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SEDIMENTATION IN RESERVOIRS:
MAGAT RESERVOIR, CAGAYAN VALLEY, LUZON PHILIPPINES
1984 reservoir survey and data analysis

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ABSTRACT

The Overseas Development Unit of Hydraulics Research Limited is involved in studies to quantify the effects of catchment management in reducing the quantity of sediment being delivered to rivers and deposited in reservoirs. Many recent reservoir studies have shown that observed sedimentation rates can be more than four times the rates estimated during the feasibility studies.

This study uses a computer program, developed for a series of Kenyan reservoirs, to calculate the change in storage capacity of Magat Reservoir in north-central Luzon, the Philippines, as the first stage in a unified study of the total catchment erosion/reservoir sedimentation system. A more detailed examination of the pre-impoundment survey data has shown that the reservoir storage capacity is some 25% greater than the original Feasibility Study and a first estimate of the catchment erosion rate is double the Feasibility Report estimate.

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1 INTRODUCTION

The initial contacts between the Overseas Development Unit (ODU) of Hydraulics Research and the National Irrigation Administration (NIA) were made by letter in mid-1981. The correspondence described some of the projects being carried out by ODU and suggested that collaborative projects examining reservoir sedimentation and irrigation water management would be mutually beneficial. The exchange of letters was followed in late 1981 with a visit to the Philippines by a member of ODU staff (Holmes, 1981). At that time, ODU were involved in similar collaborative projects examining reservoir sedimentation in Kenya and Indonesia in which field data collection and analysis techniques were being developed. Holmes suggested that the application of these techniques could provide valuable data on the rate of siltation of Magat Reservoir in Isabela Province, Luzon.

Following a visit to NIA, Manila and the Magat Reservoir site in February/March 1982, proposals for a collaborative ODU-NIA study were produced by ODU in May 1982 (Wooldridge, 1982). The main objective of the overall project was to access the benefit of a catchment reforestation programme on reservoir sedimentation. This was to be done by monitoring soil erosion rates from a well defined sub-catchment, and by analysing hydrographic survey data collected from the reservoir. The published proposals were discussed and agreed with NIA in the following October (Wooldridge, 1982).

This report describes the reservoir sedimentation data collection and analysis programme; details of the catchment erosion studies will be published in a later report.

The Reservoir Sedimentation Project is one of a number of research topics being examined by the Overseas Development Unit of Hydraulics Research. The ODU work is funded by the Overseas Development Administration of the Foreign and Commonwealth Office, London, UK. All the costs incurred in building field structures, and the collection and on-site analysis of data have been met by the National Irrigation Administration, Manila.

2 STUDY LOCATION

The Republic of the Philippines consists of over 7000 islands with a total land area in excess of 301 x 10^3km^2. The mountainous, volcanic archipelego has only a small proportion of flat lowlands and suffers from earthquakes, typhoons and sudden, local floods. The islands are situated between latitudes 21°N to 4°N and longitudes 116°E to 127°E (Fig 1).

The largest island of the group is Luzon on which is located Metropolitan Manila, incorporating the seat of government of the Republic. The total population of the Republic of the Philippines is about 48 x 10^6 people, about 12% of whom live in Manila.

The core zone of Luzon is a longitudinal lowland, about 240km by 60km, through which rise two isolated volcanic mountains - Arayat and Banahaw. In this region, the climate is distinctly monsoonal with dry, northerly winds having the major influence from November to April. During the rest of the year, the climate is dominated by warm, moist south-westerly winds making September the wettest month.

The northern area of Luzon has extensive forest-covered mountains where the more easily accessible areas are subjected to logging and shifting cultivation (known locally as Kaingin). It has been calculated (NIA -) that of the 12 x 10^6ha of forest land in the Philippines 5 x 10^6ha (about 40%) are already denuded. Permanent cultivation is only carried out in a few discontinuous areas such as the Cagayan Valley in northern Luzon.

A detailed description of the Magat catchment is given in the Erosion Control Study Project Draft Feasibility Report (NIA & Eng Cons Inc, 1978) and only a brief description is given here (Fig 3).

The dam is located 350km north-east of Manila and the catchment is bounded on the eastern, southern and western sides by three of the major mountain systems of Luzon - the Mamparang Mountains, Caraballo Mountains and the Cordillera Mountain system. The total catchment area is about 4123km^2 and the reservoir surface area, at full supply level is 45km^2. The dam, which has a crest height of 114m and a crest length of over 4km, was completed in December 1982.

The topography of the catchment ranges from undulating plain to rugged, high relief peaks and ridges. The valleys in the area of the reservoir are commonly deeply incised and V-shaped giving rise to an extremely irregular reservoir shoreline with a significant number of tributary valleys.

3 1978 BASE DATA

Two types of base data are available for the Magat Reservoir site:-

(a) Hydrographic survey data from 28 range lines crossing the Magat River, with additional ranges crossing the major tributaries - two on the Lamut River, three on the Ibulao River and two on the Alimit River.

(b) 1:50 000 topographical maps showing contours at 20m intervals, with supplementary contours at 5m and 10m intervals.

The 35 range lines were selected by NIA to be approximately normal to the original river channel and at a spacing of between 1 and 3km (Fig 4). The ends of the range lines were chosen to be above the reservoir maximum water level and each was marked with a concrete monument. A white painted concrete fence post was sited adjacent to each monument to assist with location of the range line.

The monuments and range lines were surveyed during the periods April-August 1977 and January-May 1978 by the Survey Unit of the National Irrigation Administration - Magat River Multipurpose Project (NIA-MRMP) Dam Division. Copies of tabulated and plotted sections were passed to ODU in 1985.

The whole of Magat catchment is covered by a series of 16 Topographic maps, three of which show pre-impoundment contours of the reservoir area. Because of the wealth of detail contained on these maps, the three covering the reservoir (numbers 3270-I, 3270-II and 3264-1) were enlarged to a scale of 1:25000. This enlargement did not increase the accuracy of the maps but it did make extraction of the data much easier. The standard accuracy quoted by aerial surveyors for derived contour maps relates to both the level and location of a point on a contour:

(a) level - accurate to ±25m at a scale of 1:50 000

(b) location - ±0.5mm at map scale, which is equivalent to ±25m at a scale of 1:50 000.

these accuracies relate to the scale at which the original maps were drawn and not to the enlargements produced for this analysis.

4 HYDROGRAPHIC SURVEY TECHNIQUES

The basic technique employed for the hydrographic survey of Magat Reservoir followed the method currently recommended by the HRL Field Studies Group.

NIA supplied a field team, two boats and standard field survey equipment - theodolite, staff, portable radios etc. HRL provided the specialised hydrographic survey equipment - echo-sounder, range-finder etc - and two personnel.

At each range line, the end-of-line beacon and level monument had to be located. In most cases, this was relatively straight-forward because of the size of beacon used, but there were a few problems with trying to locate the level monuments. The site for each beacon had been chosen to give the maximum inter-visibility and they had therefore frequently been located some distance above the reservoir top water level. Although this gave the best locations for the pre-impoundment topographical survey, a hydrographic survey needs range markers near to the water's edge. Prior to the 1984 survey taking place, NIA surveyors sited additional markers on many of the range lines for this purpose. The point at which each range line cut the water's edge had to be marked with a target for the range-finder. This was done by sighting from one beacon across the reservoir to the other through the theodolite and then swinging a vertical arc down to the water line (Plate 1). Instructions were relayed from the surveyor to the staffman using portable radios. The beacons and/or re-located level monuments were marked with fluorescent range boards to help with sighting from the boat. Each range line was surveyed using two methods, one for the submerged section (hydrographic) and one for the length between the level monument and the water's edge (topographic).

The hydrographic survey required a minimum team of four people - three men in a boat and one onshore. The shore man was equipped with a portable radio and a theodolite which was set up over a monument. The theodolite was aligned to sight the corresponding beacon on the opposite bank - the man was therefore looking along the range line. A small boat fitted with an echo-sounder and radio was talked along the line following instructions from the theodolite observer (Plate 2). The echo-sounder was run continuously to produce a record of the bed form along the range line. However, it is never possible, even with the most experienced coxswain, to maintain an absolutely constant speed across the reservoir and so it is essential the boat's position is "fixed" at frequent intervals. A precise location can be obtained by measuring the two horizontal angles subtended to the boat by three fixed objects on the bank. Although this would give an accurate location of each "fix", the time taken to locate and survey one, two or even three sets of three objects for each range line would far outweight the value of the data obtained. If it is assumed that the echo-souder trace is recorded along the range line, then it is only necessary to know the location of the boat along the line at any given time. This can be done by measuring one angle subtended by two known objects or by measuring the distance of the boat, and hence the echo-sounder, from one of the range beacons. At Magat, the latter method was employed by using a portable, laser range-finder firing at targets attached to the range beacons. By this technique it was possible to make fix marks at about five-second intervals across the range thus minimising any location errors caused by variations in boat speed.

The echo-sounder measures the depth of water by finding the time taken for a pulse of high-frequency sound to be fired from just below the water and to be picked up as an echo from the reservoir bed. The speed of sound through water varies with the sediment content and water temperature. Twice-daily checks were therefore made of the echo-sounder calibration by lowering a metal target to known depths below the water surface and recording its position on the charts. Any changes in calibration were allowed for when abstracting data from the echo-sounder charts.

A conventional topographic survey was conducted from the water's edge to the level monument at each range line to obtain an accurate measure of the water level and hence an individual datum for the echo-sounder on each range (Plate 4).

5 CONTOUR SLICING TECHNIQUE

Before considering in detail the ways in which the Base Data and Field Survey Data were analysed, it is necessary to consider the technique which was employed to calculate the final reservoir volume.

The field survey technique employed at Magat resulted in bed-level data being collected across range lines located at discrete intervals along the reservoir (Fig 4). Each time a survey is required, data must be collected along the same lines, although the precise location of each data point on the line may vary.

There are two basic approaches which may be adopted when converting this cross-section data into volumes; the first only takes account of cross-section area and range line spacing while the second approach attempts to make some allowance for the irregular plan shape of the reservoir between range lines.

Where there are no contour data for the site, the impounded volume may simply be calculated as a product of the mean cross-sectional area of two adjacent sections and the distance between their centre points. While giving a reasonable first estimate of the contained volume, no allowance is made for meanders in the original river channel or for irregularities in plan shape between the range lines.

The accuracy of this primary calculation may be slightly improved by measuring the distance between range lines along the centre line of the river. This technique goes some way towards making some allowance for the complicated shape of most natural reservoirs. However, the resulting calculated volume can still contain significant inaccuracies.

The analytical method used for this study make use of pre-impoundment contours, obtained from an aerial survey, to more accurately describe the deeply incised plan shape of most parts of Magat Reservoir. This method has been named the Contour Slicing Technique. The terms used in describing this technique are defined as follows:-

Range line -	The line across which reservoir bed-levels are measured;
Cross-section area -	the area of a vertical plane below a range line, bounded by a top level and the reservoir bed;
Sub-segment end area -	the cross-section area bounded between two defined contours;
Contour area -	the area of a plane surface contained by a defined contour;
Segment contour area -	a contour area contained within two given range lines;
Segment volume -	the volume of part of a reservoir contained between two given cross-sections and below the normal top water level;
Sub-segment volume - (CONTOUR SLICE)	the segment volume contained between two defined contours.

The calculation of reservoir volume following a hydrographic survey is carried out in seven steps:

Step 1: Plot the location of the survey end-of-range markers on the pre-impoundment contour map. The locations can be cross-checked by ensuring that surveyed beacon levels agree with interpolated contour levels to within the stated map accuracy.

Step 2: Ensure that all the contour lines are continuous between range lines - it is sometimes possible that the automated techniques used to produce contour lines from aerial photographs may result in incomplete lines, especially if the density of lines exceeds some pre-set parameter. In these cases, it is permissible to draw the missing lines by hand using the existing lines as a guide. It is also possible that, in extreme circumstances, the lines may cross, although with modern, sophisticated draughting machines, this is most unlikely.

Step 3 Measure and tabulate all the segment contour areas (Fig 5, a and b). The areas may be measured by computer (using a digitising table) or by machine (such as a planimeter). If neither of these tools is available, then overlaying a fine grid and counting the squares would give a reasonable answer. The areas should be tabulated in groups identified by the reservoir segments. When tabulating these data it must be remembered that the lower contour of the top contour slice is also the upper contour of the next lowest contour slice.

Step 4 Each sub-segment volume is calculated as the product of the mean contour area and the contour interval:

$$Vol = \frac{A_u + A_l}{2} \times D$$

The summation of these sub-segment volumes will evaluate the pre-impoundment segment, and total reservoir, volumes.

Step 5 As discussed earlier, current analytical techniques require that cross-section data should be obtained along identical range lines for consecutive surveys. It is essential that the comparisons should be based on the most accurate data available and so priority should be given to obtaining topographical data along the range lines prior to reservoir impoundment. If there is not sufficient time, or the volumetric analysis is taking place after impoundment, then cross-section data may be taken from the contour maps. Each cross-section must then be plotted and, using the methods described in Step 3, up-stream and down-stream sub-segment end areas may be measured (Fig 5, c and d). These should be tabulated alongside the equivalent sub-segment volumes.

Step 6 A factor is then calculated to give a form of numerical evaluation of the relationship between the plan shape of each reservoir segment and its end areas. This number is referred to as the "Constant Factor" because it is based on the pre-impoundment volume and thus remains unchanged throughout the life of the reservoir. The Constant Factor for each sub-segment is defined as being the sub-segment volume divided by the sum of the sub-segment end areas:

$$CF = \frac{Vol}{(a_u + a_d)}$$

Step 7 After any subsequent hydrographic survey - as long as the same range lines have been used - the new sub-segment volume is simply obtained as the product of the relevant Constant Factor and the sum of the newly measured end areas (Fig 5, e and f):

$$Vol' = CF\ (a'_u + a'_d)$$

As in Step 4 above, a summation of these sub-segment volumes will give the revised segment and reservoir volumes.

It must be noted that the Contour Slicing Technique assumes that the thickness of sediment deposited in the reservoir varies linearly from one range line to the next and does not allow for local variations in the rates of deposition.

6 FIELD DATA ANALYSIS

NIA supplied plots of all the reservoir cross-sections surveyed in 1978. These sections were digitised at HR using a Perex Digitising Table and the resulting co-ordinates were stored in computer files MAGPLOT78A (range lines M1-3, 5-17, 30-31) and MAGPLOT78B (range lines M18-27, 40-42, 50-51).

Data were also supplied on the range line beacon eastings, northings and levels. The NIA survey grid eastings were not the same as topograhic (map) eastings. Trial plots indicated that the correlation between the two grids was:

545 000 (reservoir) = 331 750 (topo)

With this adjustment, the range line beacons were plotted on the aerial survey maps and the range lines drawn. Using the same digitising table as before, although set in a different mode, it was possible to measure the pre-impoundment sub-segment contour areas. These data were also stored in the computer for later use.

Before proceding with the volumetric calculations, it was essential that the stored data were checked for typing errors. This was done in two ways:-

(a) proof reading the data files;

(b) plotting the section data using the GHOST plotting routines. A visual comparison between the computer plots and those supplied by NIA also confirmed the accuracy of the data.

The second data set used in the volumetric calculations was a combination of the hydrographic survey recorded by HR, and a topographic survey carried out by NIA.

In October 1984, HR used the techniques described earlier in Chapter 4 to collect cross section data for range lines M1-M3, M5-M17 and M30-M31. It was not possible for the hydrographic survey team to travel upstream beyond line M17 because the river was too shallow. Line M4 was omitted because of problems with trying to locate the end-of-range markers. When the water levels had dropped sufficiently, the NIA field team surveyed sections M18-M27, M40-M42 and M50-M51. The NIA team also surveyed along most of the remaining range lines from the water's edge to the beacon. In some cases, this amounted to a duplication of effort, but the resulting topographic data enabled a cross-check to be made on the hydrographic data.

For the volumetric calculations, it was necessary for all of the cross-sections to be continued above the design top water level of +193m Luzon Datum. This involved merging the NIA and HR data sets and details of the procedures adopted are given in Appendix 1.

