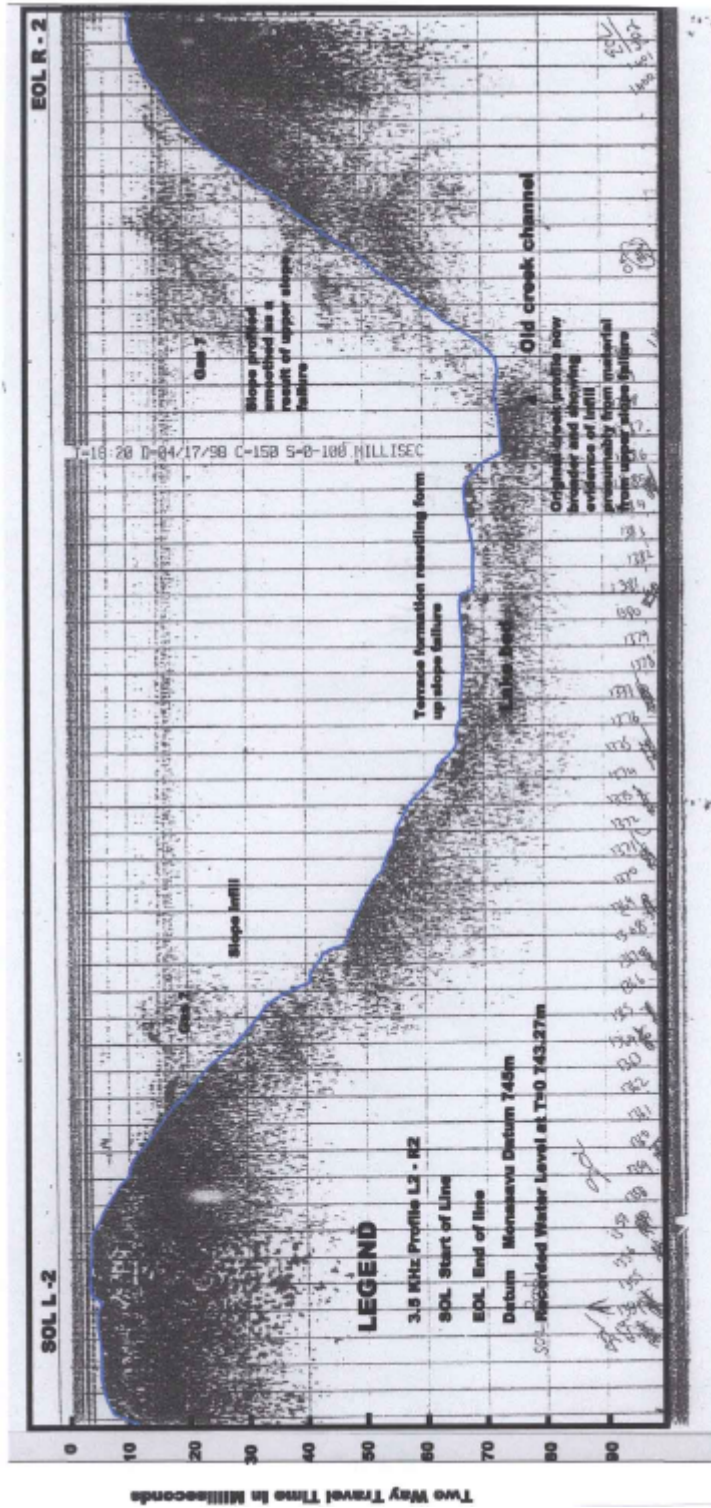


Figure 5a, b.1991, 1998 seismic profiles as surveyed from L2-R2

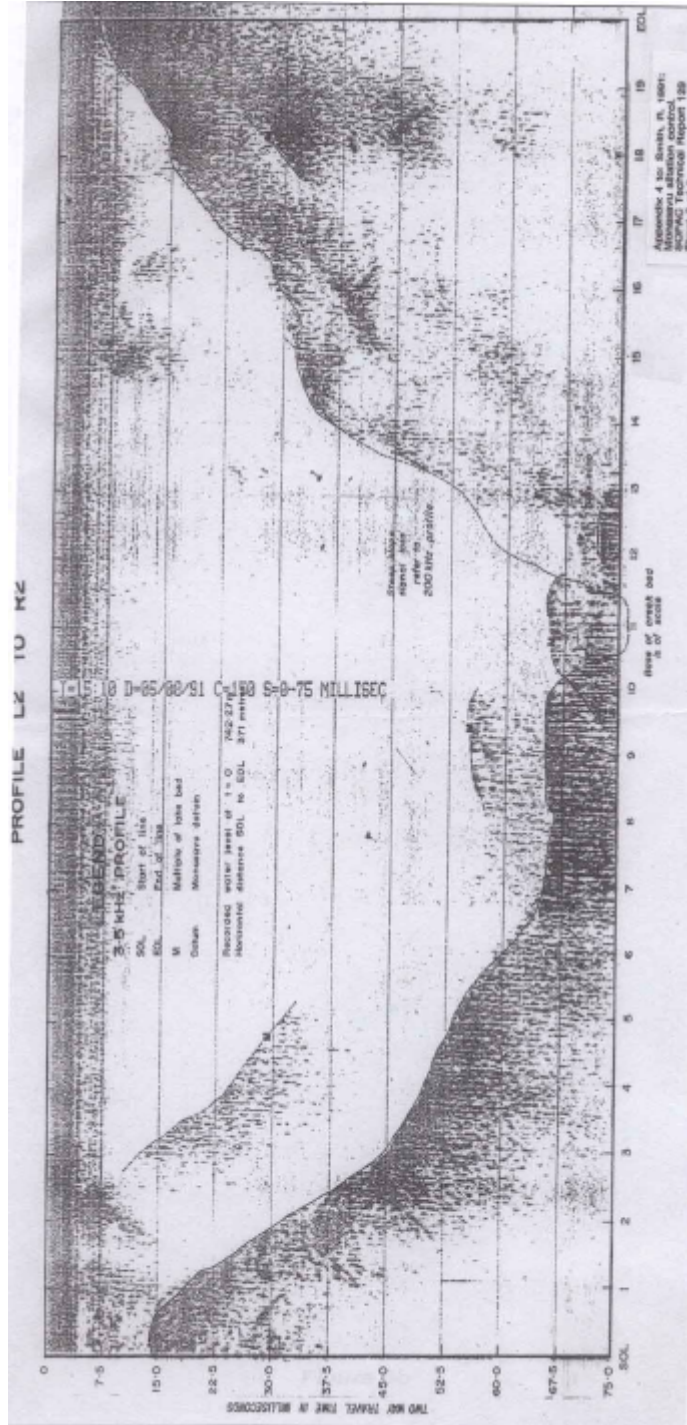


Figure 5b

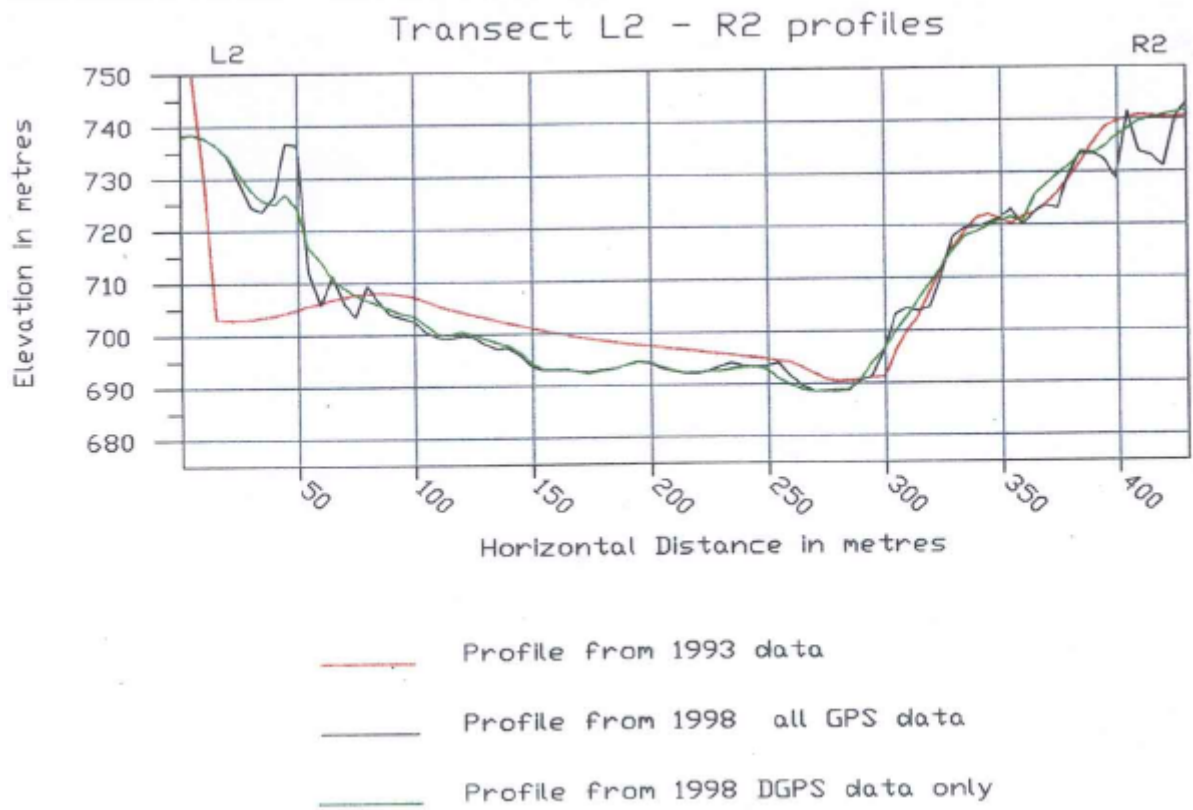


Figure 6a, b. Computed cross section profiles R2 to L2 from 1993 and 1998 models.