As a final check, the two sets of data were superimposed and plotted for each range line. These plots are shown in this report as Figures 6-23.

It will be seen that, in most cases, there are only minor variations between the two surveys, a situation which is only to be expected with a survey taken just two years after impoundment. However, there are one or two points worthy of note.

Section M1, adjacent to the dam, shows that the range line has crossed a "borrow pit" which must have been dug during the period of dam construction. The left bank shows evidence of massive accretion. However, this is most unlikely to be the result of natural processes after such a short time and has probably resulted from quarrying which was carried out in this area during the construction phase. In-filling of the perched river channel between 1600m and 2000m from the left bank could also have been due to site works. Comparison of this section with that recorded along range line M2 serves to confirm that the major topographic changes were man-made rather than the result of impoundment.

The first section to show signs of what may be described as "natural accretion" is along range line M6A. This line is just down-stream of a sudden expansion in reservoir width would result in an equivalent reduction in water velocity and hence would allow deposition to take place. There was an unresolved problem with the left bank levels on the section, but as the major discrepancies occur above the top water level, they will have little effect on the calculated reservoir volume.

Section M9A is situated at the exit from a very sharp, 180°, bend. Before impoundment, the maximum river velocities would have occurred at the outside of the bend and given rise to the deeper channel shown in the 1978 survey. After impoundment the main stream flow was still restricted to the right-hand part of the section but the velocities were so much reduced that instead of eroding, material was able to be deposited. There was virtually no flow on the inside of the bend and so there was insufficient material brought in to make any significant change to the bed level.

The 1984 hydrographic survey indicated the presence of a small channel in the right bank of section M9B. this had not been shown in the 1978 NIA survey but had appeared in the earlier survey carried out by Certeza. In 1984, it was confirmed by two survey "fix points" and so it was left as recorded.

Significant accretion is beginning to appear in section M13. By section M19, the accreted bed level is above the top water level of the impounded reservoir and from this point on, the sections are crossing a natural river channel. The accretion at section M15 is shown in Plate 5.

The two major tributaries which enter the reservoir show interesting differences in their accretion patterns. The Alimit River, which joins the Magat River between sections M13 and M14, gives little indication of any significant accretion while the Ibulao River, which has its confluence with the Magat River between sections M17 and M18, shows accretion of up to 2m. In the latter case, this may be the result of periodic changes in water level which alternate from a free-flowing river regime to the much reduced velocities of an impounded reservoir. Although there are changes in the water level at the downstream end of the Alimit River, it is always in the flooded state.

7 MAGAT RESERVOIR VOLUME

The reservoir volume is calculated using a computer program (SVPRO3) which follows the Contour Slicing Technique described above in chapter 5. A full listing of the program, together with notes, is given in Appendix 2.

Sub-segment and segment volumes are calculated for each adjacent pair of survey range lines starting at the up-stream reservoir limit and working down to the dam. Where tributaries join the main reservoir, as in the case with the rivers Alimit and Ibulao, the reservoir has be considered in a series of "limbs" because only one channel can be considered at a time. At each confluence the two up-stream sections must be combined to form one boundary - in the case of the Alimit this means that sections M30 and M14 were put together to form section M30/14. Because the program only uses data below a selected top contour level it is not necessary to allow for the true, topographical distance between the two joined sections. For the Magat Reservoir, six limbs were defined as follows:

limb 1 up stream to range line M21
limb 2 M50/21 to M19
limb 3 up-stream to range line M40
limb 4 M40/19 to M14
limb 5 up-stream to M30
limb 6 M30/14 to dam.

With these adjustments, the data were transferred to files MAGVOL78 and MAGVOL84 for the 1978 and 1984 surveys respectively.

Reservoir capacities were calculated below each of the contour levels produced from the original aerial surveys as shown on the following table:

Level (mLD)	1978 Volume ($\times 10^6 m^3$)	1984 Volume ($\times 10^6 m^3$)
+200	1638.63	1618.72
+180	808.24	804.60
+160	352.57	349.96
+140	117.17	115.48
+120	17.86	14.66

From a graph of these water levels (Fig 24) it can be seen that the calculated capacities below the top water level of +193m are:

1978 capacity below +193m = $1346 \times 10^6 m^3$
1984 capacity below +193m = $1324 \times 10^6 m^3$.

A table of technical data produced by the Magat River Multi-purpose Project showed the total storage to be $1090 \times 10^6 m^3$ and an attempt was made to achieve this value using cross-sections taken from the 1978 aerial survey.

Taking the volume of each segment to be the mean cross-sectional area (as calculated by SVPR03) multiplied by the straight line distance between the mid-points of the range lines, gives a reservoir volume below +200mLD of $1291 \times 10^6 m^3$. From the data given above, it will be seen that the volume below +193m is 82% of the calculated volume below the +200m contour. On this basis, the crude assessment discussed above implies a reservoir volume below the Top Water Level of 1059 x $10^6 m^3$. It may be argued that a more representative distance between sections would be achieved by measuring along the line of the original river channel. By this technique, the 1978 capacities below +200m and +193m become 1431 x $10^6 m^3$ and 1173 x $10^6 m^3$ respectively.

The two estimates of reservoir capacity produced above are within ±8% of the value quoted by NIA. This can be taken as confirmation that the computing methods used to calculated cross-sectional areas from discrete data points are working correctly.

As discussed earlier in Chapter 5, the Contour Slicing Technique is currently considered to be the method which produces the most representative reservoir capacity when the only available field data are infrequent cross-sections and contours produced from aerial surveys. It may be possible to increase the accuracy by surveying many more range lines or by employing extremely sophisticated field survey techniques which allow contour following or random data points. However, the greatly increased cost of such systems must be balanced against the use to which the final result will be put and it is thought, at this stage, that such a cost penalty is difficult to justify.

The analysis discussed above is based on the volume of water contained between the sediment/water interface and the +193mLD contour, that is to say the reservoir capacity. It must be stressed that a change in reservoir capacity over a given time period cannot be directly related to catchment erosion rates because of compaction and consolidation of the sediments. This aspect is discussed in the next chapter.

Previously in this chapter a reduction is indicated in reservoir volume of 22 x $10^6 m^3$ during the time between the two surveys. It is reasonable to assume that the pre-impoundment volume was the same as that recorded in 1978 and so it follows that initially, the reservoir volume was reducing at a rate of 11 x $10^6 m^3$ per year. This is exactly double the estimated rate quoted on page III.26 of the Magat Feasibility Report (NIA Eng Cons Inc (1978)).

Figure 25 shows the accretion/erosion pattern which occurred during the first two years of operation. It will be seen that the accretion rate peaks at the confluence of the Magat River with the Ibulao and Alimit Rivers. Apart from the most upstream section where the river bed is raised above the reservoir top water level, the maximum rate of accretion occurs just over 32km from the dam which agrees with the statement on page B-18 of the Feasibility Study. The peak in erosion at approximately 15km from the dam is more difficult to explain - the cross-section plot for range line M9B shows that in 1984 the section has been eroded on the outside of the curve and that there was a channel on the right bank which had not been located by the earlier NIA survey. Both of these phenomena were confirmed by more than one survey point and so it is assumed that the 1984 calculated volume is correct and that a subsequent survey will be needed to confirm or refute the erosion trend in this segment.

The minimum supply level is +160mLD but the reservoir would cease to have a useful life after the bed level at the dam reached the outlet invert level of +147mLD. From Figure 24 it will be seen that reservoir capacities below this level were:

1978 180 x $10^6 m^3$
1984 175 x $10^6 m^3$

which implies an annual accretion rate of 2.5 x $10^6 m^3$ over the two years since impoundment.

The process of reservoir sedimentation goes through at least three main phases:

Phase 1 - larger particles normally transported as suspended bed load are deposited at the upstream reservoir limit when the river enters a body of still water.

Phase 2 - these deposits are gradually re-worked as the reservoir goes through cycles of filling and emptying.

Phase 3 - Eventually the sediment reaches the area immediately up-stream of the dam and is retained in the "inactive" (or "dead") storage area.

At the time of the 1984 survey, Magat reservoir was entering Phase 2 and this can clearly be seen in Figure 25 which shows the bulk of the accretion to be occurring upstream of the Alimit river. Following the logical progression of the three phases given above, it seems reasonable to assume that the sedimentation rate in the "inactive" storage area will reach 11 x $10^6 m^3$/year during Phase 3; this, of course, presupposes that there will be no significant change in the catchment sediment yield during this period. An estimate of reservoir life - the time taken for the sediment surface to reach the reservoir outlet level -

can therefore be based on a mean of the present ($2.5 \times 10^6 m^3$/year) and future ($11 \times 10^6 m^3$/year) sedimentation rates.

The curve plotted in Figure 26 is based on a sedimentation rate of $7 \times 10^6 m^3$/year and it shows that the turbine invert level of +147mLD will be reached in about 40 years.

8 CATCHMENT SEDIMENT YIELD

As has been stated earlier, hydrographic surveys of reservoirs are specifically designed to locate the sediment/water interface and thus to enable the change in capacity to be calculated. Any attempt to convert a volumetric estimate to a gravimetric estimate, in order to evaluate catchment erosion rate, requires a knowledge of the consolidation and compaction behaviour of the specific sediment involved. A number of empirical studies have been undertaken in an attempt to understand these processes and they have been examined by Bolton (1986).

In the case of Magat Reservoir however, the short time interval between impoundment and the first hydrographic survey means that the effects of consolidation and compaction are so small that they are lost within the other inaccuracies of the field data collection and analysis techniques. Hence, it is only possible to make a very crude assessment of catchment sediment yield based on the volumetric calculation made in the previous chapter.

The analysis in Chapter 7 only takes account of the volume of material which is trapped in the reservoir, but some of the eroded material will remain in suspension and will pass through the turbines or over the dam. The proportion of material trapped to material supplied is termed the "trap efficiency" of the reservoir and Brune (1958) showed this to be closely related to the capacity/inflow ratio of the reservoir. Using Brune's data, the trap efficiency for Magat Reservoir is about 92%; it can therefore be assumed that an accretion rate of $11 \times 10^6 m^3$ per year represents 92% of the material eroded from the catchment. On this basis, the annual catchment erosion rate for Magat is $12 \times 10^6 m^3$. Taken over a drainage area of 4123km^2, this is equivalent to an erosion rate of 2911m^3/km^2/year or 2.9mm/year averaged over the whole catchment.

As was stated earlier, the conversion from volumetric to gravimetric values is open to question, but in order to compare these erosion rates with those quoted in the feasibility draft report (NIA & Eng Cons. Inc (1978)), some estimate has to be made. On page B-16 of the report it is stated that (based on the USBR method for calculating sedimentation rates and applying them to the Magat site)..." the unit weight of the first year's deposit is 1320kg/m^3". Using this as the conversion factor then an erosion rate of 2896m^3/km^2/year is equivalent to an annual sediment yield of about 3800 t/km^2 or 38t/ha.

9 DISCUSSION AND CONCLUSIONS

The preceding chapters have described the methods by which pre- and post-impoundment survey data have been obtained and analysed. The resulting values may be directly compared with estimates derived during the Magat Reservoir Feasibility Study as follows:

Parameter	Feasibility Report	Survey Report
Reservoir sedimentation rate	5.5 x 10^{6}m^3/year	11 x 10^{6}m^3/year
Time to fill to +147m	100 years	40 years
Catchment erosion rate	2000 t/km^2/year	3800 t/km^2/year

The feasibility report values were, of course, based on average sediment and water yields whereas the hydrographic survey provides more of a "snap-shot" answer which may be some way away from the mean. However, many previous studies have shown measured rates of siltation to be significantly greater than the design values and some examples are listed in Table 1. In the examples shown, the annual rates of reservoir siltation range from 1.46 to 16.36 times the designed values and on this basis, the factor of two for Magat indicates a good initial estimate.

One reason for the disparity between assumed and observed siltation rates may be that actual erosion rates vary with time. Displacement of the indigenous population when a reservoir is impounded leads to new land, frequently with steeper slopes, being brought under cultivation (Plate 6). This increases the erosion risk and, when combined with the likely influx of settlers attracted by the supply of water, is bound to give rise to a high siltation rate that is difficult to predict. A limited number of studies have been made of the change in sediment yield with time and they indicate increases in yield of between 25% and 50% per decade for the Asian region.

The differences between reservoir volumes calculated for the Feasibility Report, and as re-worked in this report have been explained in Chapter 7.

Parameter	Feasibility Report	Survey Report
Reservoir vol below +147m	$150 \times 10^6 m^3$	$180 \times 10^6 m^3$
Reservoir vol below +193m	$1075 \times 10^6 m^3$	$1346 \times 10^6 m^3$

However, there is still a need for further work to be done on producing an optimum method for the collection and analysis of reservoir hydrographic survey data. In the meantime, provided that pre-impoundment contour data are available for the site, then the contour slicing technique would seem to be the best method available at present. The method makes assumptions about the way in which sediment is distributed between range rise and these may not be strictly correct, but it does make allowance for irregular reservoir boundaries which the comparisons made in Chapter 7 have shown to be very important.

Because of inaccuracies inherent in both the collection and analysis, it is recommended that the next survey should be considered in three years time (that is to say in 1987, five years after impoundment) and thereafter at not less than five year intervals.

10 ACKNOWLEGEMENTS

The reservoir surveys and data analysis described in this report form part of an investigation being undertaken by the Overseas Development Unit (ODU) of Hydraulics Research Limited (HRL), in collaboration with the National Irrigation Administration (NIA) of the Philippines.

NIA provided field staff, road transport, boats and accommodation throughout the duration of the survey. NIA also supplied all the data and maps for the pre-impoundment survey.

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Mr R Medina	Division Manager
Mr R Baloloy	Senior Hydrologist
Mr J Abelos	Surveyor
Mr E Bucao	Engineering Aide

The hydrographic survey was carried out in 1984 under the supervision of an HRL surveyor, Mr J C M Binks. Much of the data analysis was carried out at HRL by Mr A P E Green and Mrs S Helby.

The Overseas Development Unit at HRL is headed by Dr K Sanmuganathan and the ODU input to this project was funded by the Overseas Development Administration of the Foreign and Commonwealth Office, London, UK.

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Table

Table 1: Designed and observed reservoir siltation rates

Reservoir	Annual rate of siltation (million cubic meters) designed	observed	Source
Karangkates (East Java)	0.33	2.04	Brabben (1982)
Wlingi (East Java)	0.38	1.42	Fish (1983)
Bhakra (Punjab, India)	28.4	41.6	Patnaik (1975)
Panchet (DVC, Bihav, India)	2.5	11.8	Patnaik (1975)
Tungabhadra (Karnatika, India)	12.1	50.6	Patnaik (1975)
Nizam Sagar (Andra Pradesh, India)	0.66	10.8	Patnaik (1975)
Ukai (Gujarat, India)	9.2	26.8	Patnaik (1975)
Kamburu (Kenya)	0.3	2.3	Wooldridge (1984)
Magat (Philippines)	5.5	11.0	

Figures

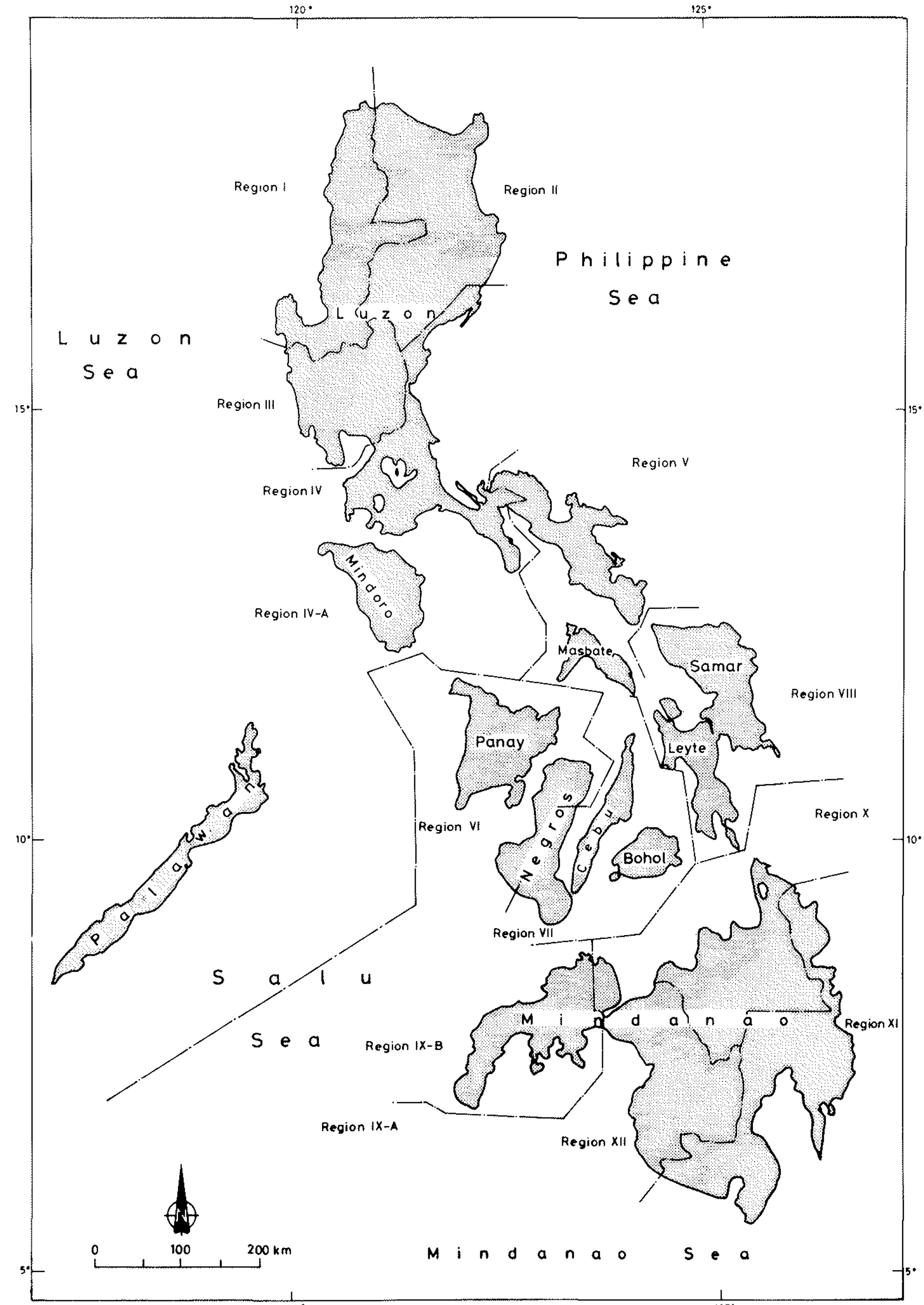


Fig 1 Map of the Philippines

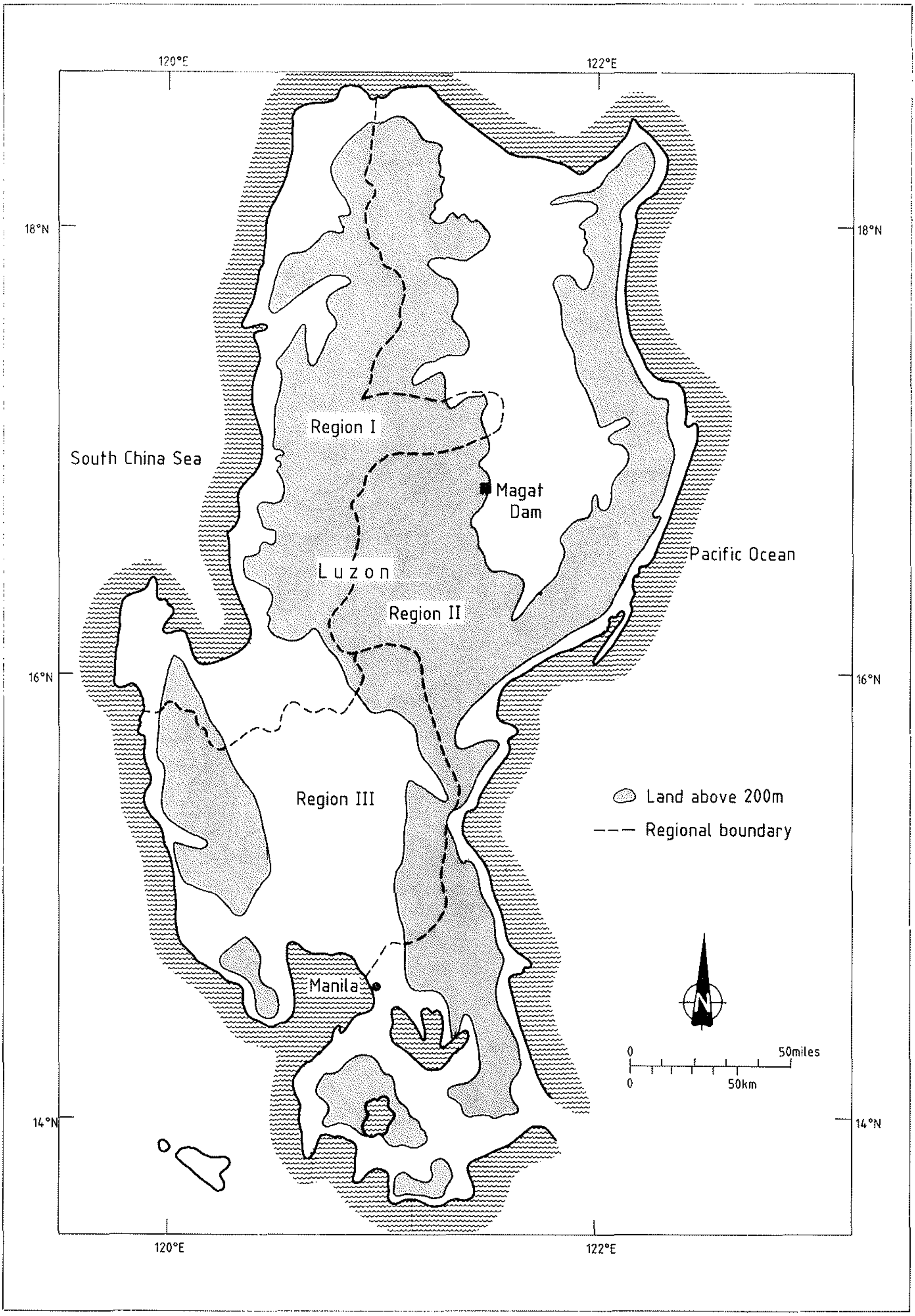


Fig 2 Map of Luzon

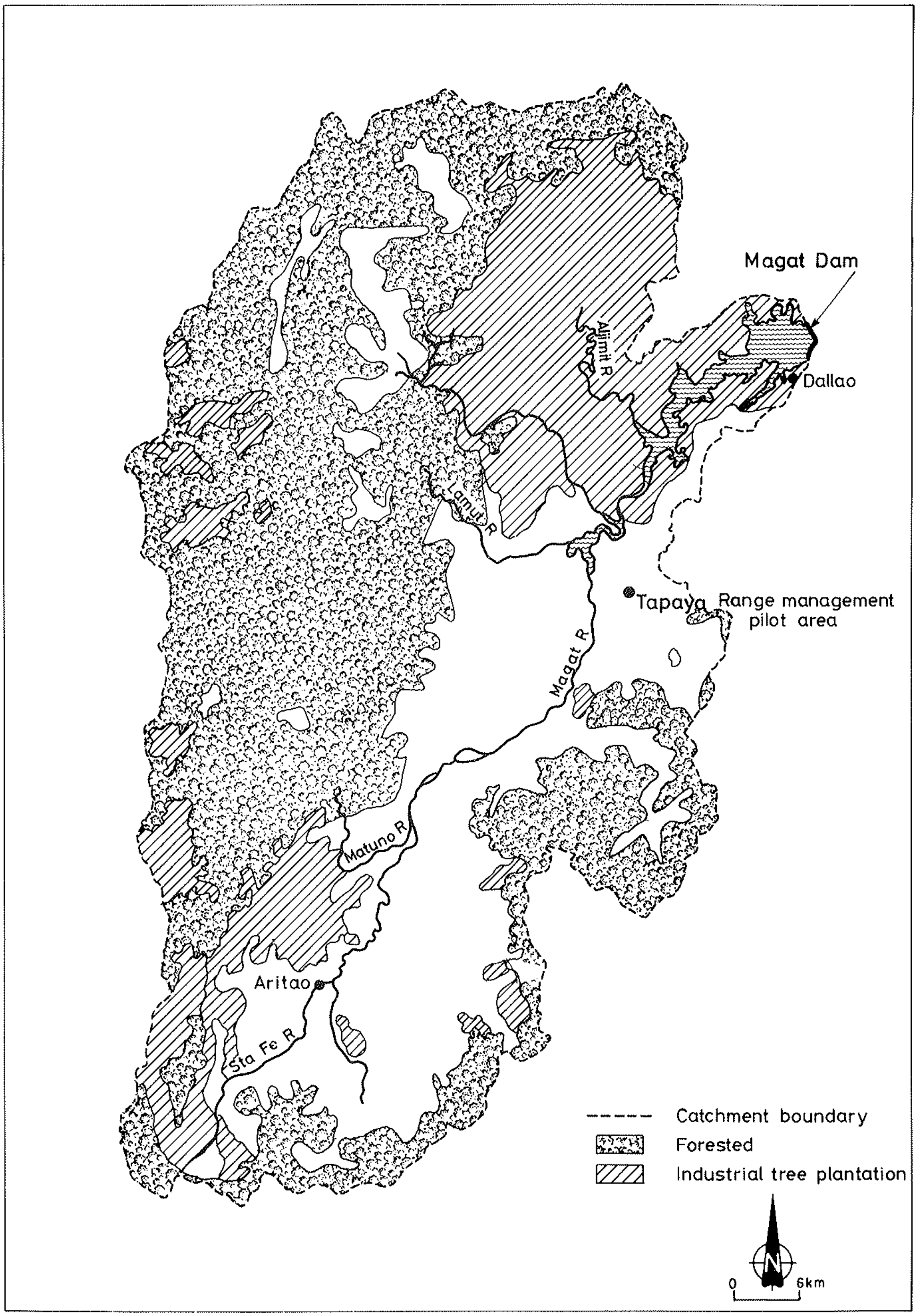


Fig 3 Magat reservoir catchment

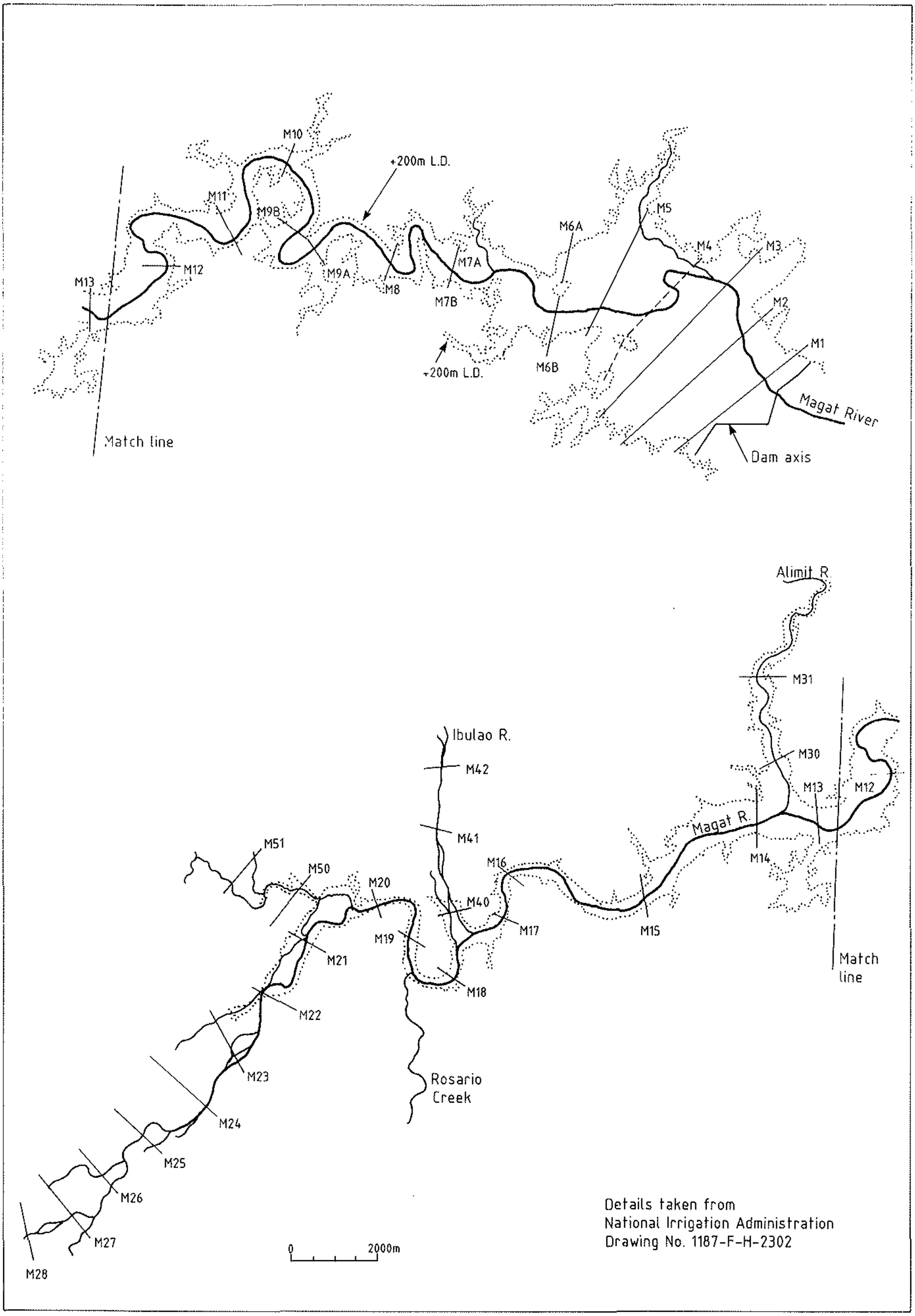
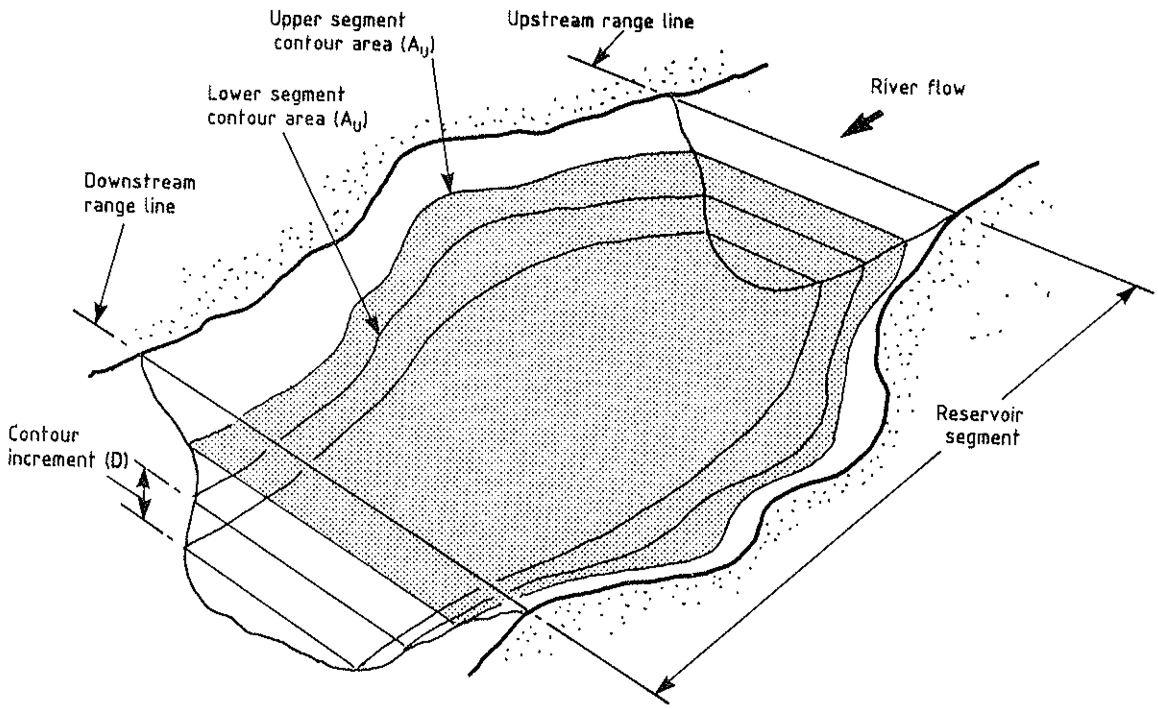
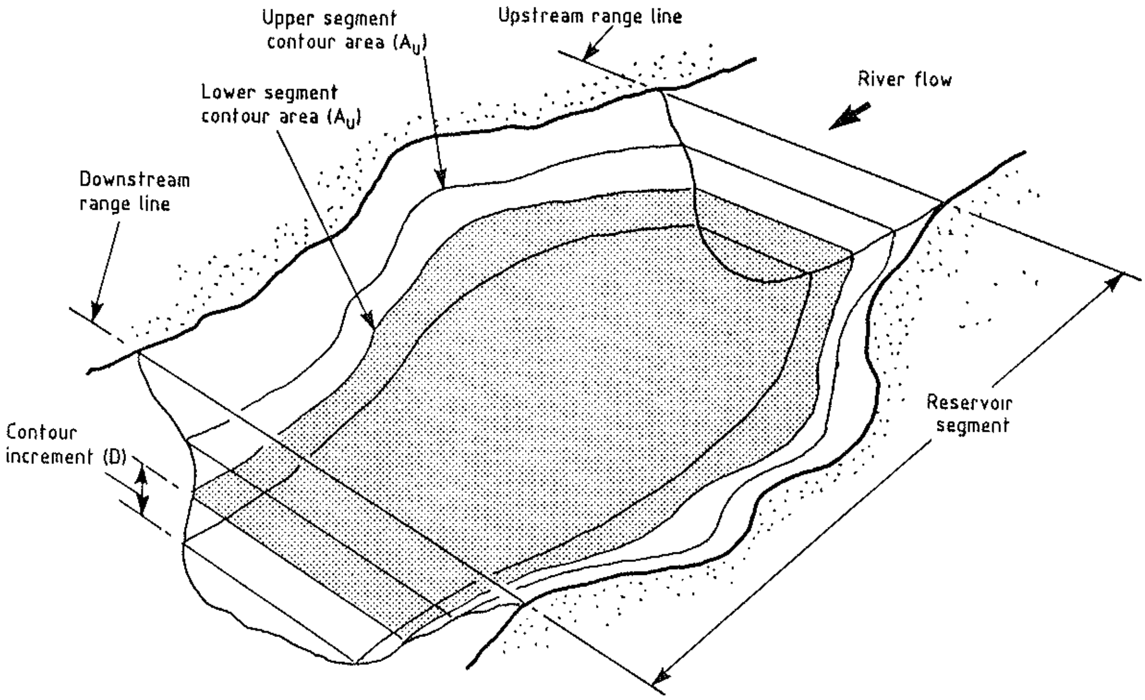