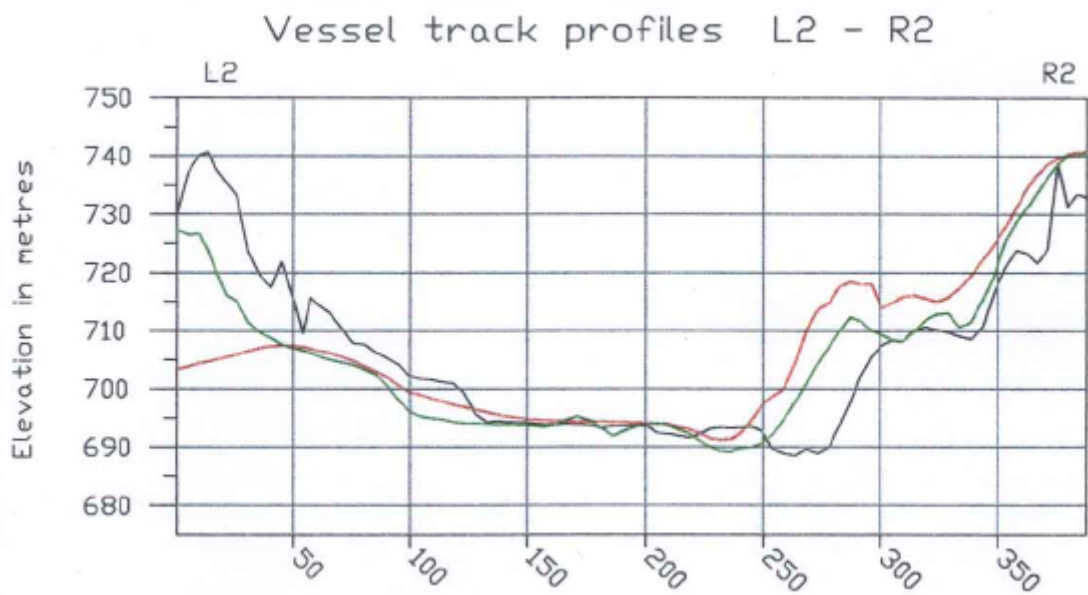


Figure 6b

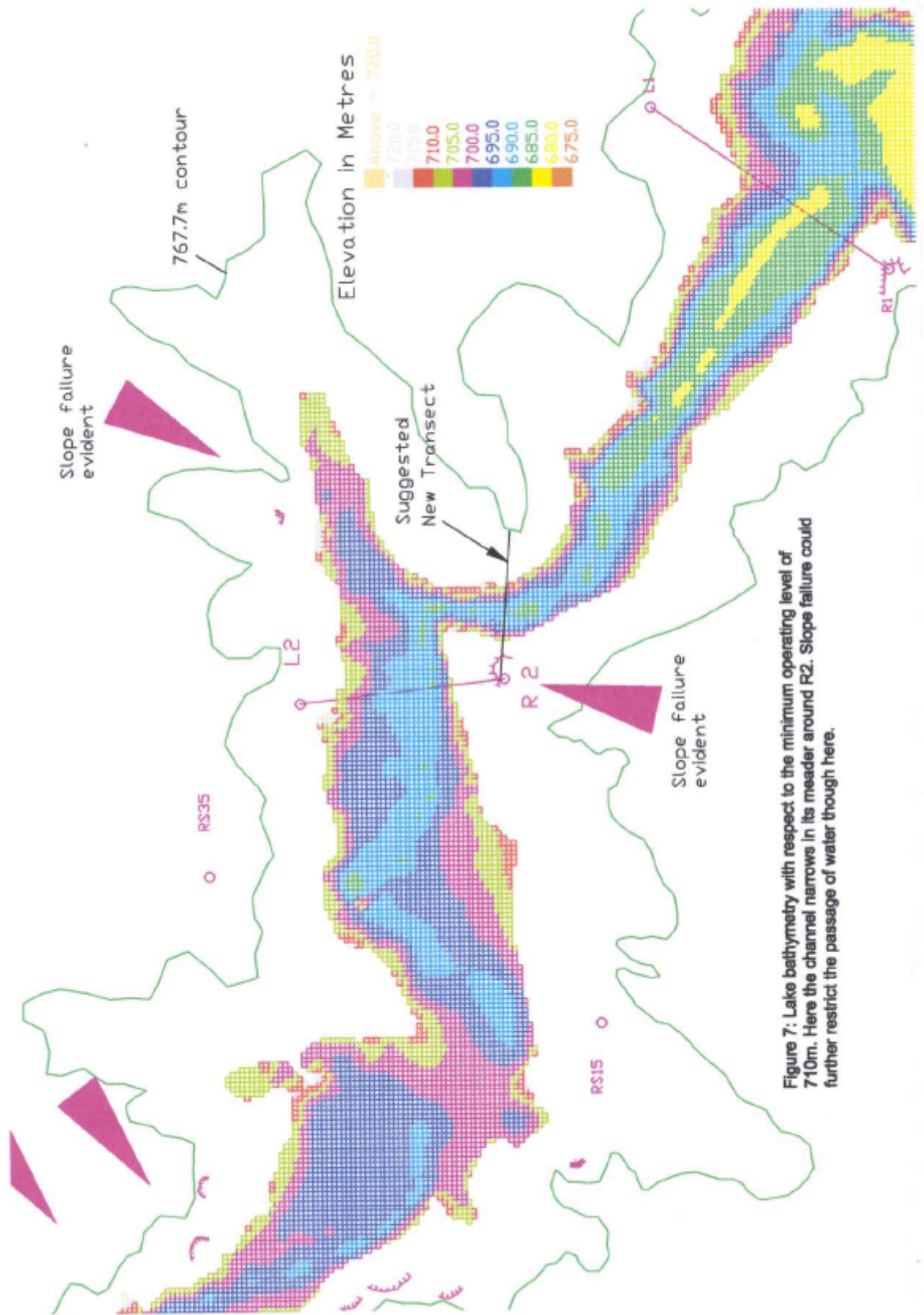


Figure 7: Lake bathymetry with respect to the minimum operating level of 710m. Here the channel narrows in its meander around R2. Slope failure could further restrict the passage of water though here.

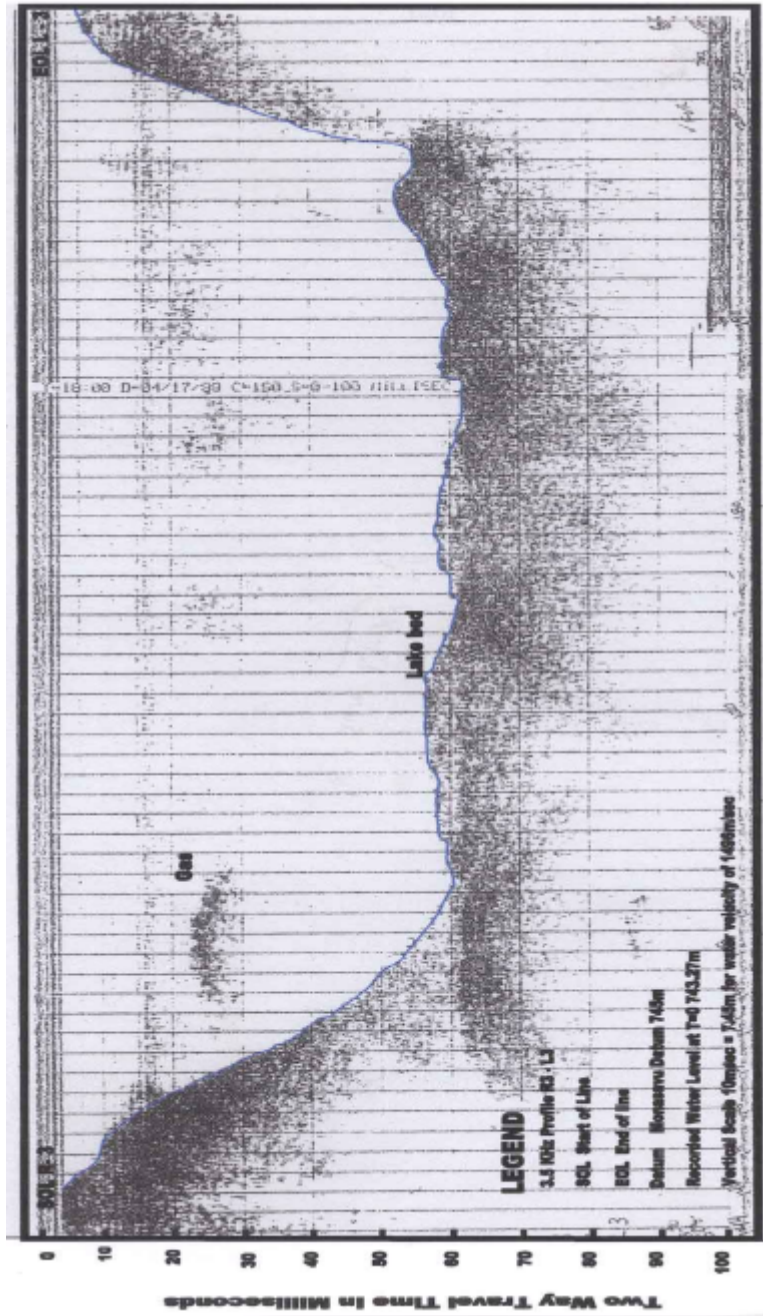


Figure 8b

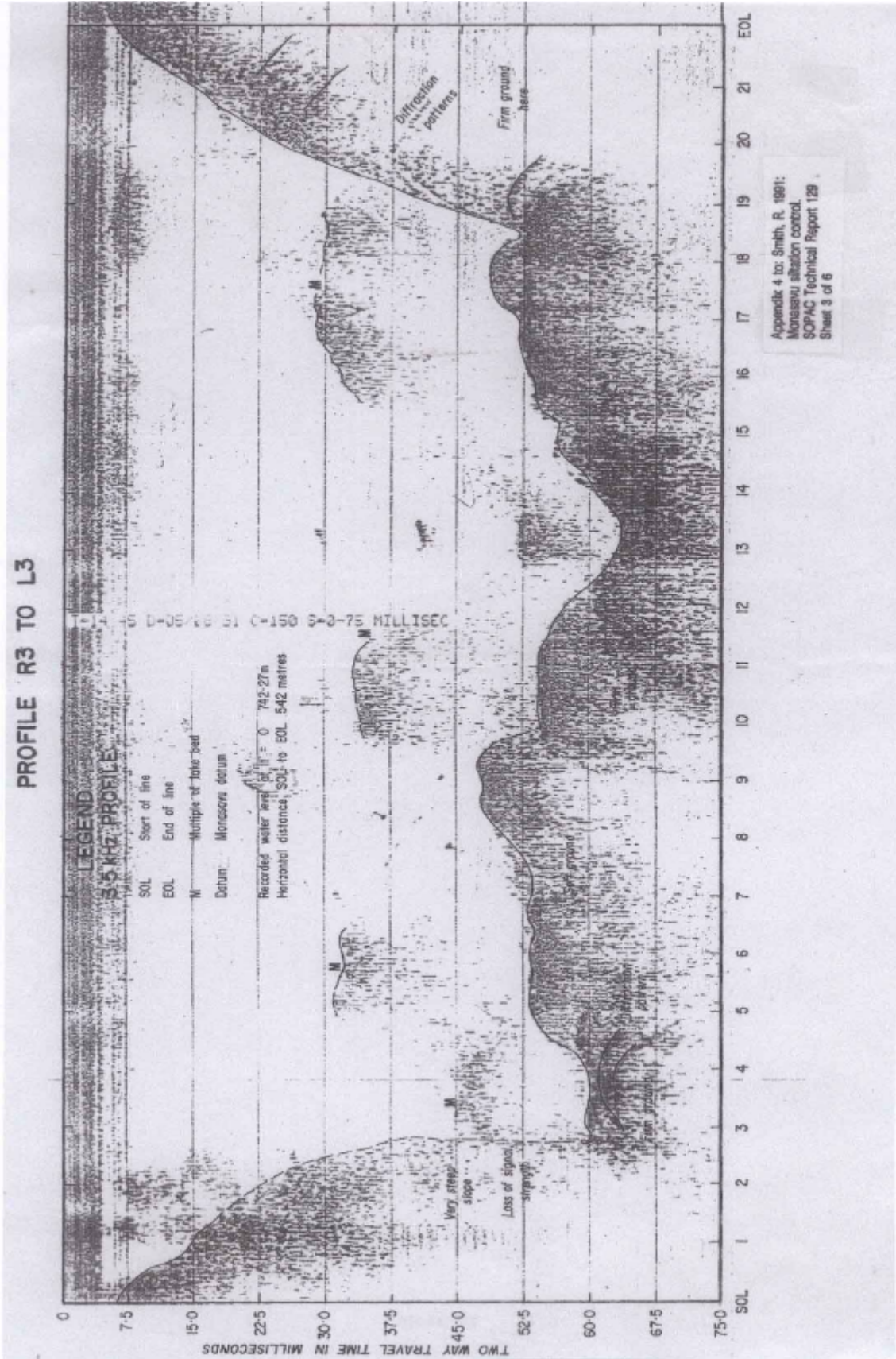


Figure 8a,b.1991,1998 seismic profiles as surveyed from R3 – L3

Comparison of the 1991 and 1998 profiles show a number of changes have taken place. Significant change in the slope profile from R3 to the lake floor can be seen. In the 1991 profile the slope is more convex. In the 1998 profile as a result of upper slope failure the profile has been modified and appears concave and the channel/gully at the base of the slope in the 1991 profile at R3 appears to have been infilled. At around the 60 msec-time line the lake bed has also undergone modification with apparent erosion and infill occurring of up to 3 m in some sections. The original creek profile is no longer apparent in the 1998 profile. No significant change is seen in the slope profile up to L3, except for some sediment infill at the base of the slope.

In the cross section plots computed from the lake bathymetry models; similar changes are evident and are measurable based on the computed 3D lake models. Figure 9 a, b show the computed cross sections for the actual vessel track profile and a straight-line track profile from R3 to L3. Three cross section plots are presented.

Changes in the cross-section profiles on the red (original profile) and the green cross-section plots indicate erosion due to slope failure, which also can occur above the profile or below the profile in a lateral sense. The cross-sectional transects would therefore reflect change along the profile without taking into account what happens above the profile or below the profile. Again it is difficult to appreciate the geometry of slope failure in a single profile.

Profile R4–L4

Figure 10 a, b show the seismic profiles R4–L4 for 1991 and 1998 respectively. For the 1998 profile, the data was recorded in a traverse from R4 to L4 at a scale of 100 msecs whilst the 1991 profile was also surveyed from R4–L4 but at a scale of 75 msecs.

Comparison of the 1991 and 1998 profiles showed there is no change in the profile shape, except between 15 and 20 msecs levels at the L4 end of the profile. Here above the 15 msecs level, an upper level landslip has infilled the upper slope gully by an estimated 3.6 metres. Figure 11 is a close up of change in profile.

In the cross-section plots computed from the lake bathymetry models, similar changes are evident and are measurable based on the computed 3D lake models. Figure 12 a, b show the computed transect profile from R4 to L4 and the vessel track profile presented in three cross sections representing the data sets used.