Fig 4 Magat Reservoir - sediment range system

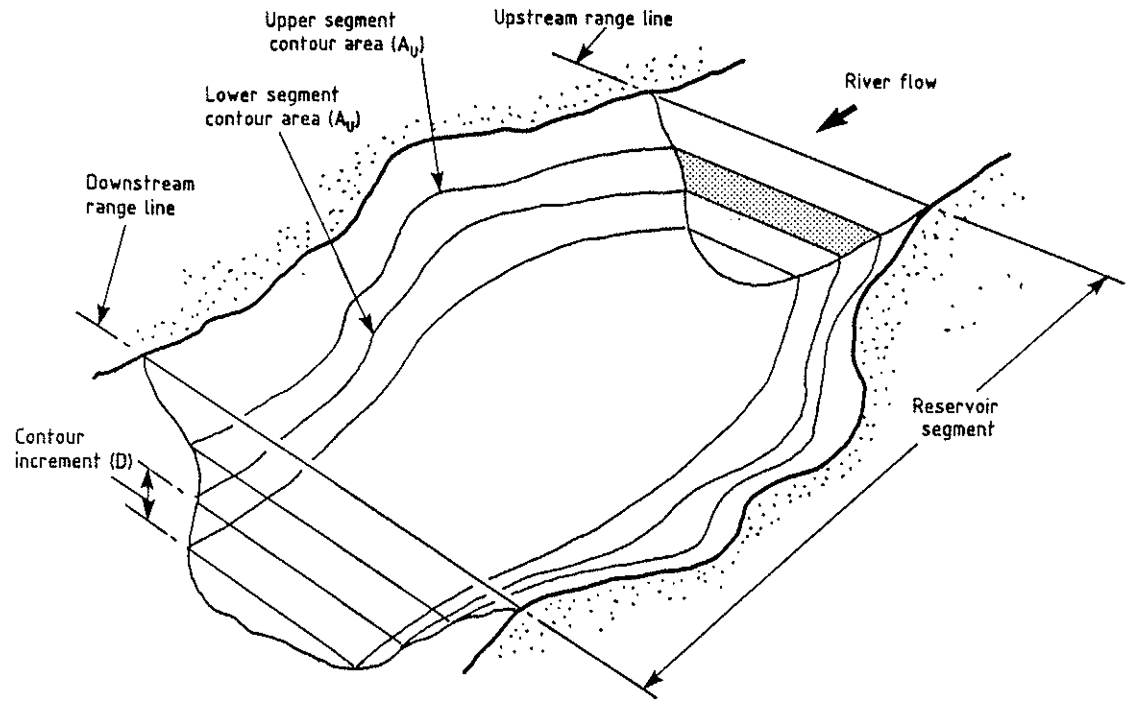


A. Upper segment contour area (A_U)

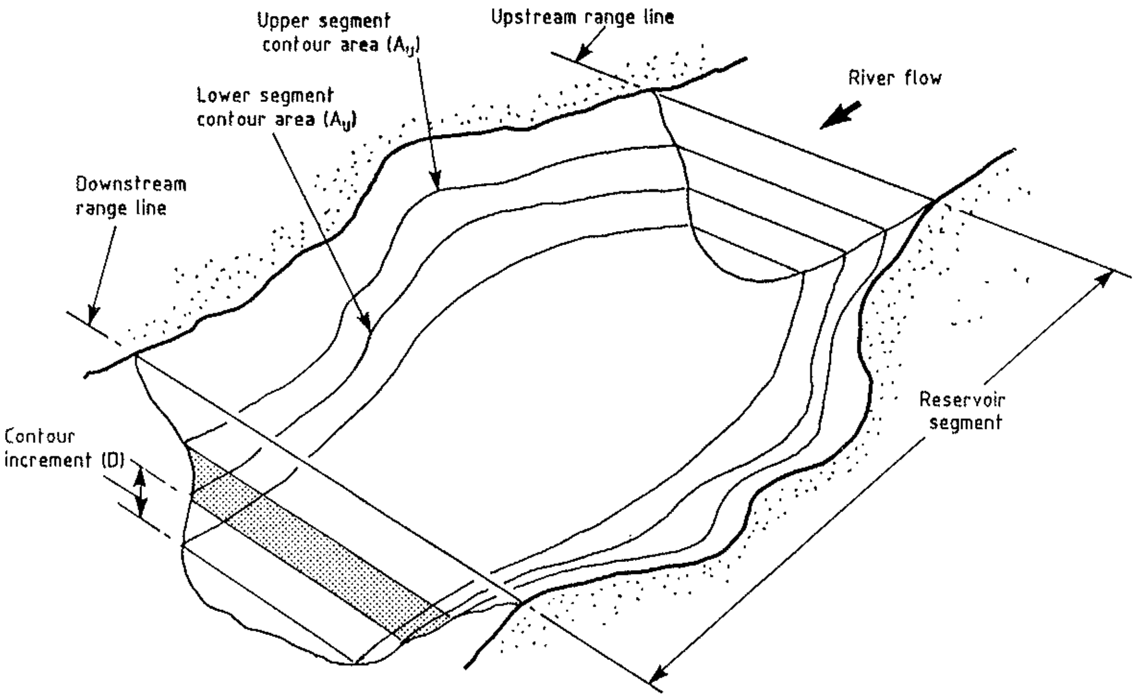


B. Lower segment contour area (A_L)

Fig 5A & B Contour slicing technique - definition

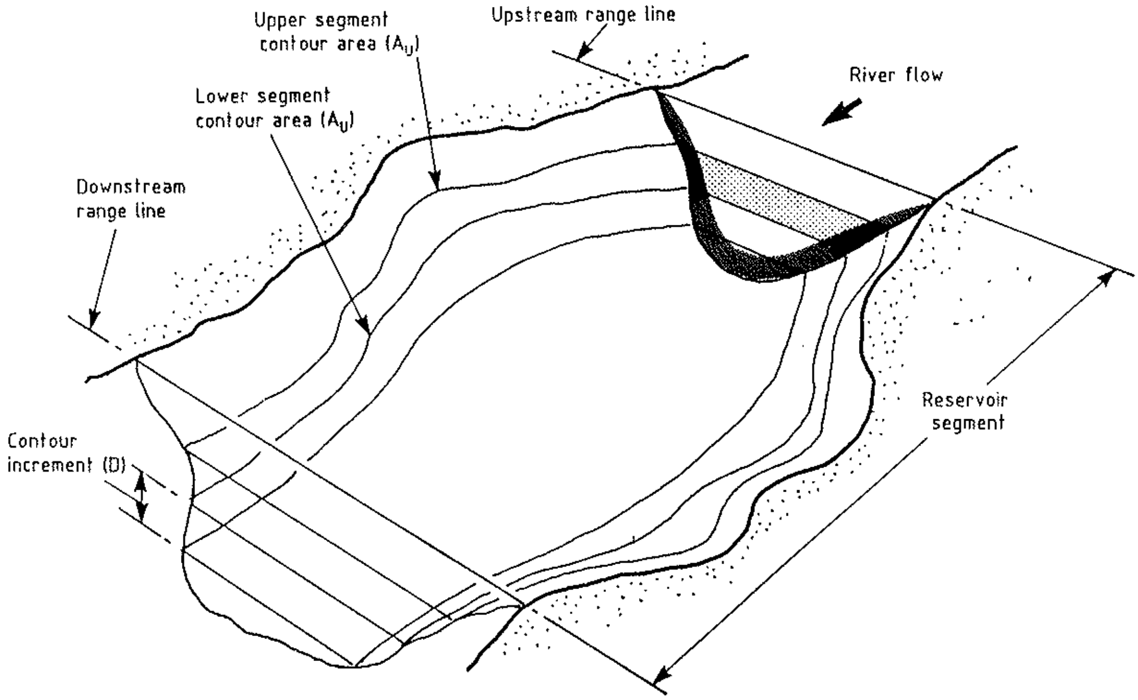


C. Up-stream sub-segment end area (a_u)

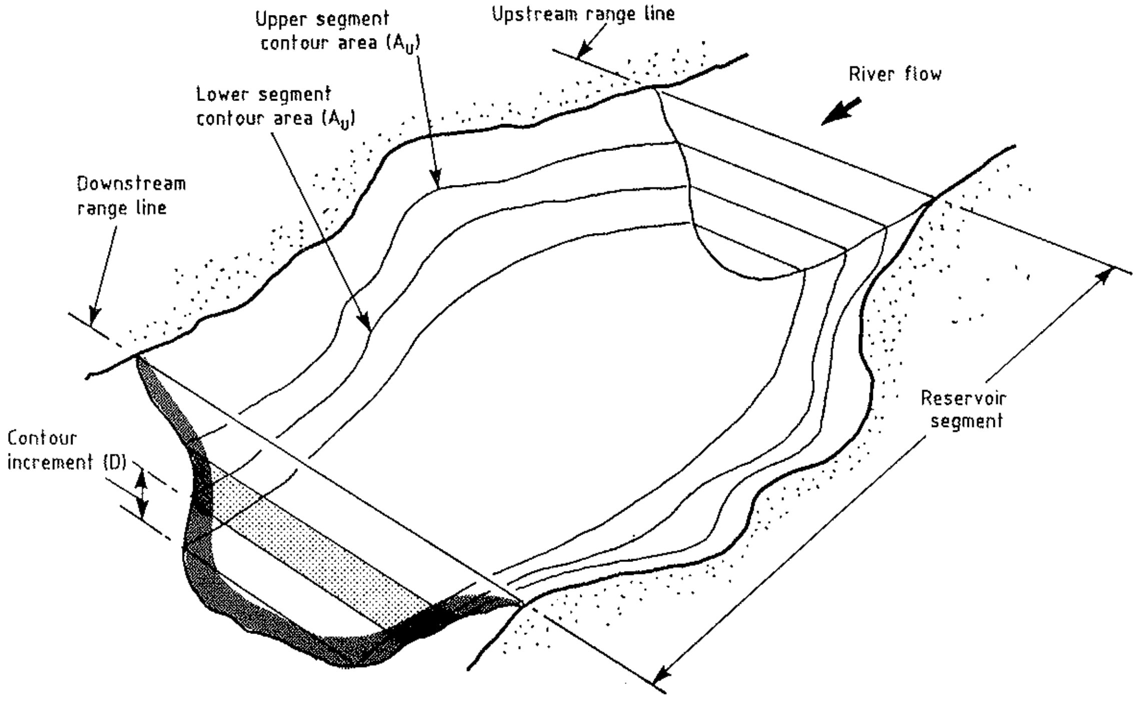