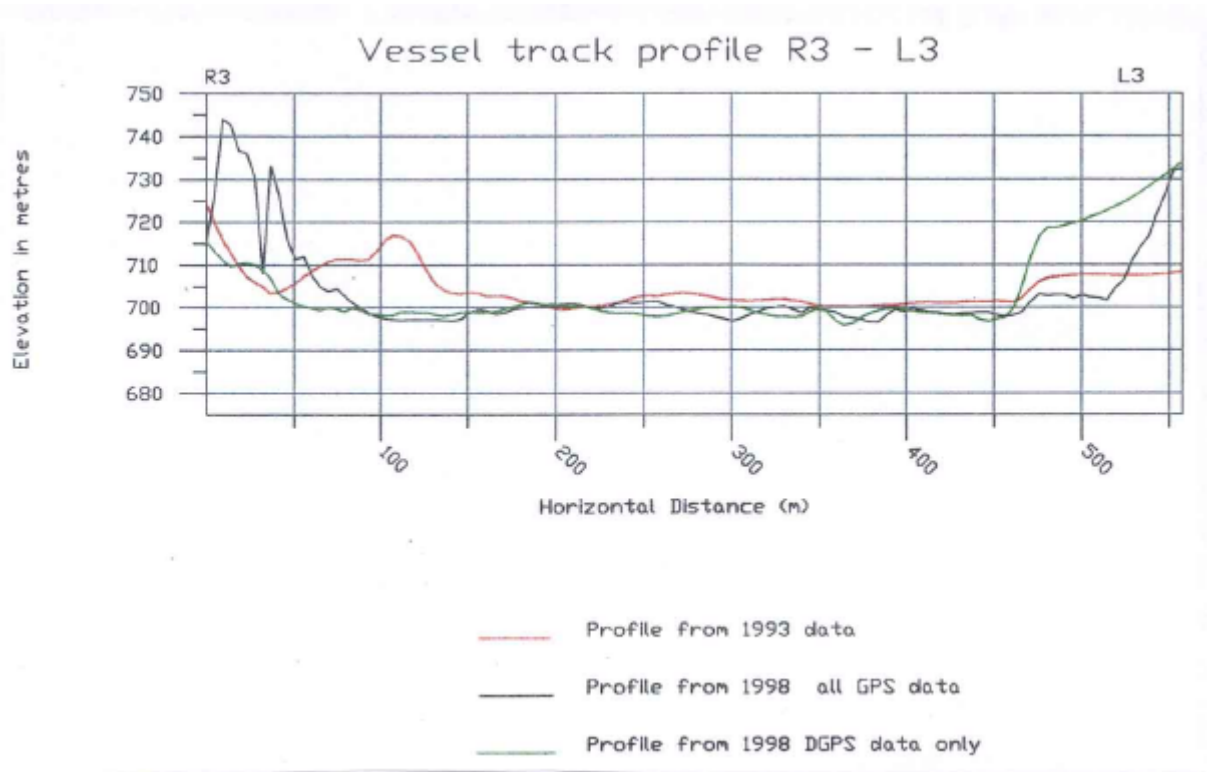


Figure 9a,b. Computed cross section profiles R3 to L3 from 1993 and 1998 models

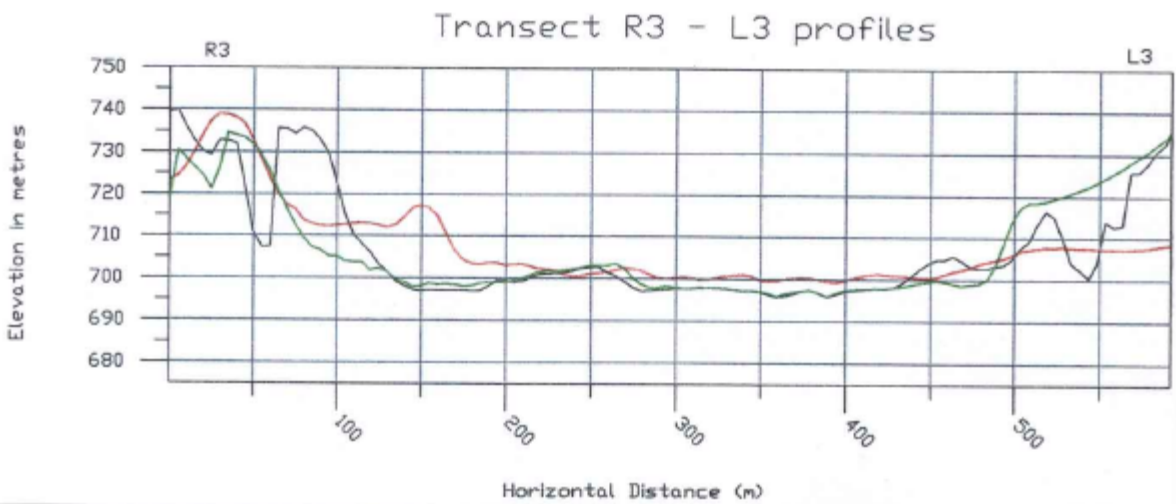


Figure 9b

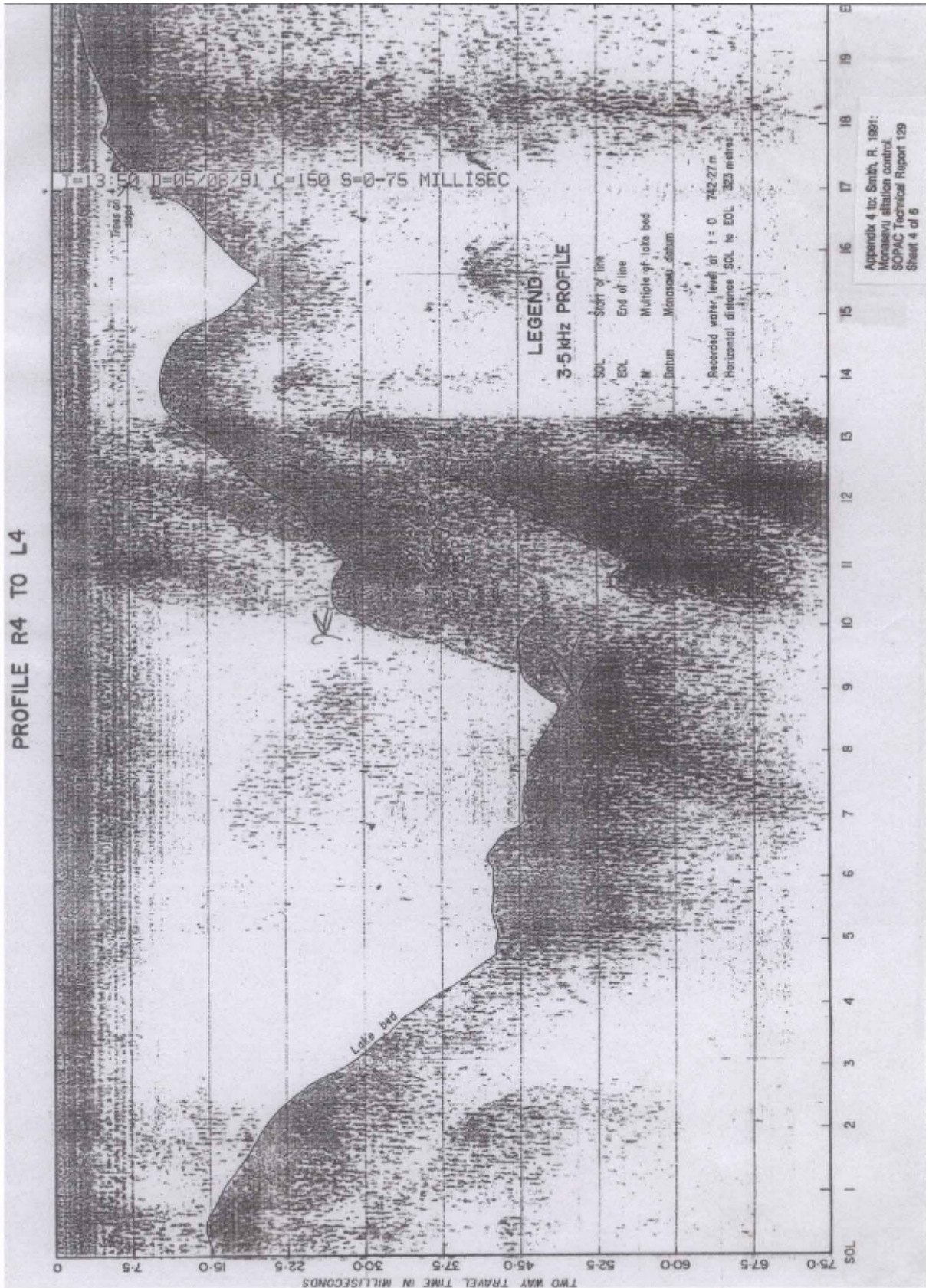


Figure 10a,b.1991,1998 seismic profiles as surveyed from R4-L4

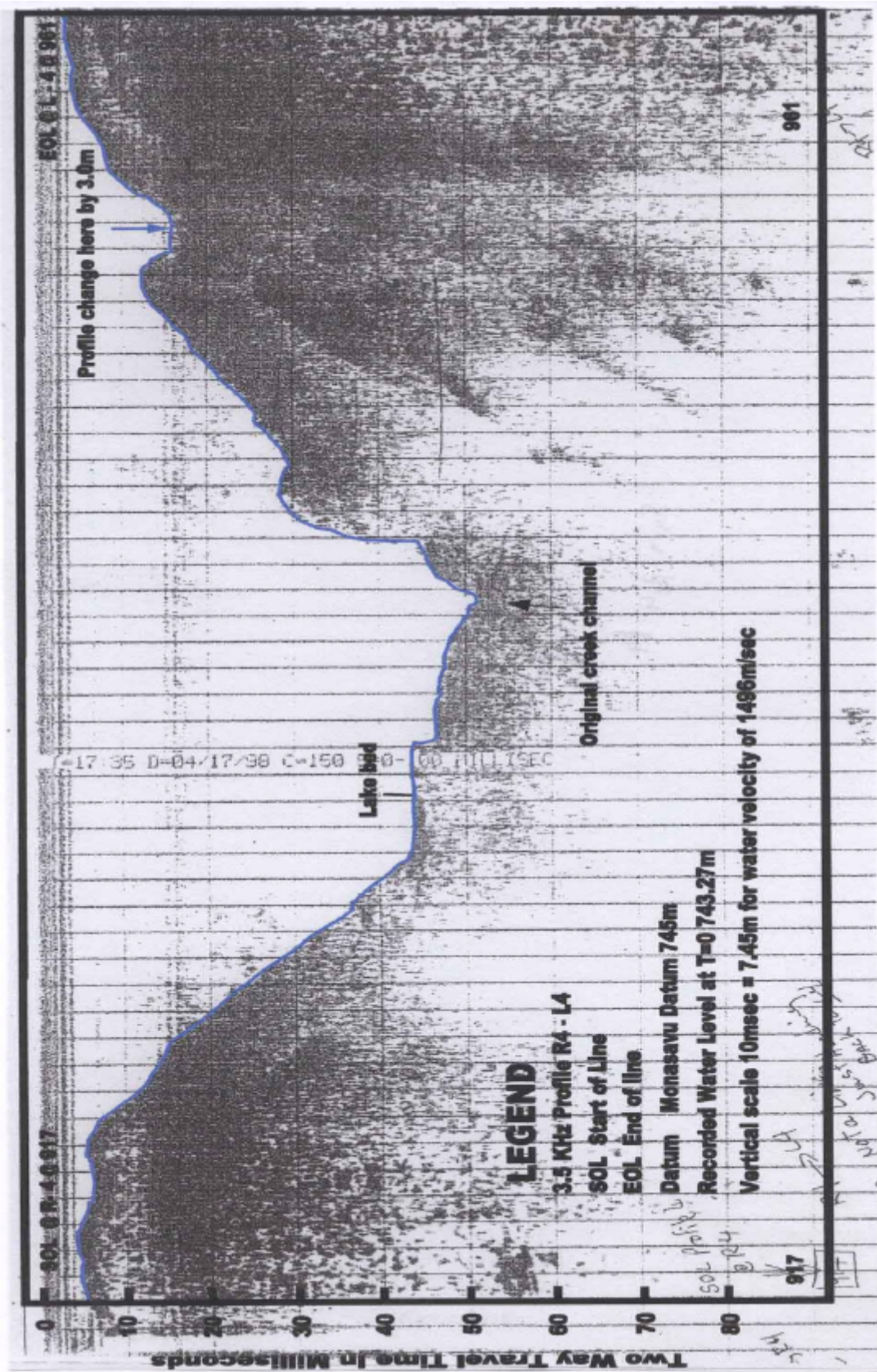


Figure 10b

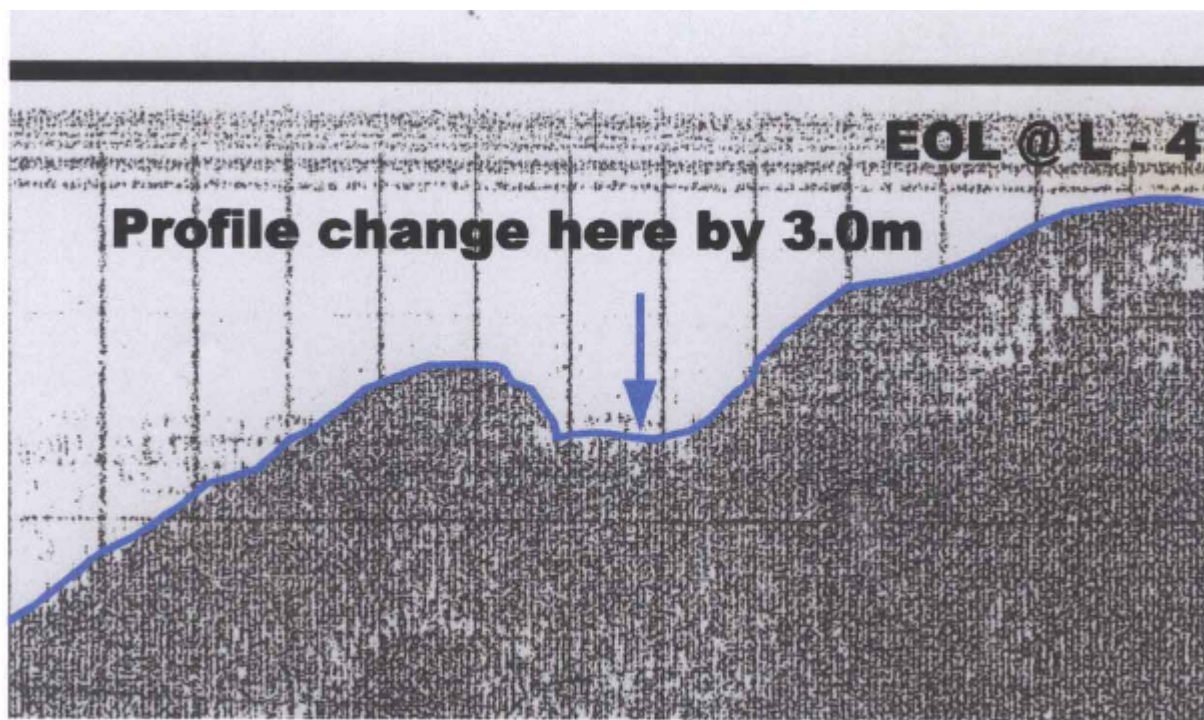


Figure 11. Slope failure resulting in an infilled upper slope gully near L4.

Profile L5–R5

Figure 13 a, b show the seismic profiles L5–R5 for 1991 and 1998 respectively. For the 1998 profile the data was recorded in a traverse from L5–R5 at a scale of 100 msecs whilst the 1991 profile was also surveyed from L5–R5 but at a scale of 75 msecs.

Comparison of the 1991 and 1998 profiles show no indication of sediment build-up in the profile of the original creek bed or changes in the flanks of the lake bed either side of the channel.

Profile L6–R6

Figure 14 a, b show the seismic profiles L6–R6 for 1991 and 1998 respectively. For the 1998 profile the data was recorded in a traverse from R6 to L6 at a scale of 100 msecs whilst the 1991 profile was also surveyed from R6 to L6 but at the scale of 75 msecs. Although the lake water level was higher at 743.27 than the water level in the 1991 profile at 742.7 the profile is incomplete due to a “bathymetric high” in the lake bed which was too shallow to cross.

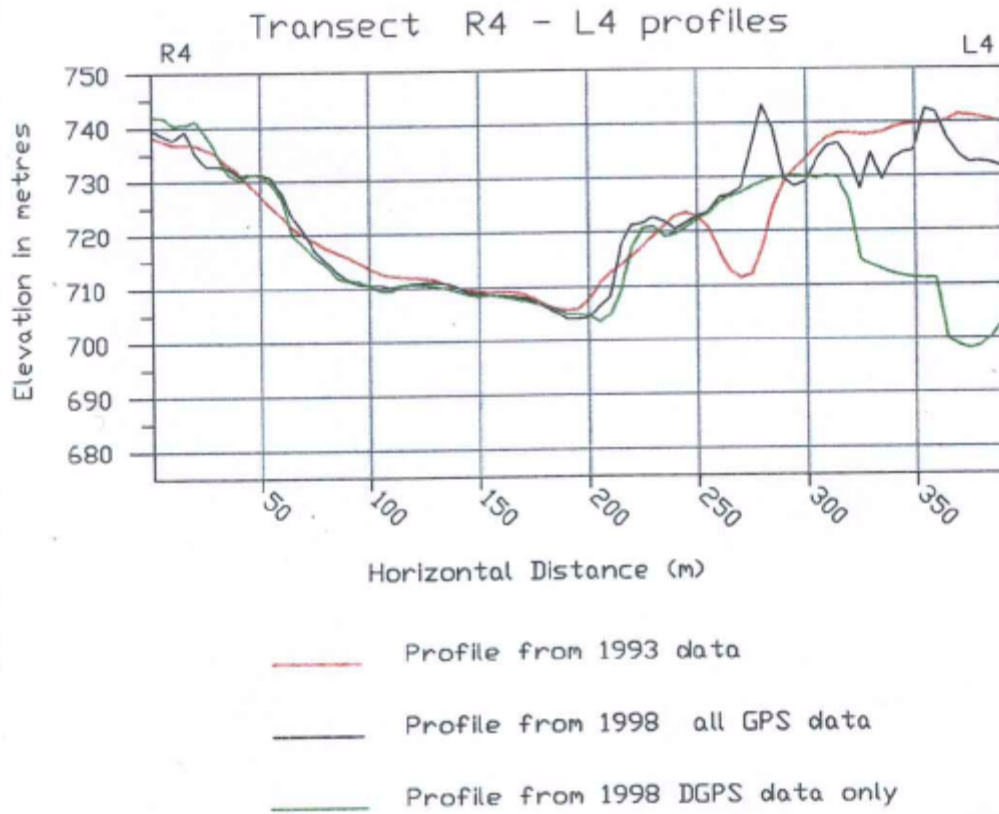


Figure 12a, b. Computed cross section profiles R4 to L4 from 1993 and 1998 models.

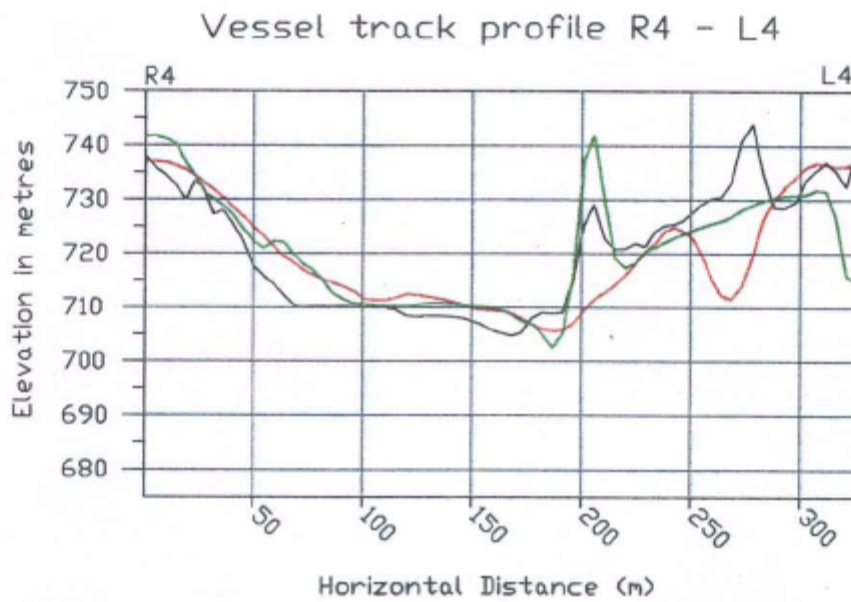


Figure 12b

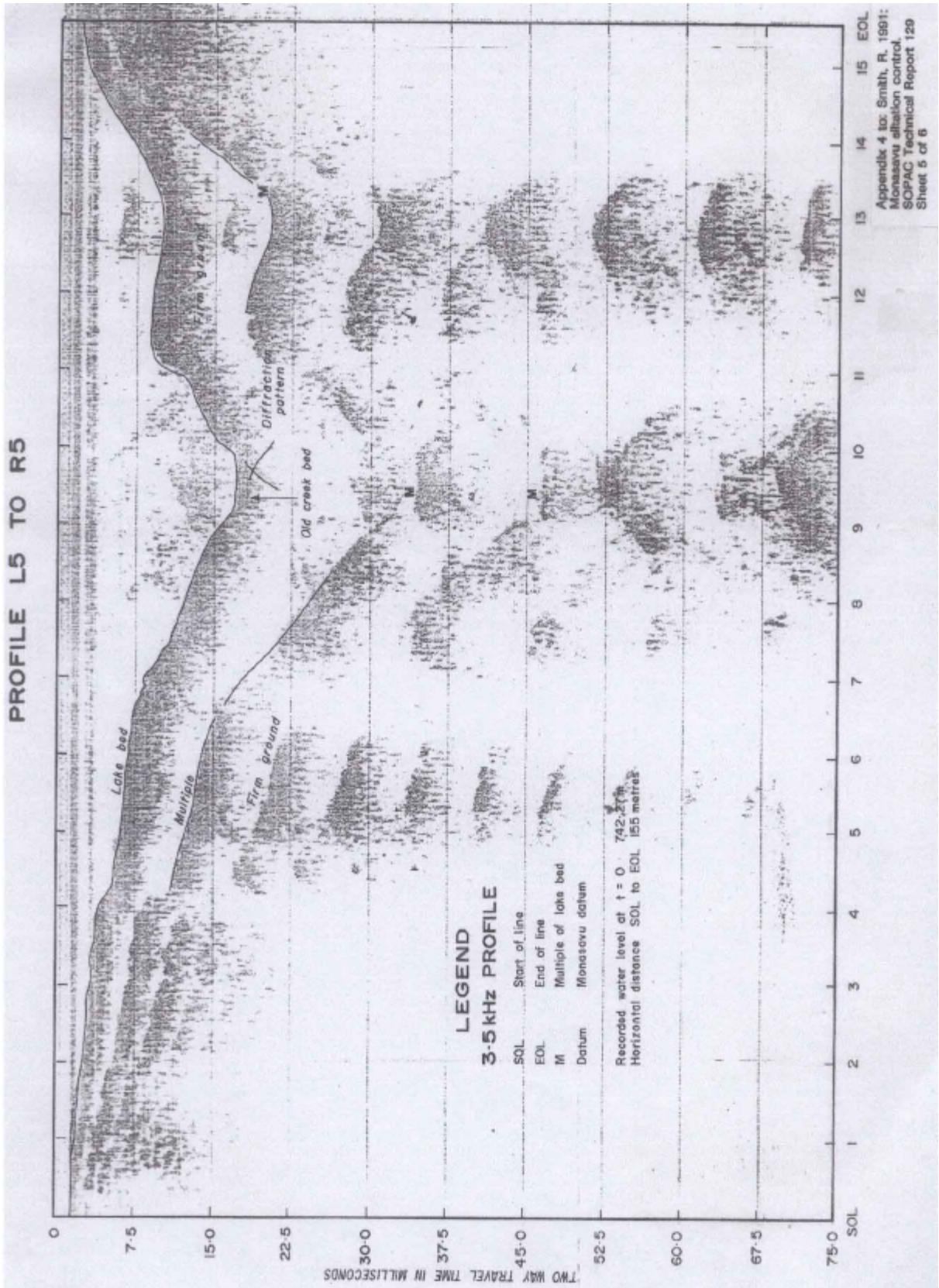


Figure 13a,b.1991,1998 seismic profiles as surveyed from L5-R5

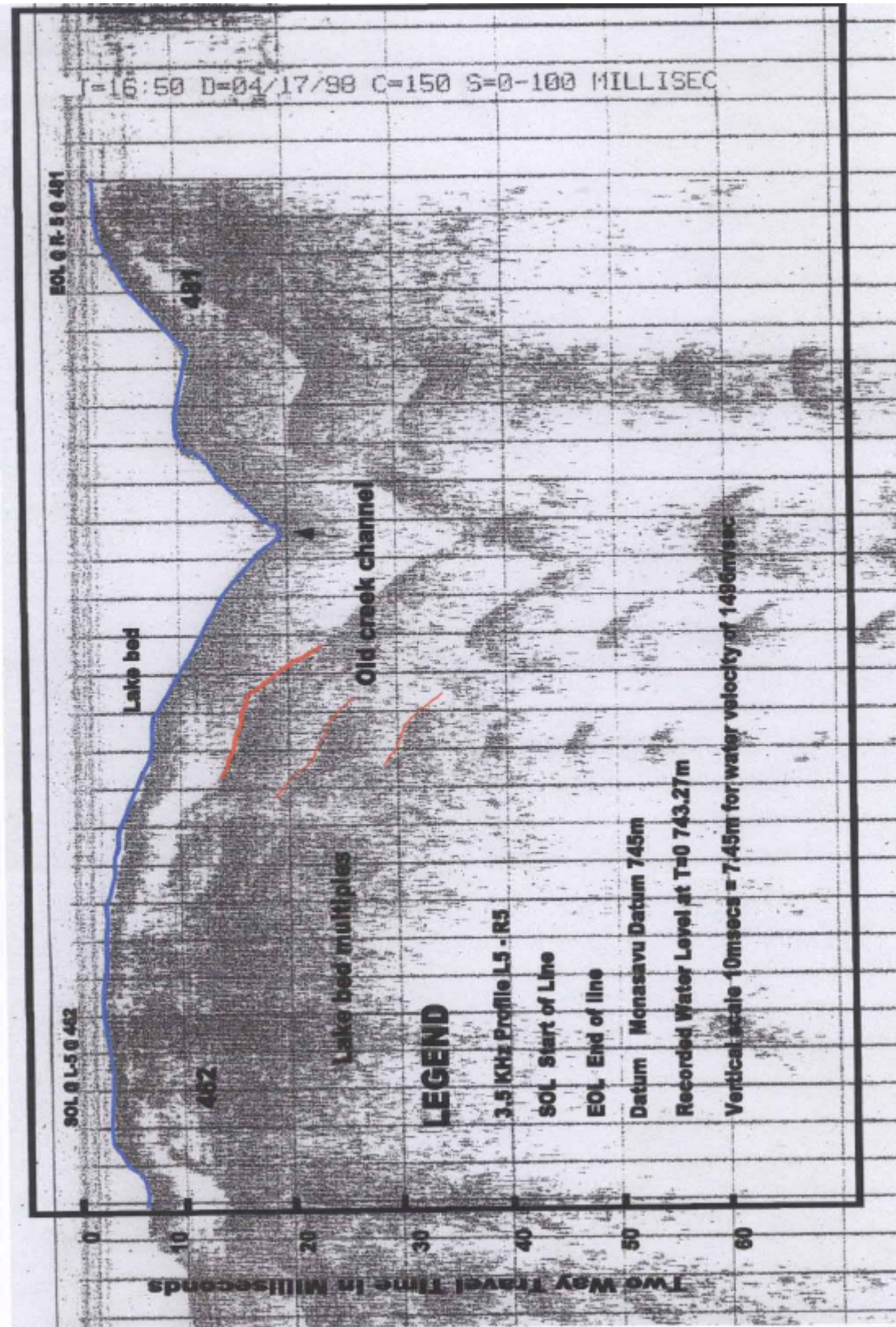


Figure 13b

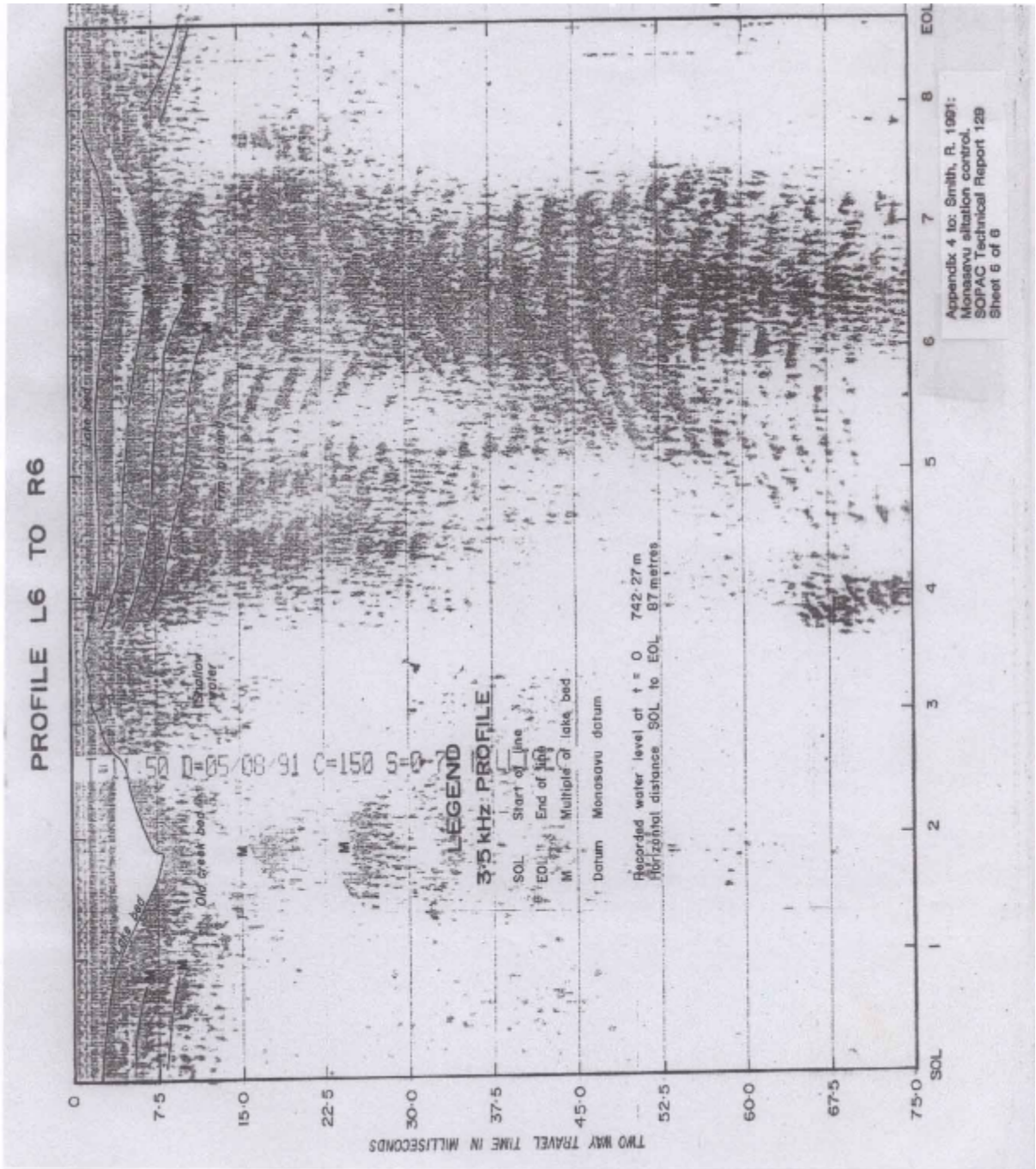


Figure 14a,b.1991 seismic profiles as surveyed from L6 –R6

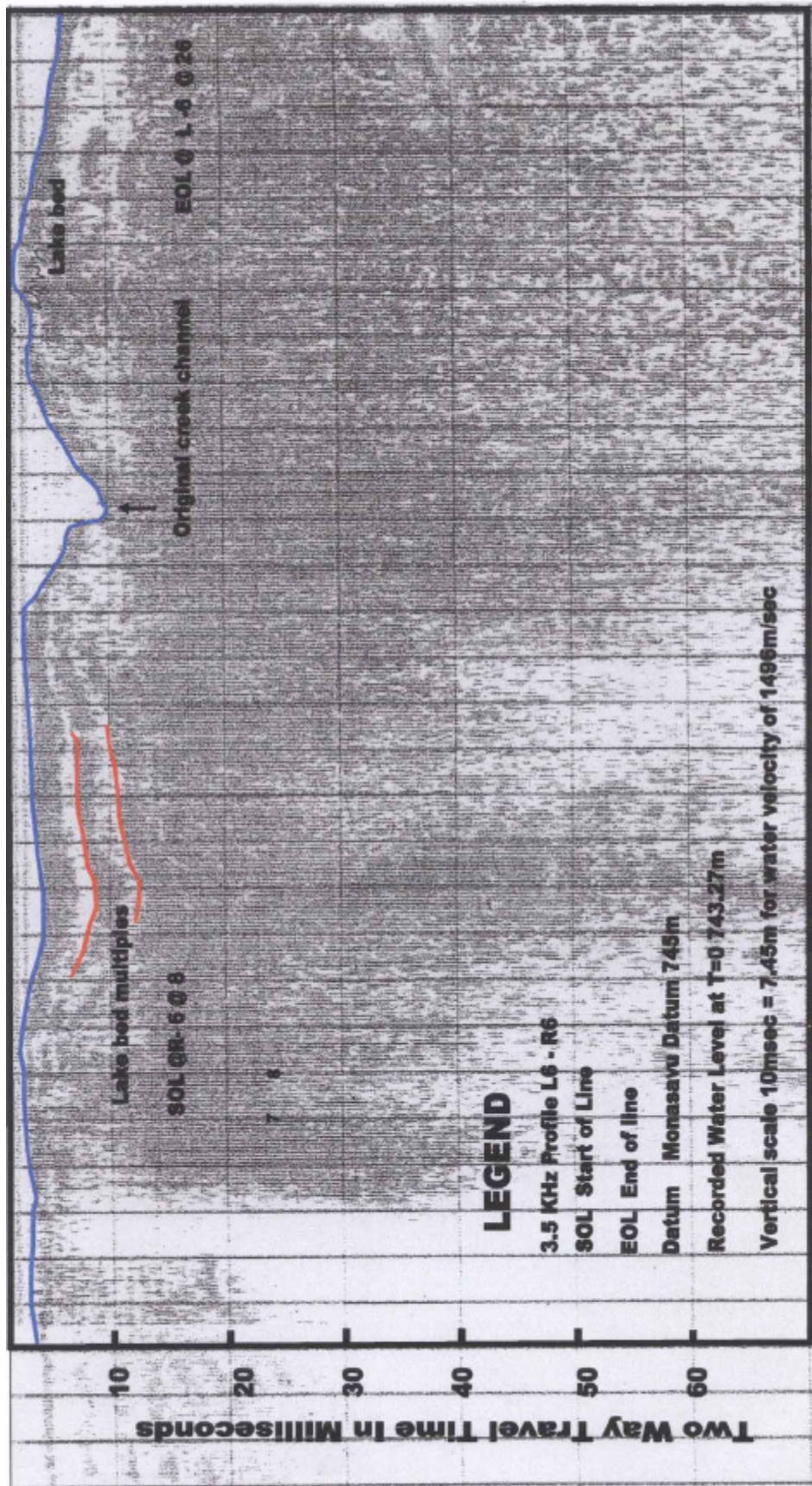


Figure14b

Comparison of the 1991 and 1998 profiles showed no evidence of accumulation of sediment in the profile of the original creek bed or changes in the flanks of the lake bed either side of the channel.

Bathymetric Changes in Lake Bed 1993-1998

A bathymetric survey was completed for the Department of Energy in 1993 (Smith and Saphore 1993). With this data it was therefore possible to model change in the overall lake-bed topography by comparing the computed bathymetric models for 1993 and 1998 data sets.

However as the 1993 dataset was based on triangulation from two known points the data set was therefore based on Cassini Soldner for Viti Levu co-ordinates, while the 1998 data set was based on the Fiji Map Grid co-ordinates. To maintain some consistency between the two data sets, only those depths that were located with the real time differential GPS were used in the model compilation. For the 1993 data set the co-ordinates for the depth values were recomputed into FMG co-ordinates using the same procedure as described in the section on navigation control.

To compute differences that may have occurred in the general lake-bed morphology, a regular grid with the same origin and cell size was computed for both sets. Krigging was used to produce a gridded data set from a random data set. Data set boundary lines for the 93 and 98 bathymetry data sets were constructed to control extrapolation of the gridding and contouring outside the data points sets.