D. Down-stream sub-segment end area (a_d)

Fig 5C & D Contour slicing techniqne - definition

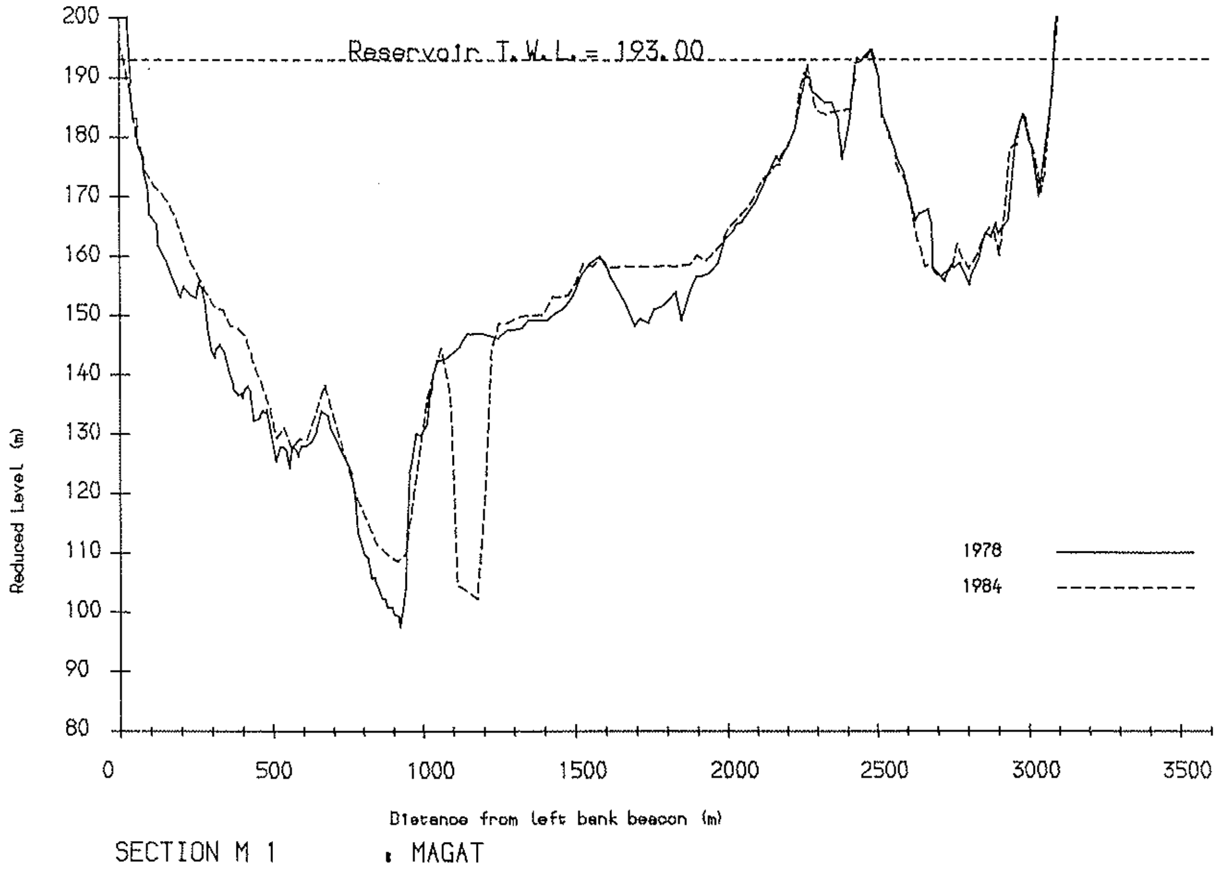


E. New u/s sub-segment end area (a'_u)



F. New d/s sub-segment end area (a'_d)

Fig 5E & F Contouring slicing technique - definition



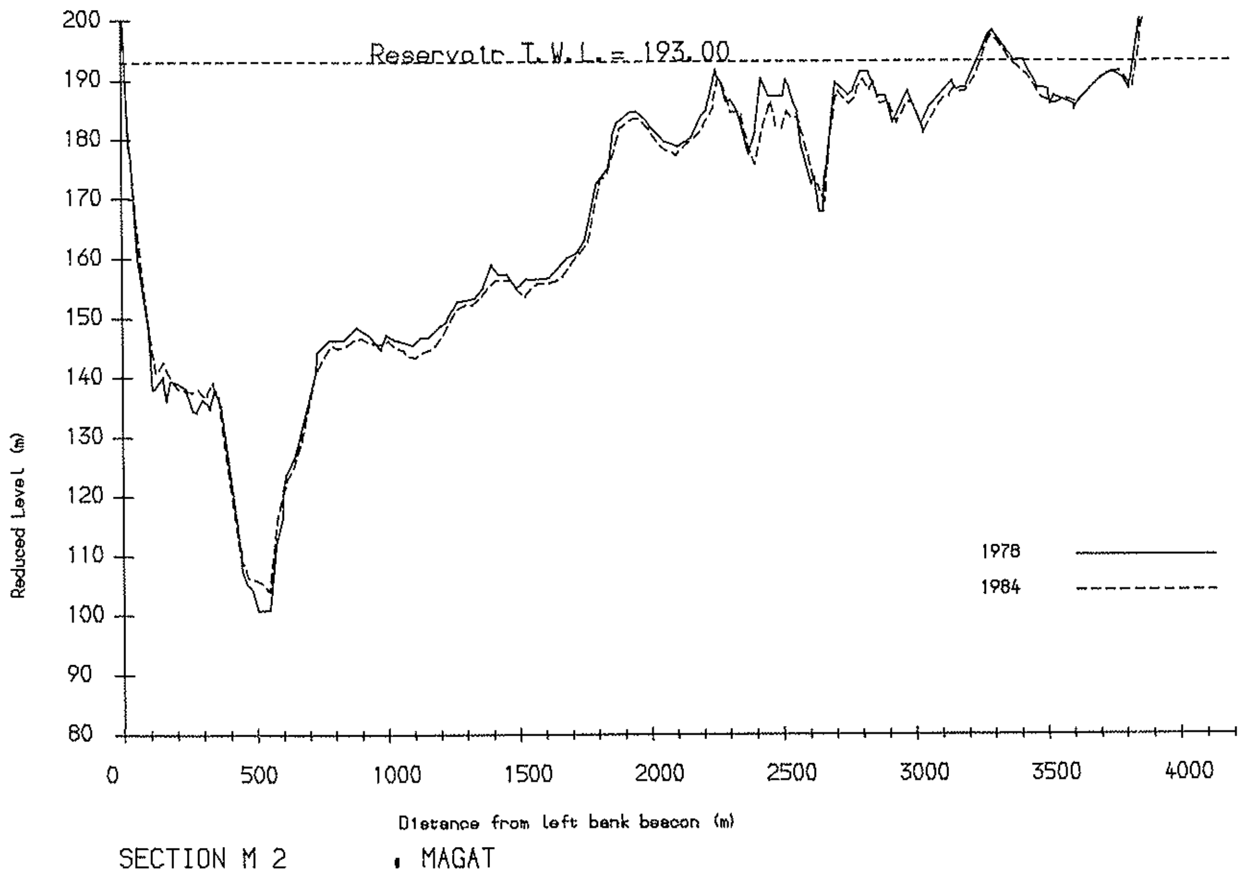
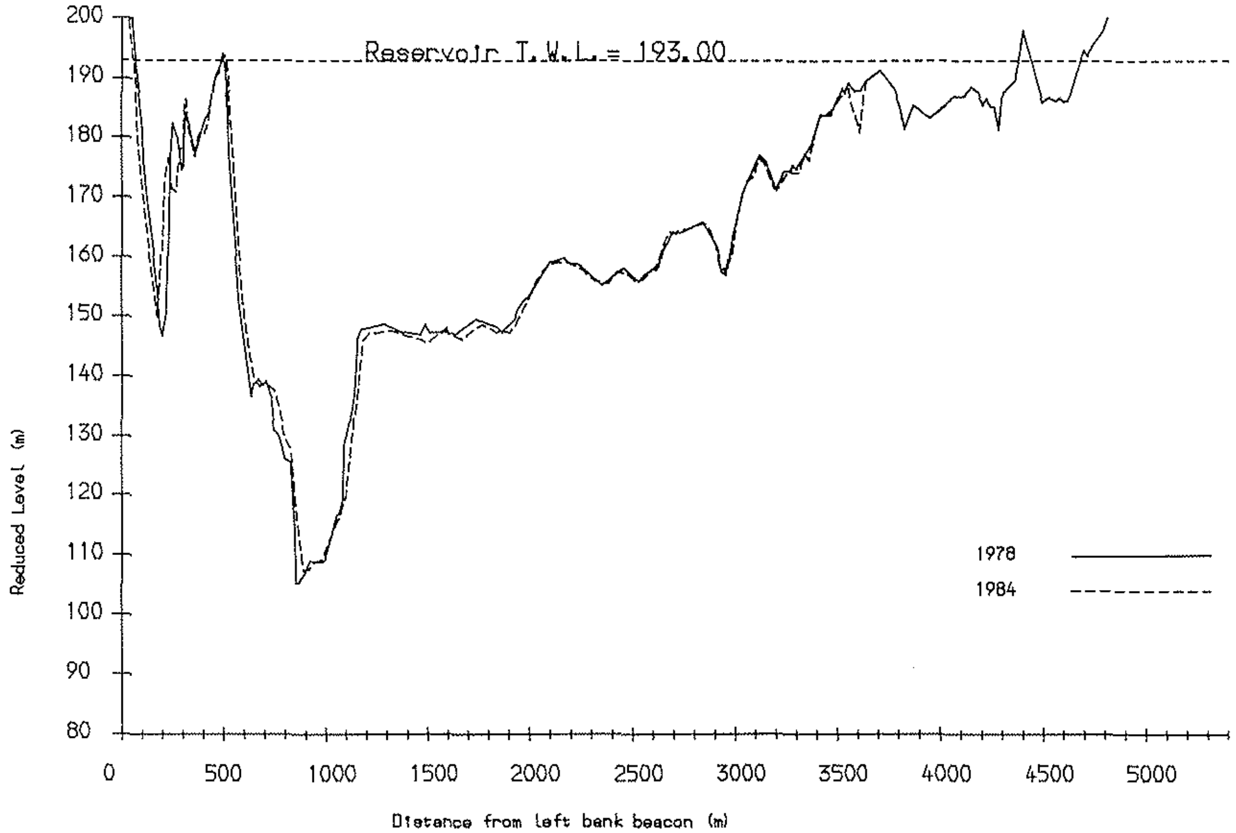
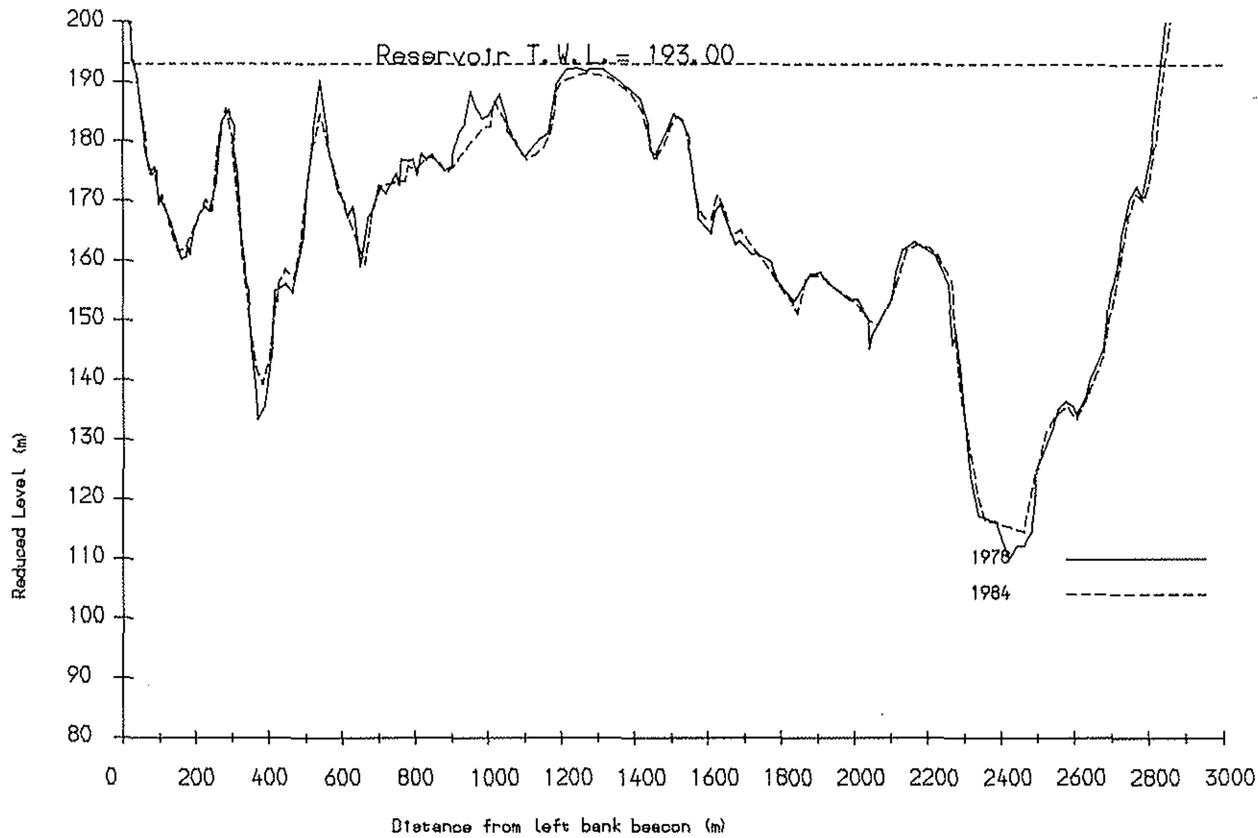