It must be noted that lake-bed coverage in the 98 survey was more extensive, due to the flexibility of GPS over the triangulation methods used in the 1993 survey (see Figure 1). This will be important when trying to assess changes in the lake bed between 1993 and 1998. To reduce the possibility of introducing anomalous changes in the lake bed when subtracting the gridded data sets for 1993 and 1998, the 1998 data points that fell outside the control boundary line for the 1993 data set were excluded from the calculation.

The resultant changes in the general shape and depth of the lake are illustrated in a colour-coded map of the lake, see Figure 15. The resulting picture is quite complex showing both accretion and erosion with changes in the order of 10 m having occurred in the bathymetry of the lake bed. Many of these changes can be attributed to slope failure. Visual evidence noted during the course of the survey indicated slope failure, the general position of which was noted

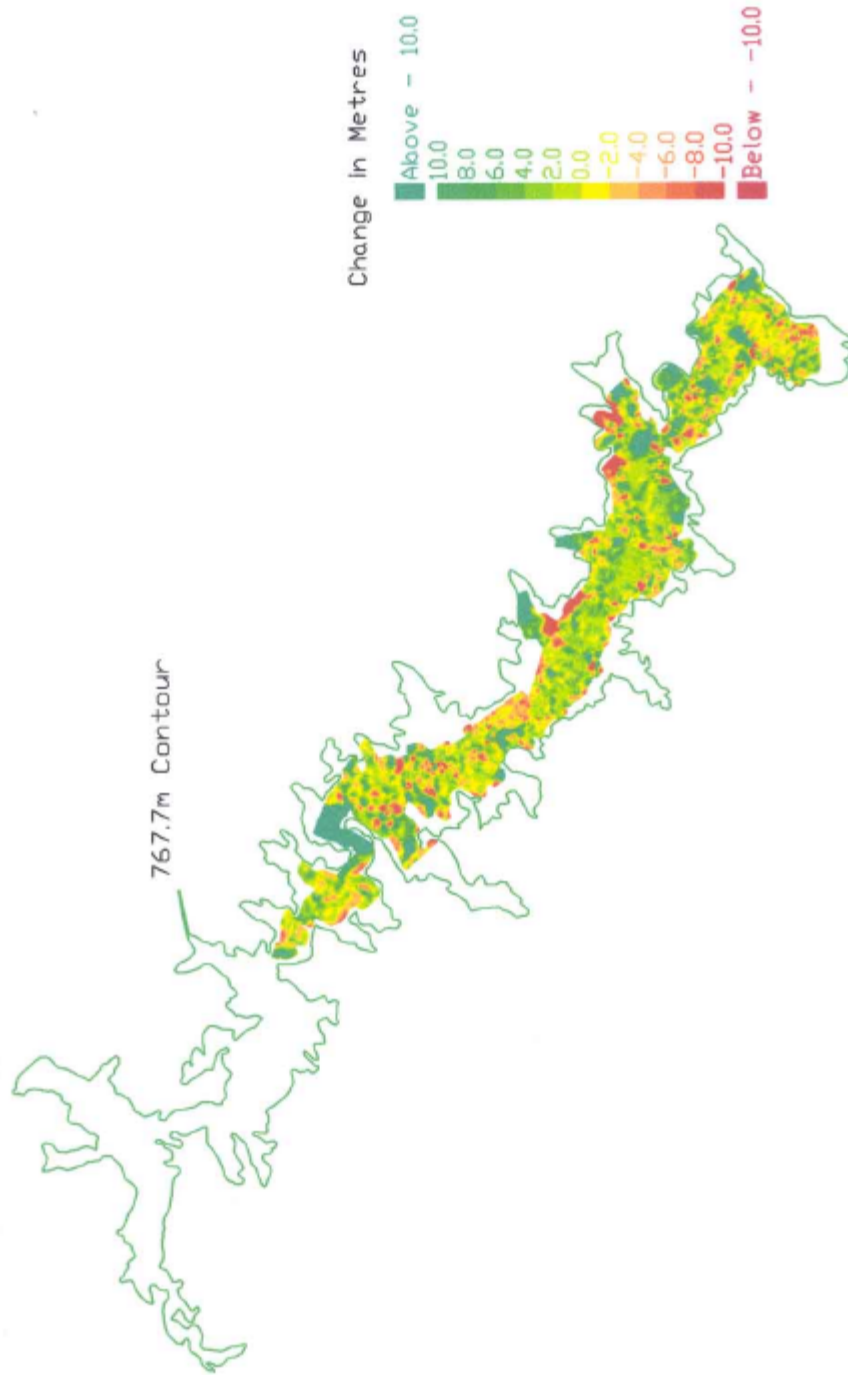


Figure 15: Computed change in lakebed topography between 1993 and 1998

and approximate lateral extent were recorded with GPS. Based on this, a map illustrating the extent of slope failure along the shoreline of the lake is shown in Figure 16.

Slope failure has occurred on both flanks of the lake from the head of the dam as far as transect R4–L4 (Figure 16). In an area from transect 2 to transect 3, between R2 and R3 on the west side of the lake, the lateral extent of the slope failure is most pronounced with slides in excess of 100 m.

Two other areas where significant changes in bathymetry occur around the dam basin proper are adjacent to where R1 used to be located north east of MOM 8 near the old quarry site. These sites are shown in Figure 16. An anomalous change in bathymetry is also evident in the area of the old quarry. This anomalous change is attributed to a the small number of data points in the 1993 data set and resulting extrapolation into the gridded data set. However as this is the area where the low pressure intake is located, the area should be mapped in greater detail.

Volume Calculations

Volumetric figures calculated from the model are presented in Table 2. These were calculated using the Area volume utility programme available in QuickSURF. Volume estimates were calculated from the 93 and 98 models where the lower surface of the solid is defined by the gridded data set representing the lake floor and an upper surface defined as a plane representing the lake level at any one time. The volume computations are best if the defined surface is as smooth as possible from the data available, with a dense grid line spacing and grid cells that are square. For both the 93 and 98 models a 10 x 10 m-grid cell was computed with a Krigging algorithm.

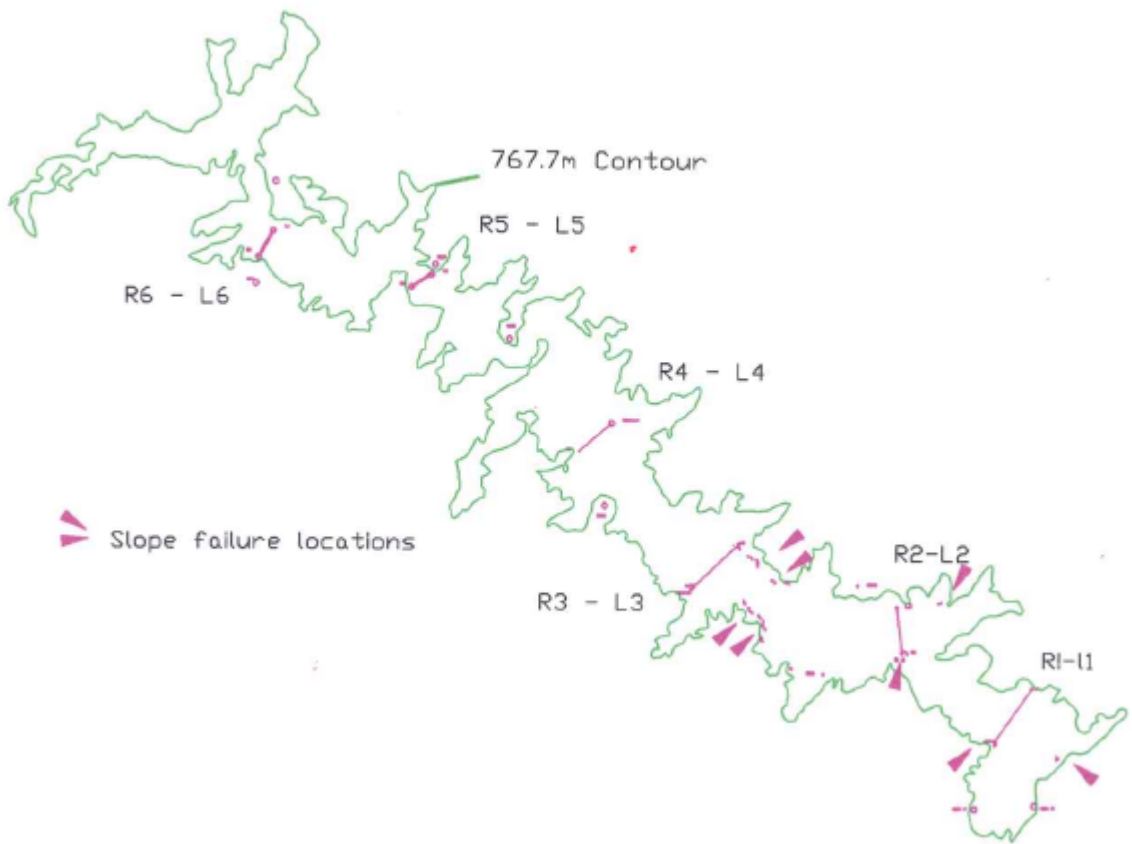


Figure 16. Sketch map showing areas where slope failure has occurred.

Table 2. Model volumes.

Lake level (m)	93 Model-volume (million cubic metres)	98 Model volume (million cubic metres)	Formula volume (million cubic metres)
MOL 710	14.7	17.33	17.56
715	22.6	25.86	25.932
720	32.7	36.36	36.792
725	44.8	49.17	50.519
730	59.1	64.6	67.510
735	75.7	83.2	88.177
740	94.8	105.74	112.945
744	111.4	125.88	142.25

For comparison purposes (Table 2) the respective volumes for lake levels 710 m through 745 m in 5-m increments were calculated using the formula:

$$V = (\text{EL}-669)^{3.39} \times 10^3 \quad \text{Equation 1}$$

16.707

Where V = volume and EL = lake level.

Values shown in Table 2 reflect the degree of uncertainty of the computed volumes for both the 1993 data and 1998 data against the volumes computed from equation 1 as one approaches full supply level at 745 m. At the minimum operating levels the computed volume figures for the 1998 model compare to within 1% of the figures derived from the formula in equation 1. Near the full supply level they are within 10% which reflects the problem in delineating the upper boundary of the lake and mapping of the areas of restricted access. Where reservoir volume computations are involved inadequate information on terrain roughness and intervening tributary arms and embayments can significantly affect computational accuracy.

Reservoir Sedimentation Processes

With oscillating water levels in Monasavu lake, a large part of the storage area is alternatively subjected to reservoir and river processes. From a hydrodynamic point of view, there is a difference in these processes. River processes are characterised by large values for a horizontal component of velocity whereas the reservoir processes this may be

negligible and variable with depth. However the vertical velocity component can play an important part in the hydrodynamic behaviour of the reservoir because of the role of density gradients.

In terms of sediment transport the dominant mechanism in the reservoir is particle settling because entrainment and resuspension are really limited by the small intensity of the currents. As a consequence the only mode of transport is through suspension which limits the particle size to the finest grain-size fractions (silt and clay) which constitute most of the bottom composition. This was clearly evident in the grab samples taken in the reservoir at locations profile 2, profile 1 and the dam basin proper. An aspect of slope failure in reservoir sedimentation is that under certain conditions the incoming water and sediment plunges to the bottom of the reservoir and moves toward the dam in the form of a density or turbidity current, depositing the sediment once the flow has slowed to a point where it cannot continue to hold the sediment in suspension. When slope failure occurs the mass displaced will also generate a turbidity flow, a tongue-like flow of dense, muddy water moving down a slope which will also lift bottom sediment back into suspension. In offshore conditions this form of sediment transport occurs as a result of slumping, triggered by an earthquake which in turn produces a turbidity flow that travels at great speed along the ocean floor. Such an event occurred offshore Suva during the 1953 earthquake which resulted in a local tsunami flooding greater Suva at that time.

Based on the interpretation of the seismic profiles an average value of sedimentation rates maybe inferred. For profile R1–L1 an average rate of 0.57 m yr^{-1} is inferred based on the interpretation of changes seen between the 1991 and 1998 profiles. Likewise for profiles R2–L2 and R3–L3 inferred rates of sediment deposition are 0.28 m yr^{-1} and 0.42 m yr^{-1} respectively.

However based on the models developed from the 1993 and 1998 bathymetry surveys the change in lake bathymetry can also be used to calculate an estimated sedimentation rate for a 5-year period. For this calculation the accumulated sediment during the five years is the volume between the existing surface (the 1998 lake bathymetry) and the original (proposed) surface which in this case is the 1993 lake bathymetry. The area representing the volume calculated is a boundary line, defined by the perimeter of the 1993 data set (see Figure 1). The calculated volume change during the period 93-98 is 4.2 million cubic metres representing a sedimentation rate of approximately $83\,7640 \text{ m}^3$ or 0.22 m yr^{-1} annually for a boundary area of 3.7 million m^2 . Based on this sedimentation rate it is estimated that it would take 20 years before sedimentation approaches the minimum operating level of 710 m.

A similar calculation was done in the vicinity of the low pressure tunnel to assess sediment accumulation with respect to the 701 m level. As the low pressure tunnel is at an elevation of 701 m with respect to the existing 1998 lake bathymetry model, there is a volumetric freeboard of approximately 6.6 million m³ within the boundary defined by the 93 data set. Based on this volume and assuming the accumulation rate remains constant, it would take 8 years before sediment levels reach the 701 m.

A comparison of sedimentation rates derived from the seismic profiles and the two digital bathymetry models place them in a range from 0.22 m yr⁻¹ to 0.57 m yr⁻¹. Considering the complexity of reservoir sedimentation and noting the variability reflected in the different areas of the lake profiles and models, an average sedimentation rate of 0.37 m yr⁻¹ was calculated. These figures provide the first estimate on the sedimentation rates for Monasavu lake and should be considered indicative rather than absolute.

However, as most of the sedimentation is the result of slope failure, the size and timing of an event will depend upon the geology, climatic conditions, slope and lake level. This is particularly important to consider when interpreting the existing lake bathymetry in the vicinity of profile R2–L2 where the original creek narrows considerably as it meanders around R2. Here the lake bed is 15 m below MOL. Assuming that the average sedimentation rate is 0.37 m yr⁻¹ it would take 40 years to reach 710 m or for the higher rates as in profile R1–L1 at a sedimentation rate of 0.57 m yr⁻¹ it would take only 26 years. Again, as slope failure is the primary cause for sedimentation, it is difficult to put a time frame on when this would begin to affect the live storage volume. As events leading to slope failure are governed by low water, high rainfall, slope and geology, the 'right' combination of conditions could produce the worst-case scenario in a single event.

Impacts of Slope Failure

There are a number of impacts associated with the occurrence of slope failure both positive and negative. A positive impact of slope failure is an increase in lake surface area at full supply. This would result in an increase in the live storage volume. However this increase is difficult to compute without accurately defining the upper water level boundary. This is best achieved with aerial photography from which an accurate digital elevation model can be derived. If the photography is taken when levels are down and with suitable ground control in place, image rectification can be done.

Negative impacts associated with slope failure include increased siltation and reduction in live volume storage capacity. However from the 1998 data set, siltation has not impacted the live storage volume.

Another serious aspect of slope failure associated with the dislodgement of large blocks of sandstone is their capability of generating a wave of significant height that could have an impact on the dam structure. Engineers have reported that one of the more notable features of the bed of Nanuku creek was the presence of very large blocks of sandstone some over 100 m³ in volume. These appear to have rolled down into the river from sandstone outcrop above the creek bed (Gibb1978).

The apparent mechanism for the sandstone blocks to fall as described in the report by Gibb, was that a clay seam on which movement has occurred underlies the sandstone blocks. The morphology of the sandstone outcrop indicate that they are remnants of a slope failure process that removed material on either side and the large blocks were then displaced from the underlying clay seam and eventually toppled and fell. A slope failure of this form occurred during December 1977. In the same report they alluded to the problem of not being able to complete more detailed geological mapping of the area because of the difficulty with traversing extensive areas covered by residual clay soils and thick forest.

Alternative Mapping Technology

Alternative mapping technology which can be used to assess conditions of the dam and reservoir is swath mapping technology. Swath mapping is essentially a multibeam echosounder with as many as 100 beams with each beam oriented at a slightly different angle capable of providing information on any part of the lake bed that it hits. The multibeam is capable of updating each of the beams simultaneously at up to 30 times a second. The end result is a swath of a width determined by water depth of the lake bed measured and swath operating frequency. The swath width is a function of the multibeam frequency and water depth, so that the actual swath coverage of a lake bed can be as wide as 7.4 times the water depth. For example, for a water depth of 50 metres and a frequency of 240 kHz a swath width of 350 m of the lake bed can be covered simultaneously.

Swath mapping technology has the capability producing digital maps with 100 % coverage of a lake bed or seafloor. An advantage of swath data is that conditions of a dam face, dam floor, the flanks of the reservoir are available in such detail that, changes in the armour layer position of the dam face, slope geometry, changes due to slope failure can be interpreted with a high degree of precision. Subsequent surveys using swath data can then be used to produce differential maps, showing the difference between the actual state of the dam face armour layer, slope changes, and allow computation of accurate volumetric changes.