Fig 6 Section Nos. M1 and M2

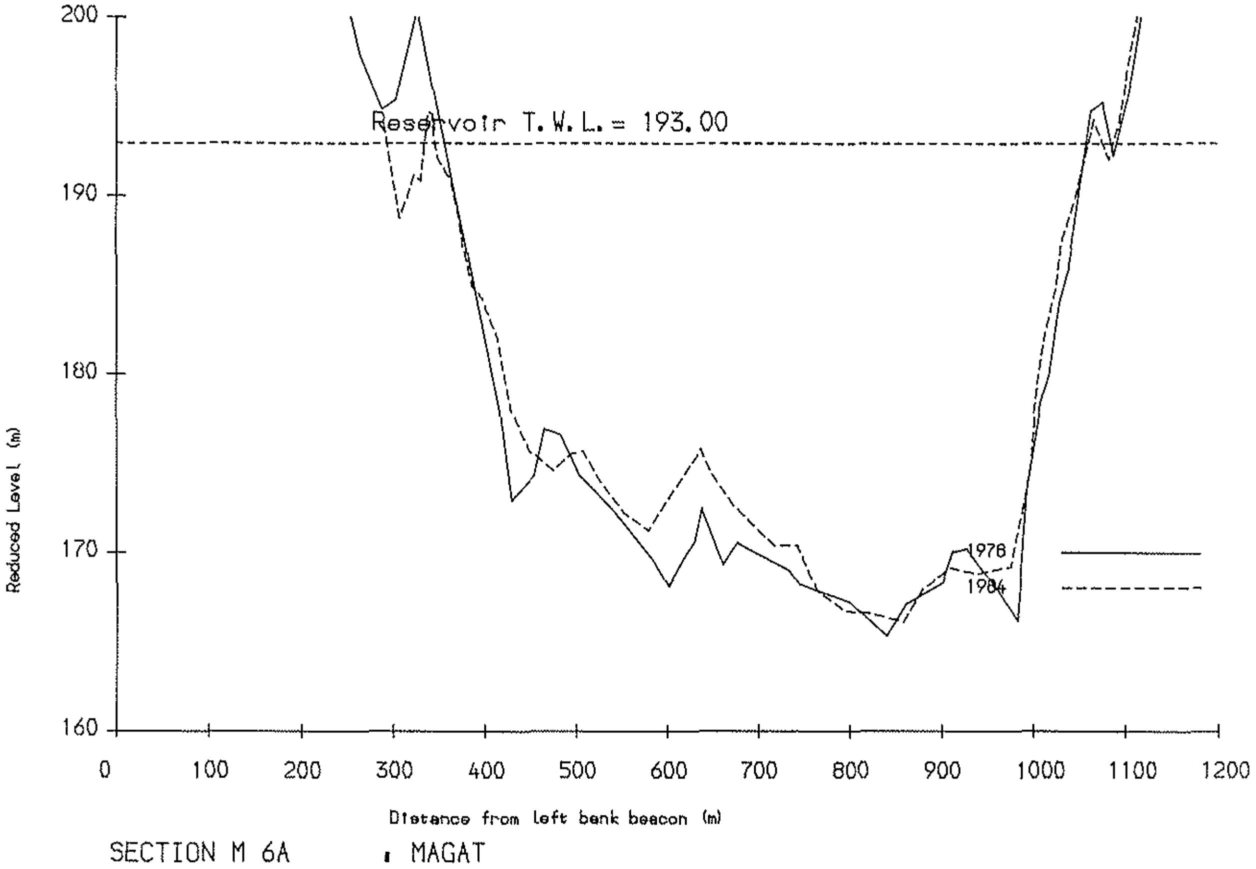


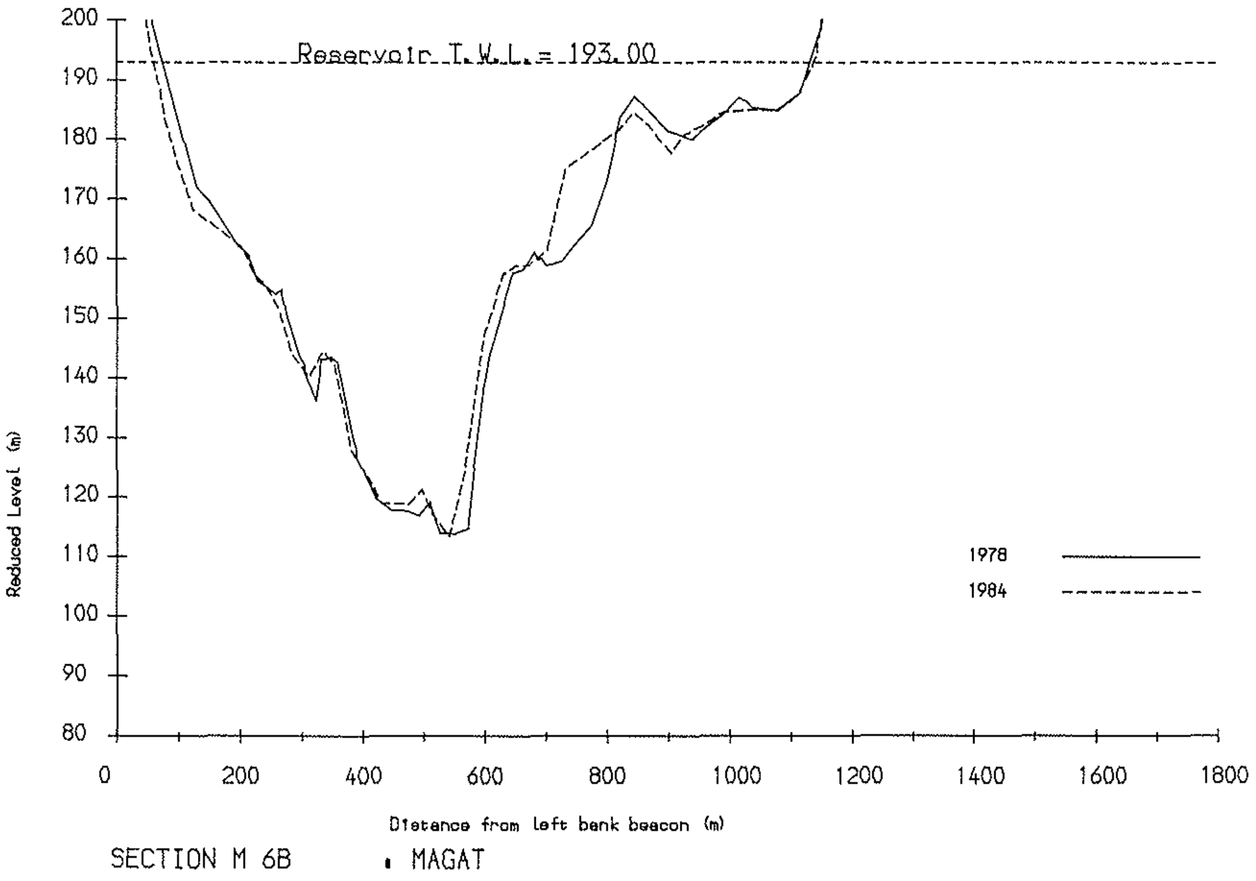
SECTION M 3 : MAGAT



SECTION M 5 : MAGAT

Fig 7 Section Nos. M3 and M5





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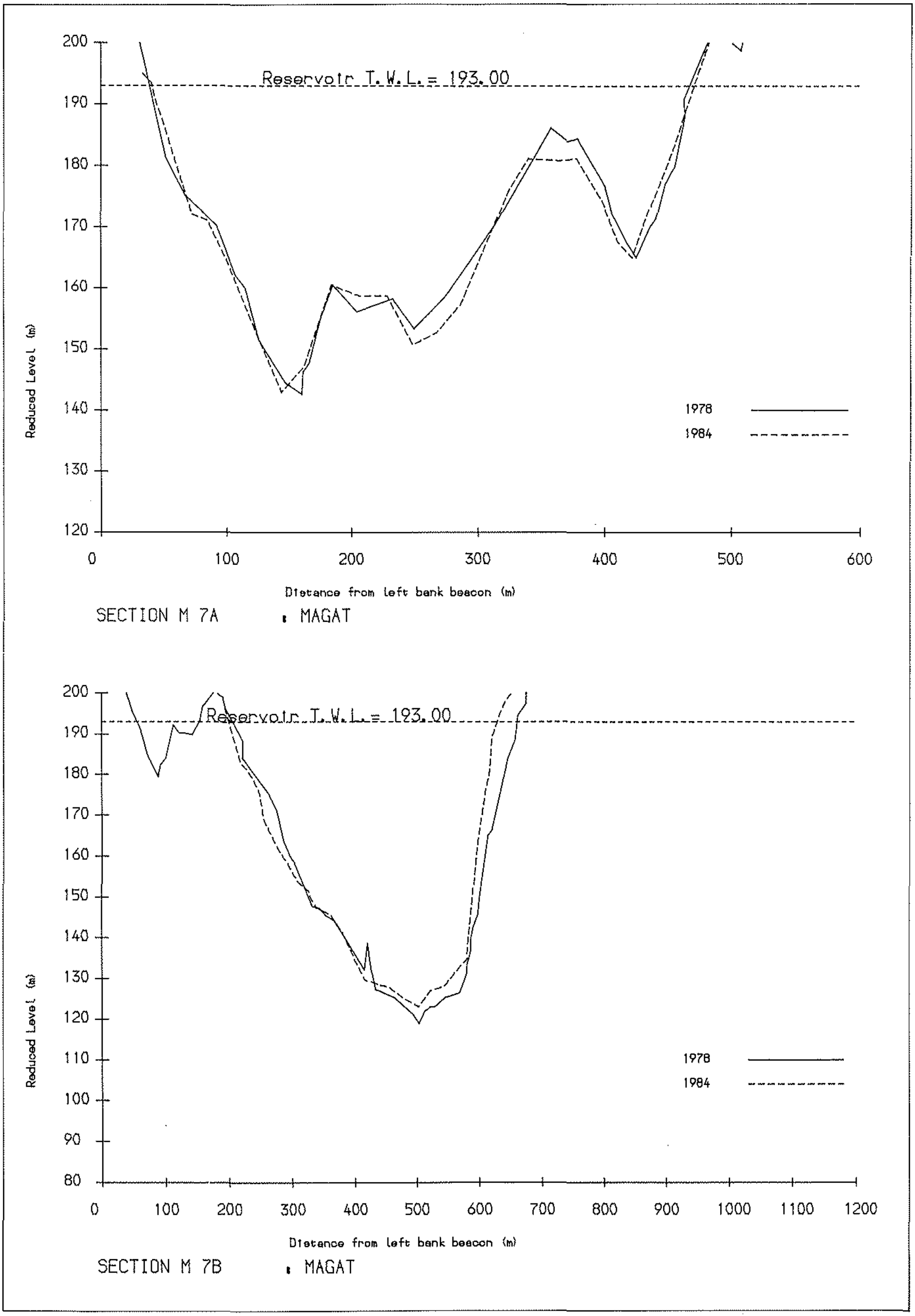

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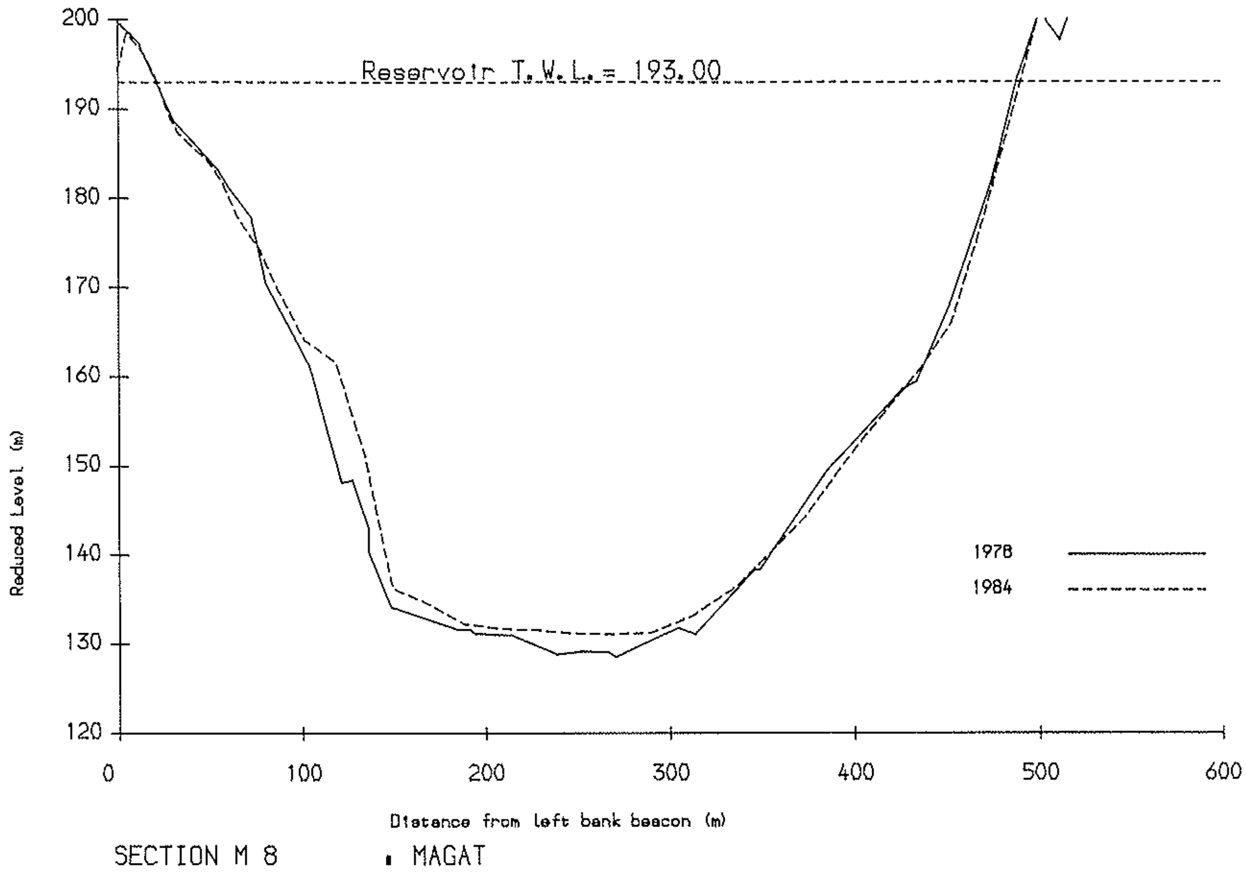

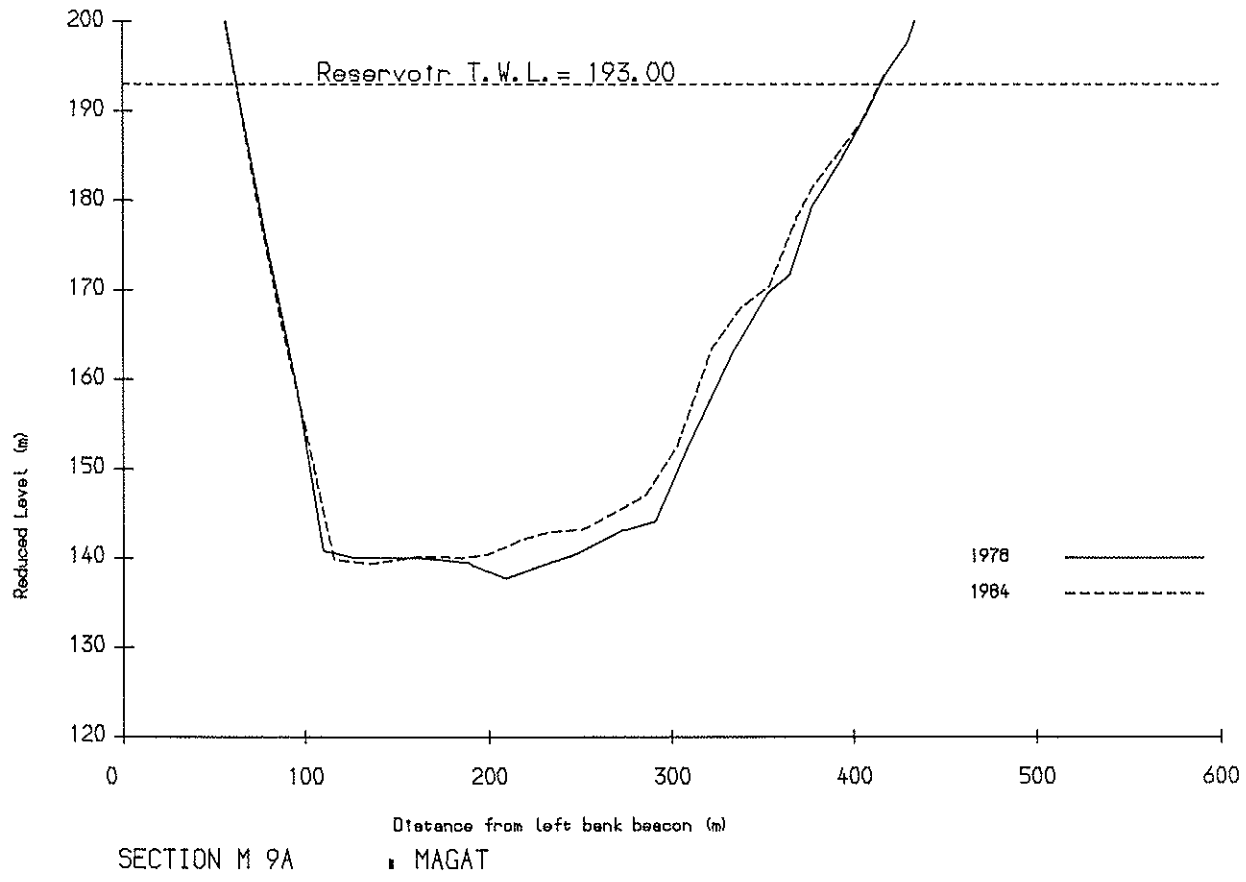

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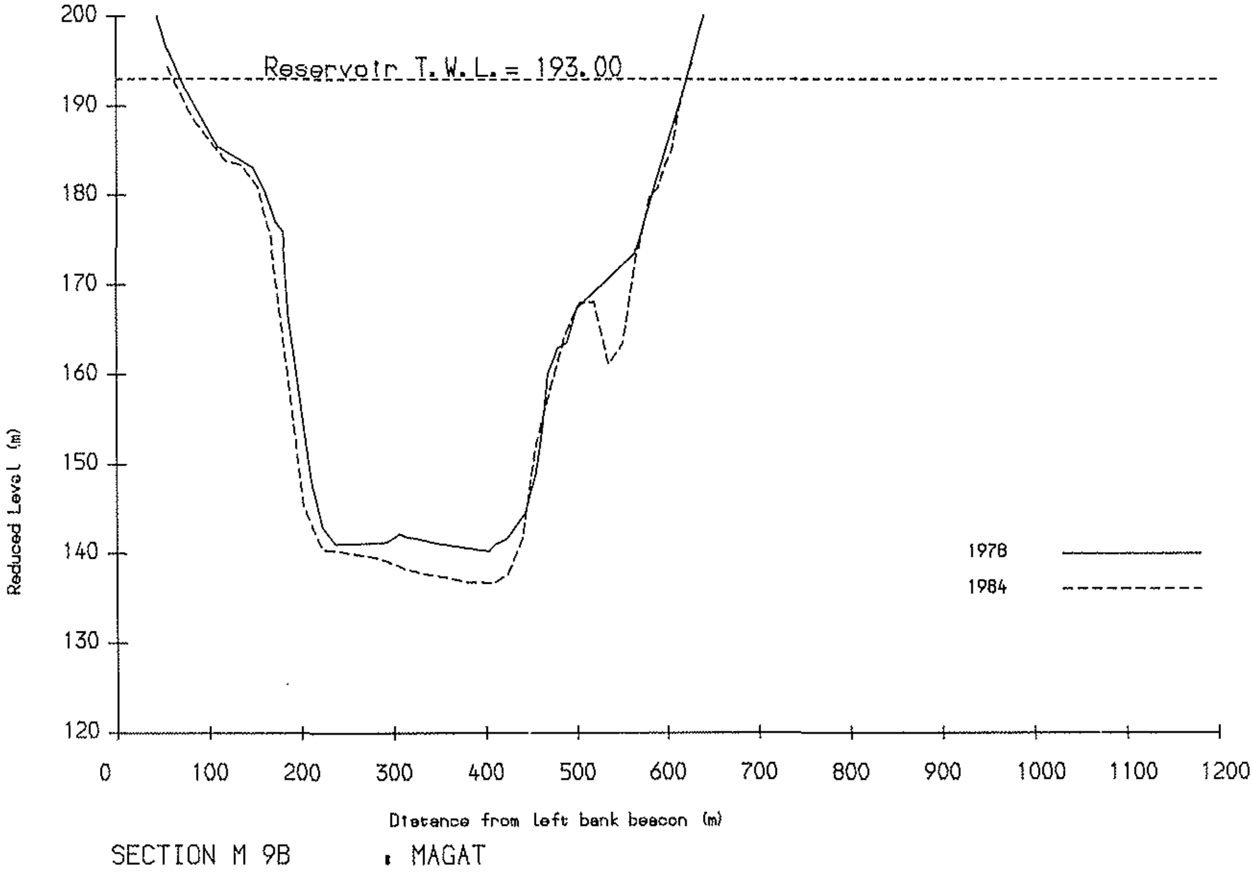