Numerical Modelling of Reservoirs

Numerical models have been developed to simulate siltation in navigation channels, flushing events or different stages of reservoir emptying. Currently available within in SOPAC is the MIKE 21 modelling software which can be applied to problems in hydraulic and water resource engineering. However, in order to apply a mathematical model to a river or reservoir, test and calibration data are needed to establish the applicability of the model. Typical field data required for testing and calibrating the model include reservoir configuration, flow records, sediment records and sediment characteristics. The bathymetry models now available provide the foundation on which to develop two-dimensional simulations of the hydrodynamics and sediment process that are active in Monasavu lake.

Another aspect of the modelling is its usefulness in assessing the erosion of the banks due wave action and its contribution to the overall sediment budget. Here waves generated by wind across the lake erode and undercut unvegetated banks resulting in bank collapse. This process is clearly illustrated in Figure 17 at R2 profile location.

Future Survey Considerations

In view of the results of this work, it is recommended that the Authority consider as immediate priority a geological mapping program of the lake area to delineate the extent of the units that are prone to slope failure; and that this information be combined with a slope digital elevation model. Clearly identifying areas prone to slope failure will increase confidence in the prediction of an event and its potential size.

Even though data, to date, include two seismic and bathymetry surveys from which models have been developed to assess reservoir sedimentation at 7 and 5 years respectively, another survey should be considered around 2003. However with SOPAC's acquisition of swath mapping technology can now afford a detailed and more conclusive survey of the lake, more promptly. Swath mapping of the lake, in particular the area around the low-pressure intake tunnel, should therefore be considered sooner.



Figure 17. Erosion and turbidity generation of the shoreline from waves generated by wind. This picture was taken at profile location R2–L2. Slumping on a small scale continues to occur at the shoreline due to undercutting of the bank by waves.

CONCLUSIONS

Reservoir sedimentation is a very complicated and difficult problem, owing to the number of parameters involved. The surveys completed to date show that:

1. Slope failure appears to be the primary source of the sedimentation in the lake.
2. Indicative rates of sedimentation are estimated to range from 0.22 m yr^{-1} to 0.57 m yr^{-1} .
3. There has been significant changes in the profiles 1 through 4 due to slope failure.
4. There is no evidence for sedimentation in profiles 5 and 6.
5. The lack of sediment appearing in profiles 5 and 6 also suggest that the sediment seen in the other profiles is locally derived and principally a result of slope failure.
6. Slope failure is most apparent on the right flank of the lake between profile locations 1 and 3.

7. Slope failure varies considerably in size from small features, no more than a couple of metres wide, to slide scars over 100 m wide. The larger slides appear to have resulted in up to 30 m of lake shoreline retreat.
8. The potential for large blocks being displaced and falling into the lake as a result of slope failure cannot be fully realised with the existing data on the local geology.
9. Changes of the order 10–20 m have occurred in the lake bathymetry. These being a result of slope failure.
10. To date, sedimentation has not reached levels which could impact on the live storage volume.
11. The lack of baseline data in the vicinity of the low-pressure tunnel intake to assess change is a concern.
12. The lack of detailed geology maps for the lake reservoir area and catchment area to better assess the impacts of slope failure is a concern.

RECOMMENDATIONS

1. Aerial photography with good ground control for image rectification to delineate the full supply level boundary and areas of slope failure should be conducted.
2. Geological mapping in detail to assess the full impact of slope failure and the risk due to large boulders being displaced and generating a wave climate that may affect dam structure integrity should be completed.
3. That all ground control points be relocated with respect to the Fiji Map Grid.
4. That missing ground control points for profiles 1 and 3 be relocated.
5. To measure the current regime associated with the low-pressure intake tunnel to assess the sediment transport regime – best done using an acoustic doppler current profiling technology to measure current fields.
6. A new profile be inserted to monitor change on the southern side of profile 2.
7. Consideration be given to the use of swath mapping techniques to define lake-bed morphology and conditions, particularly for areas below the dam minimum operating level, prior to the year 2003. Swath mapping can also be used to monitor and map the conditions of the dam face and low-pressure tunnel intake area.

8. Consider implementing a GIS, such as MapINFO, for an integrated reservoir management and monitoring systems incorporating the digital datasets from the 1991, 1993 and 1998 surveys.
9. Future consideration be given to numerical modelling to assess hazard potential associated with sedimentation, slope failure and wave setup due to wind and boulder impact.

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APPENDIX 1

Navigation Control Monasavu Lake

Date	Data Files	Stations	Remark
17-4-98	R6L603		Single channel GPS
18-4-98	MOM7BA35	MOM7	FEA Bench Marks, Differential GPS control
	R2BA35	R2	FEA Bench Marks, Differential GPS control
	R1L1BA35	R1	FEA Bench Marks, Differential GPS control
19-4-98	R2BA35-1	R2	FEA Bench Marks, Differential GPS control
	R3BA35	R3	FEA Bench Marks, Differential GPS control
20-4-98	RSOPBA35	RSOP	position established with Differential GPS
			Differential GPS control
21-4-98	WATABA35	WATA	position established with Differential GPS
	R2BA35-2	R2	FEA Bench Marks, Differential GPS control
	R2BA35-3	R2	FEA Bench Marks, Differential GPS control
22-4-98	GPSBA03		Single channel GPS
	WABA35-1	WATA	Differential GPS control
	WABA35-2	WATA	Differential GPS control

STATION	EASTING (FMG)	NORTHING (FMG)	ELEVATION (MSL)
MOM7	1925462.35	3916120.97	767.927
R2	1924799.18	3917529.56	745.123
L2	1924691.46	3917971.84	746.299
L3	1923310.68	3918519.92	748.084
R3	1922888.18	3918075.61	751.163
R4	1921822.47	3919399.50	746.494
L4	1922139.78	3919622.08	754.838
L6	1918950.81	3921380.11	747.678
R6	1918845.64	3921158.35	745.988
L5	1920437.54	3920943.41	745.879
RSOP	1923285.68	3918057.69	748
R5	1920225.85	3920831.90	745.161
WATA	1926065.15	3917557.92	802

APPENDIX 2

Data Set Descriptions

17-4-98

R6L6ba03.DAT

1484 points (all Non-Differential GPS fixes)

Start of data set @16:01 hr End of data set @ 18:31 hr

This data set is of the bathymetry data collected during the 3.5 kHz profiling and contains the following profiles: R6–L6 (sol @fix16 EOL @fix26). L5–R5 (sol @ fix462 EOL @ 481). L4–R4 (sol @ fix874 EOL @fix913). R4–L4 (sol @fix917 EOL @961). R3–L3 (sol @fix1140 EOL @fix1205). L2–R2 (sol @fix1354 EOL @fix1402). To reduce this data to the 745 m datum, the daily recorded dam level for the respective survey days data was used.

18-4-98

R1L1ba35.DAT

192 points (Non-Differential GPS & Differential GPS fixes)

Start of data set @10:12 hr End of data set @ 10:57 hr

Reference station on MOM7 (-17 45 24.302 178 02 49.934 WGS84 Z = 767.927 m)

This data set is the bathymetry data collected during 3.5 kHz profile of RI–L1

MOM7ba35.DAT

810 points (Non-Differential GPS & Differential GPS fixes)

Start of data set @11:52 hr End of data set @ 13:20 hr

Reference station on MOM7 (-17 45 24.302 178 02 49.934 WGS84 Z = 767.927 m)

This data set is the start of bathymetric profiles

R2ba35.DAT

1321 points (Non-Differential GPS & Differential GPS fixes)

Start of data set @15:19 hr End of data set @ 17:37 hr

Reference station on R2 (-17 44 37.985 178 02 27.349 WGS84 Z=745.123 m)

Bathymetric profile data

19-4-98

R2ba35-1.DAT

1911 points (Non-Differential GPS & Differential GPS fixes)

Start of data set @09:39 hr End of data set @12:58 hr

Reference station on R2 (-17 44 37.985 178 02 27.349 WGS84 Z = 745.123 m)
Bathymetric profile data

R3ba35.DAT

1380 points (Non-Differential GPS & Differential GPS fixes)

Start of data set @15:10 hr End of data set @17:29 hr

Reference station on R3 (-17 44 18.823 178 01 21.8 WGS84 Z = 751.163 m)

Bathymetric profile data, do R2–L2 bathymetric profile @16:58 hr

20-4-98

RSOPba35.DAT

2538 points (Non-Differential GPS & Differential GPS fixes)

Start of data set @11:10 hr End of data set @15:15 hr

Reference station on RSOP (-17 44 21.033 178 01 36.291 WGS84 Z = 748 m)

Bathymetric profile data, do R4–L4 bathymetric profile @15:20 hr

21-4-98

WATAba35.DAT

698 points (Non-Differential GPS & Differential GPS fixes)

Start of data set @11:58 hr End of data set @13:12 hr

Reference station on WATA (-17 44 37.632 178 03 10.579 WGS84 Z = 802 m)

Bathymetric profile data

R2ba35-2

305 points (Non-Differential GPS & Differential GPS fixes)

Start of data set @14:56 hr End of data set @15:27 hr

Reference station on R2 (-17 44 37.985 178 02 27.349 WGS84 Z=745.123 m)

Bathymetric profile data

R2ba35-3

532 points (Non-Differential GPS & Differential GPS fixes)

Start of data set @15:33 hr End of data set @16:27 hr

Reference station on R2 (-17 44 37.985 178 02 27.349 WGS84 Z=745.123 m)

Bathymetric profile data

22-4-98

GPSba03.DAT

2723 points (all Non-Differential GPS fixes)

Start of data set @08:41 hr End of data set @13:17 hr

Bathymetric profile data

WAba35-1.DAT

42 points (Non-Differential GPS & Differential GPS fixes)

Start of data set @15:27 hr End of data set @15:32 hr

Reference station on WATA (-17 44 37.632 178 03 10.579 WGS84 Z = 802 m)

Bathymetric profile data

WAba35-2.DAT

532 points (Non-Differential GPS & Differential GPS fixes)

Start of data set @15:32 hr End of data set @ 18:31 hr

Reference station on WATA (-17 44 37.632 178 03 10.579 WGS84 Z = 802 m)

Bathymetric profile data

All data sets appended

17-22_35.DAT

14460 points (Non-Differential GPS & Differential GPS fixes)

Start of data set @16:01 hr (17-4-1998) End of data set @18:31 hr (22-4-1998)

This master data set contains all of the data sets(Non-Differential GPS & Differential GPS fixes) merged into one file

Appendix 3

Water and Grab Sample Log

2 x Water samples

Z = 5 m

time: 14:31 hr

location: -17 44 39.939 178 02 26.964 WGS84

labels: WS1 (blue lid)

WS2 (yellow lid)

Grab sample in mid channel R2–L2

Z = 49 m

time:

location: -17 44 32.554 178 02 26.144 WGS84

label: GS1 (blue lid)

Grab sample in mid channel R1–L1

Z = 60 m

time: 14:52 hr

location: -17 44 58.018 178 02 59.710

label: GS2 (orange lid)

Grab sample in main dam

Z = 62 m

time: 16:32 hr

location: -17 45 5.897 178 03 9.435

label: GS3 (brown lid)

Appendix 4

Digital Data Files (CD- ROM)