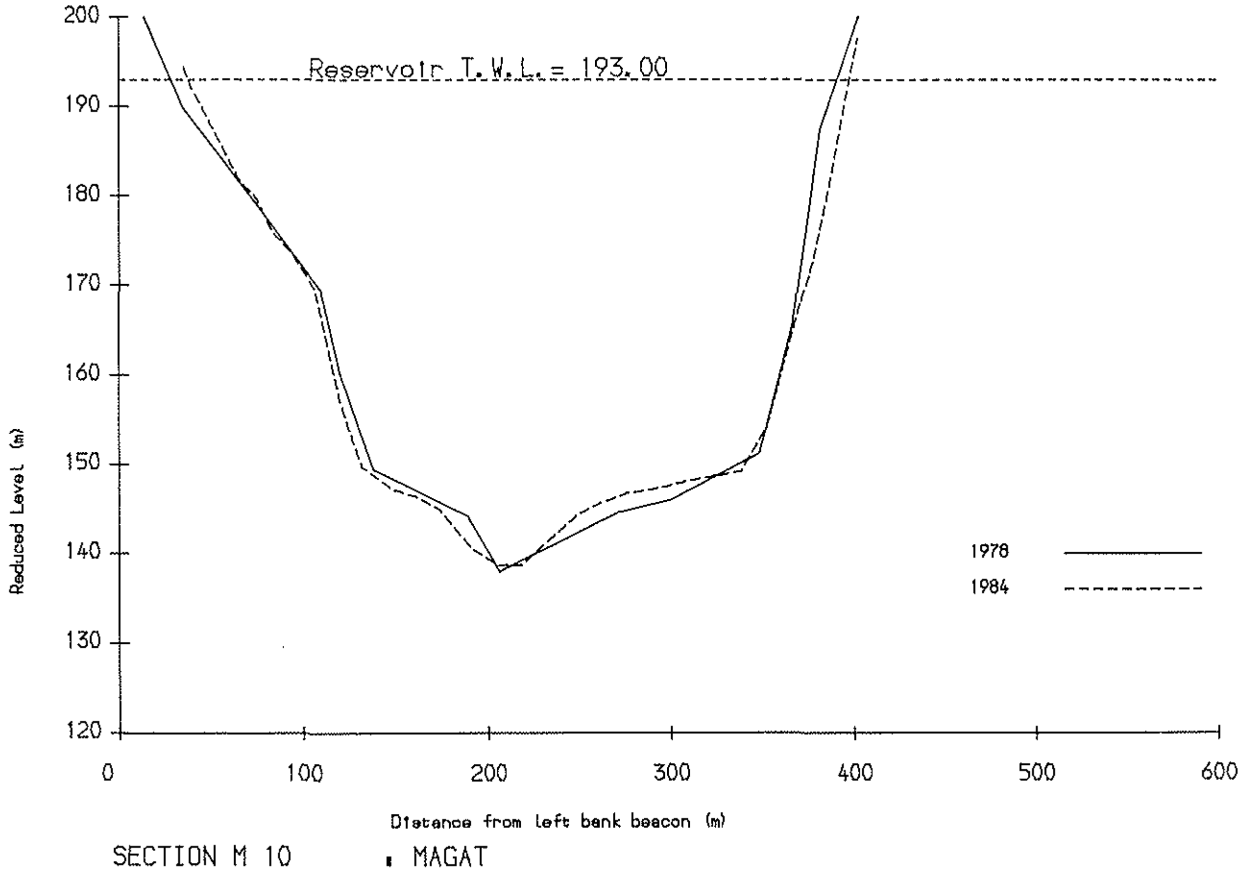
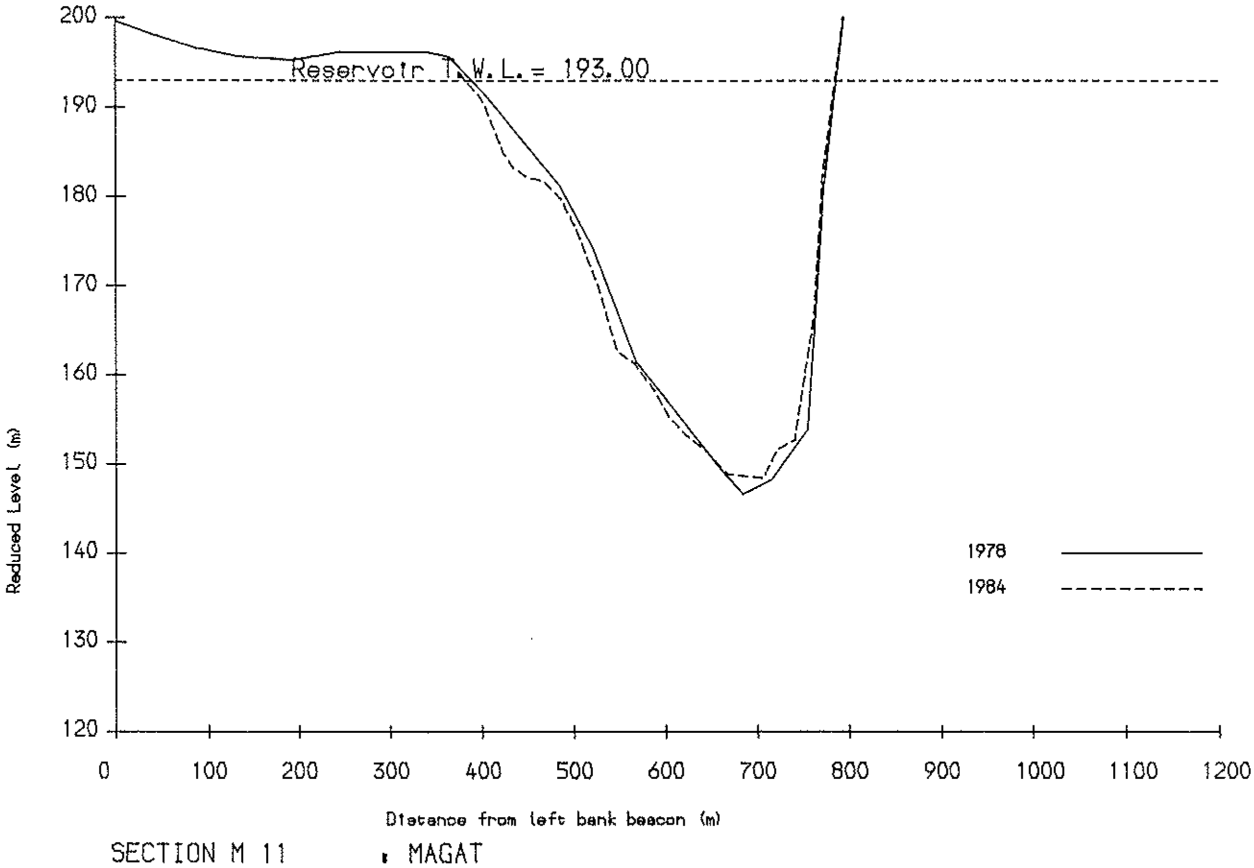
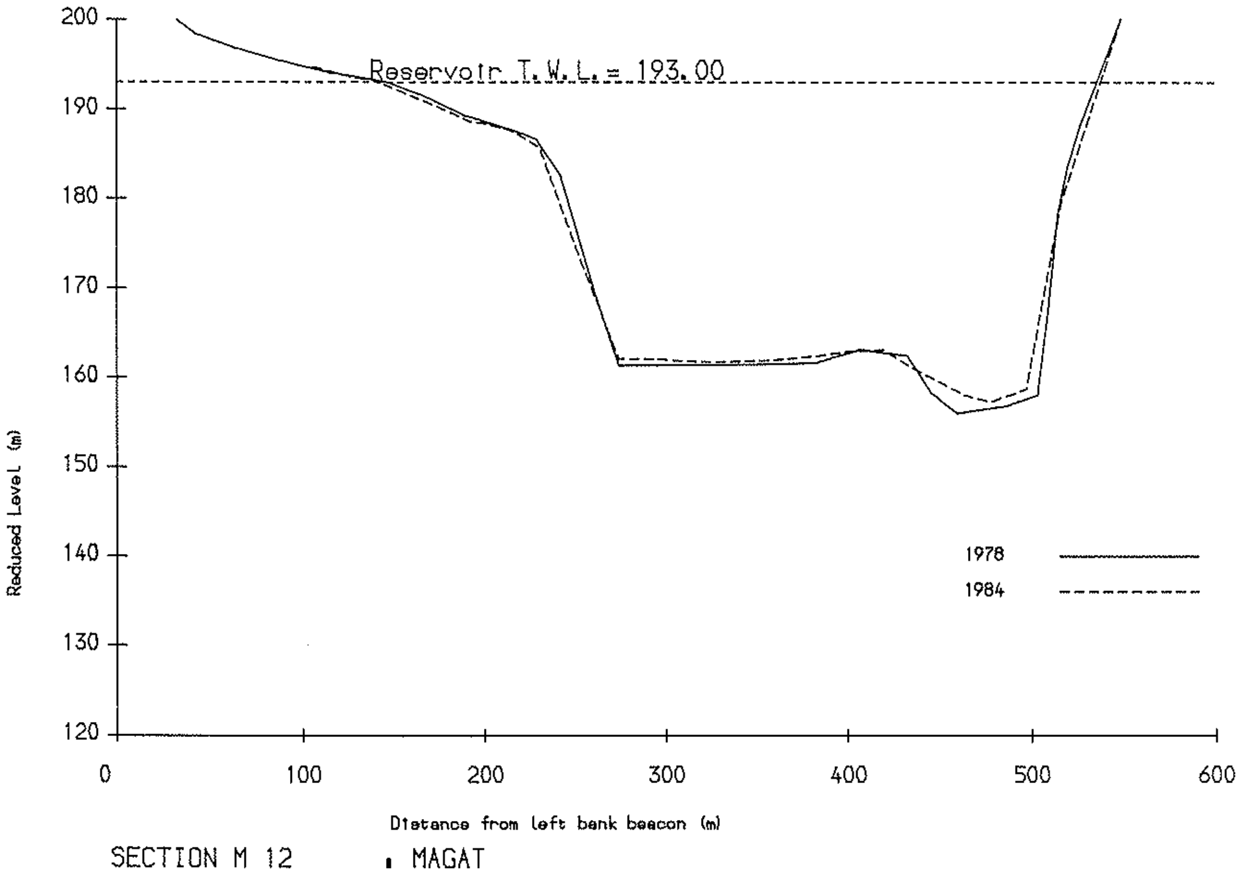


Fig 11 Section Nos. M9B and M10





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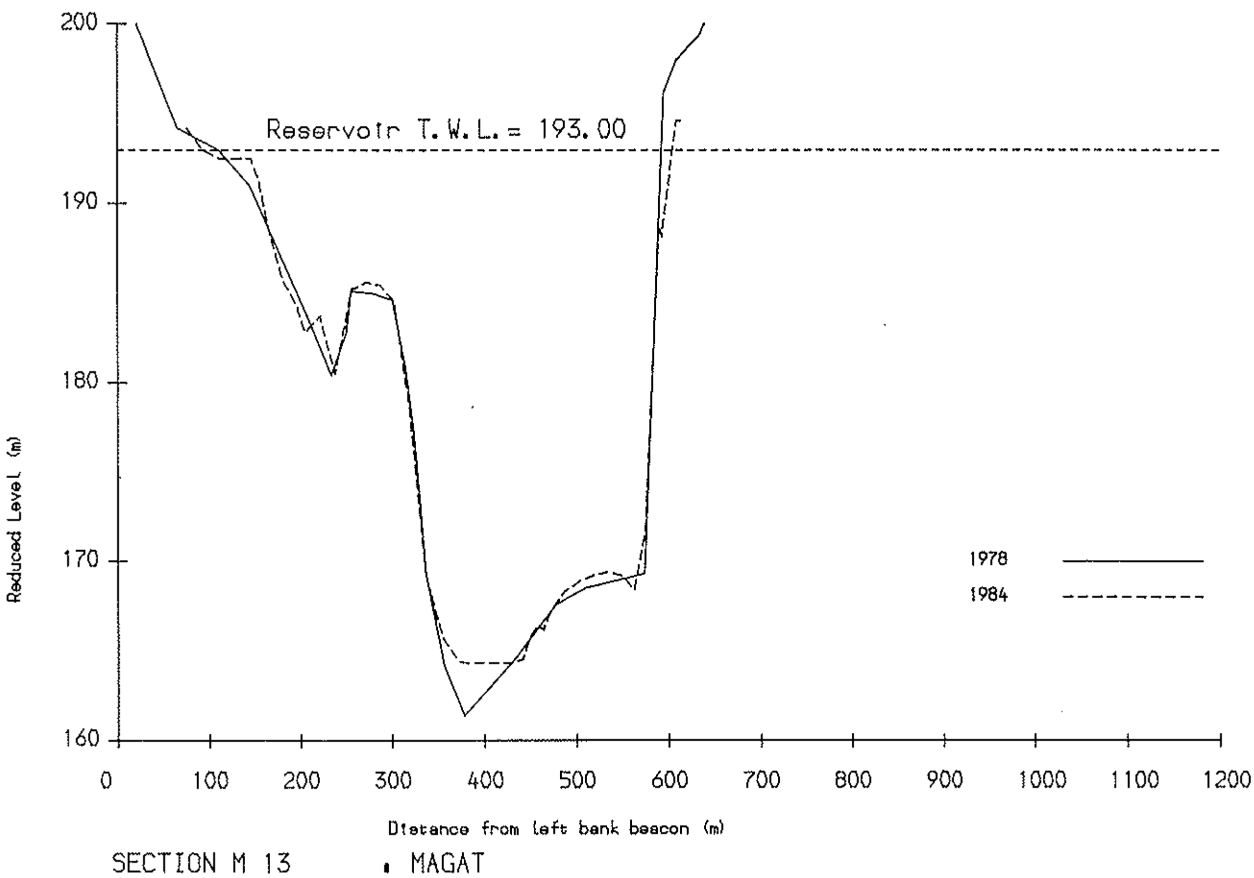

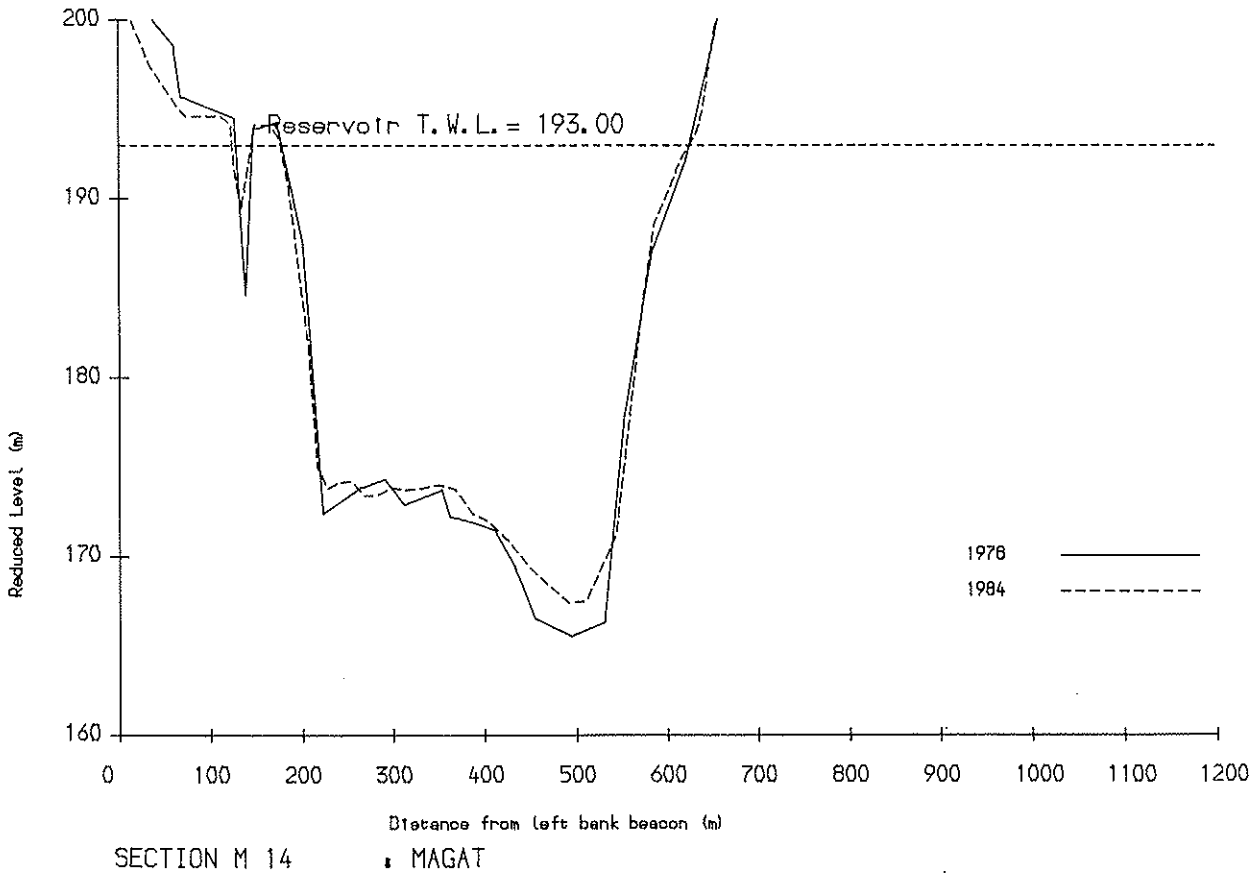

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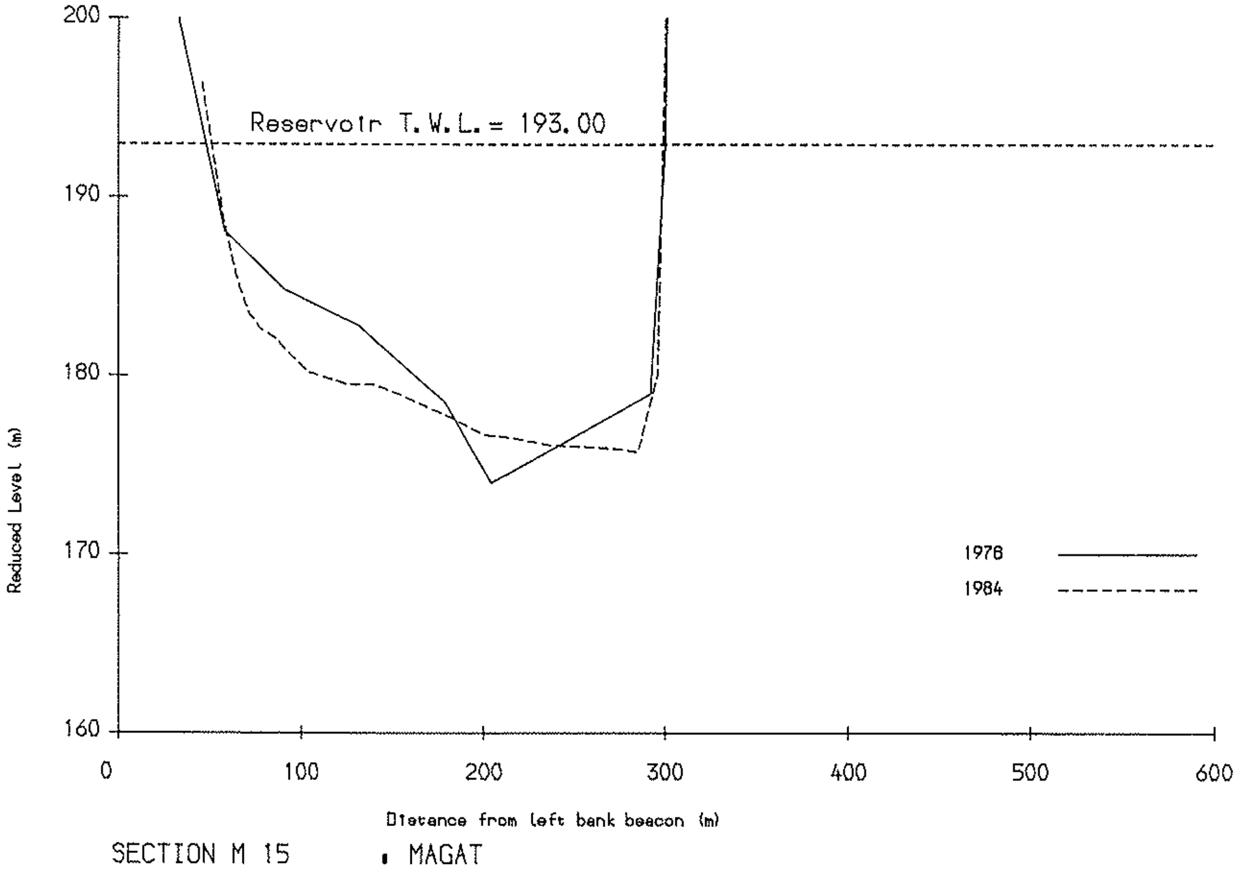


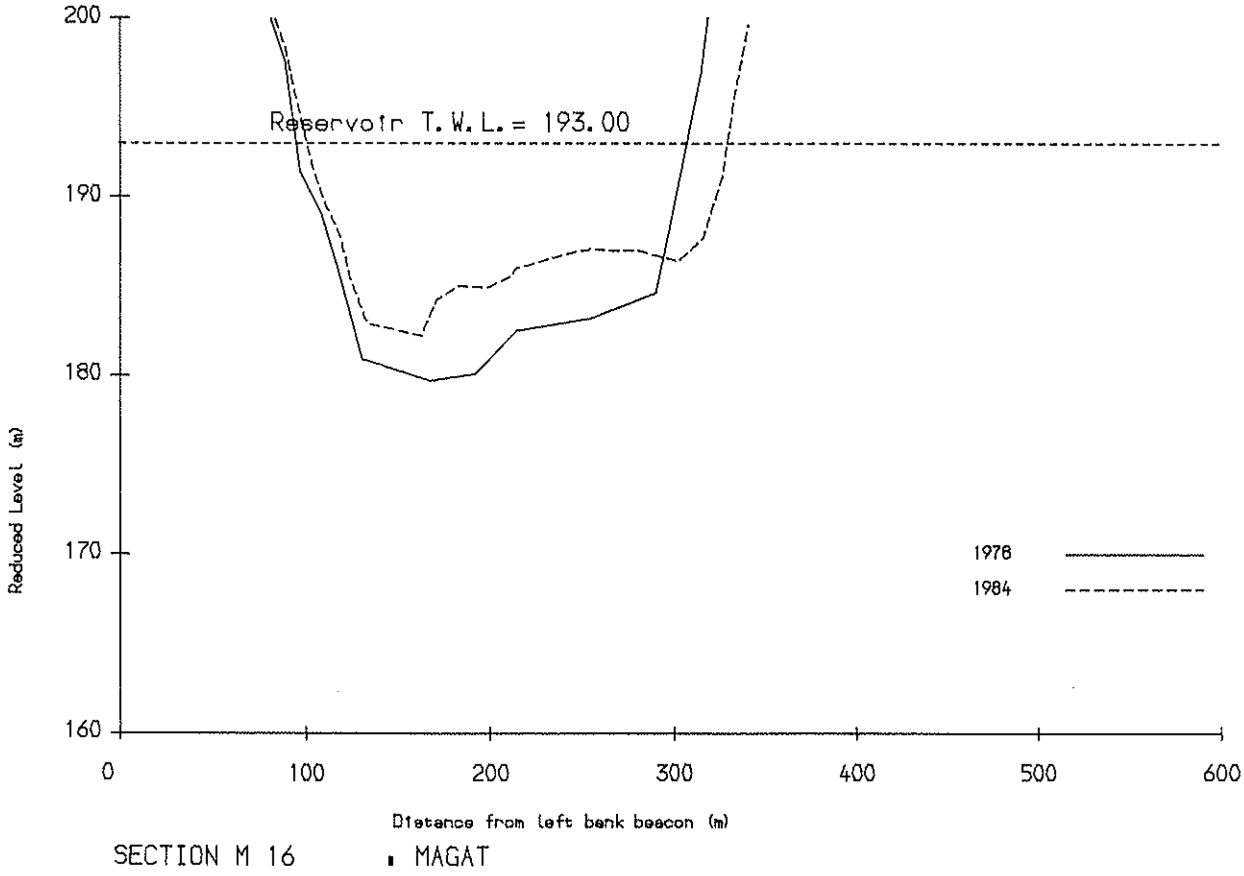
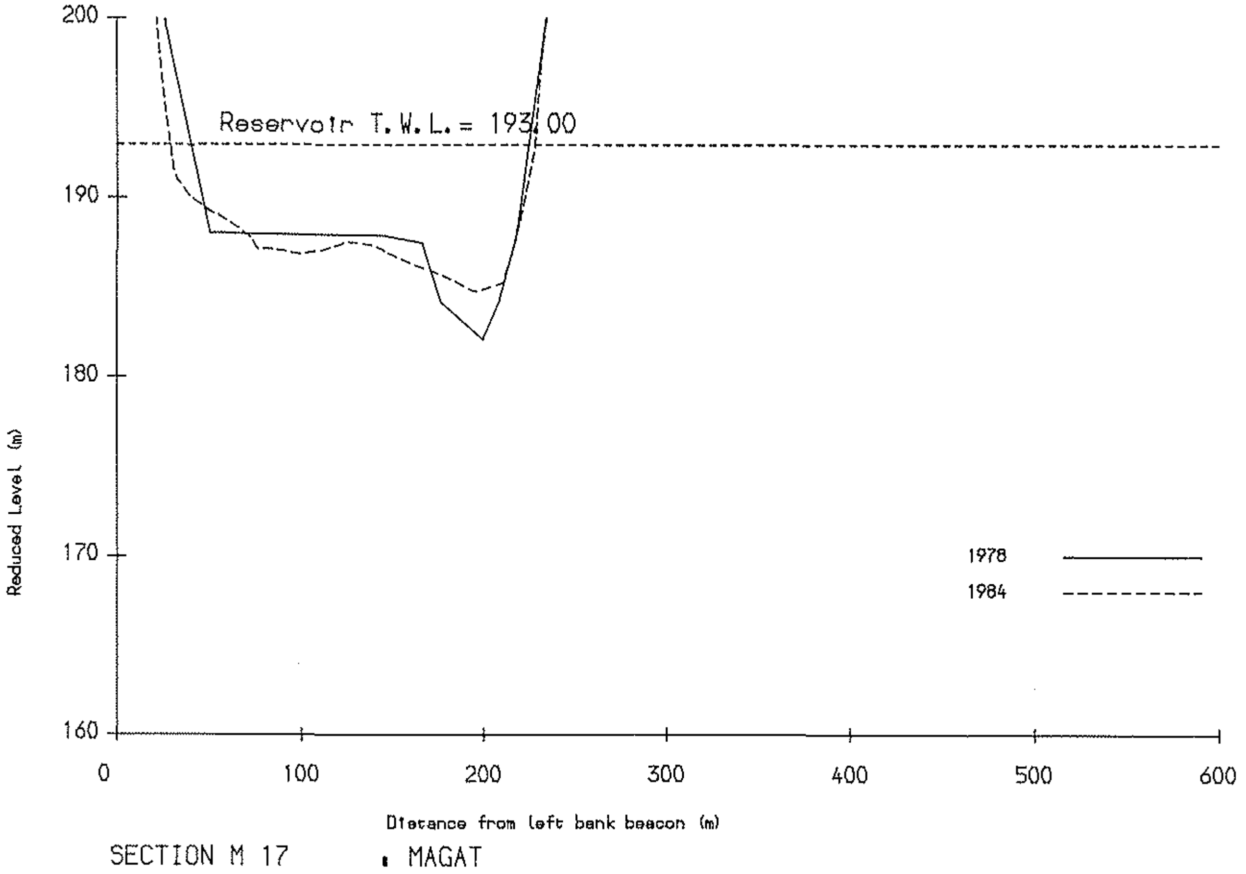
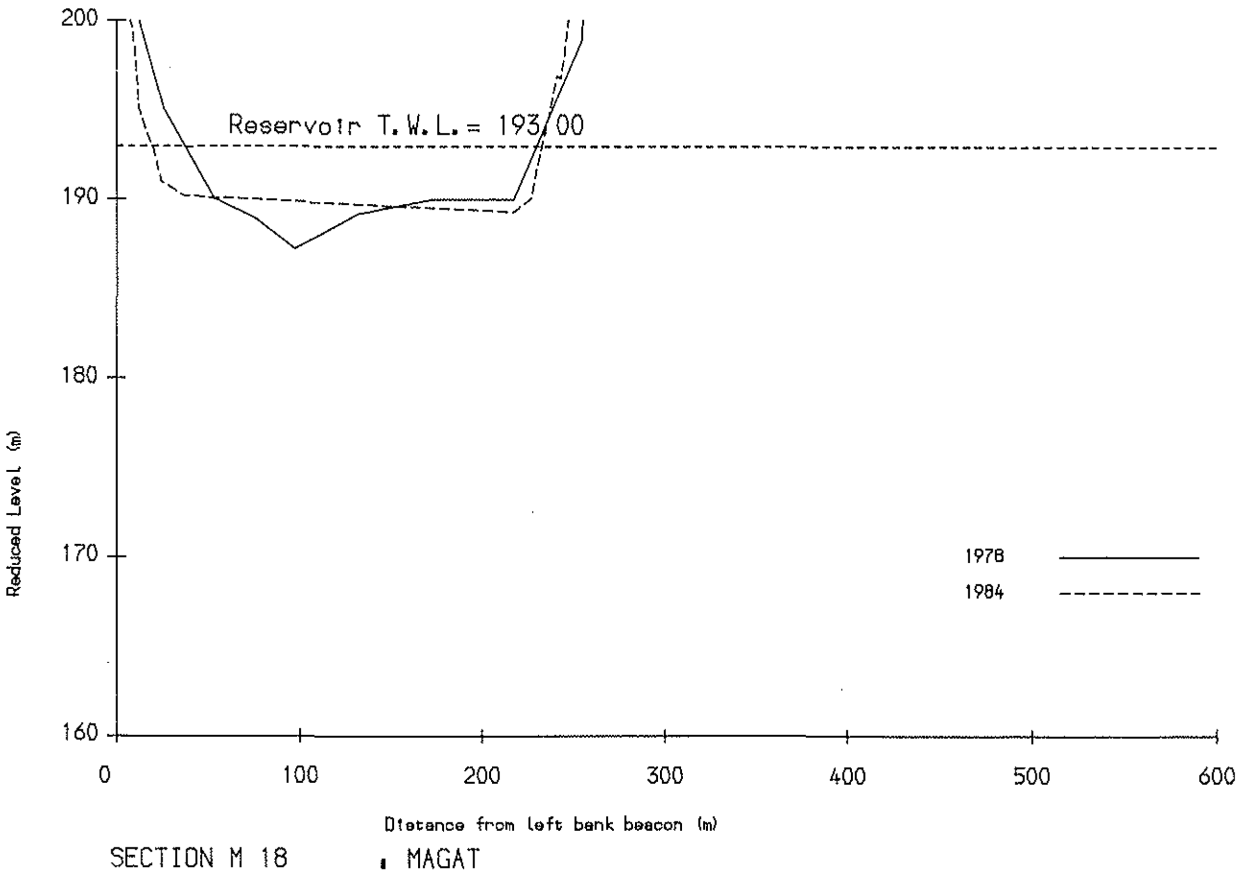


Fig 14 Section Nos. M15 and M16





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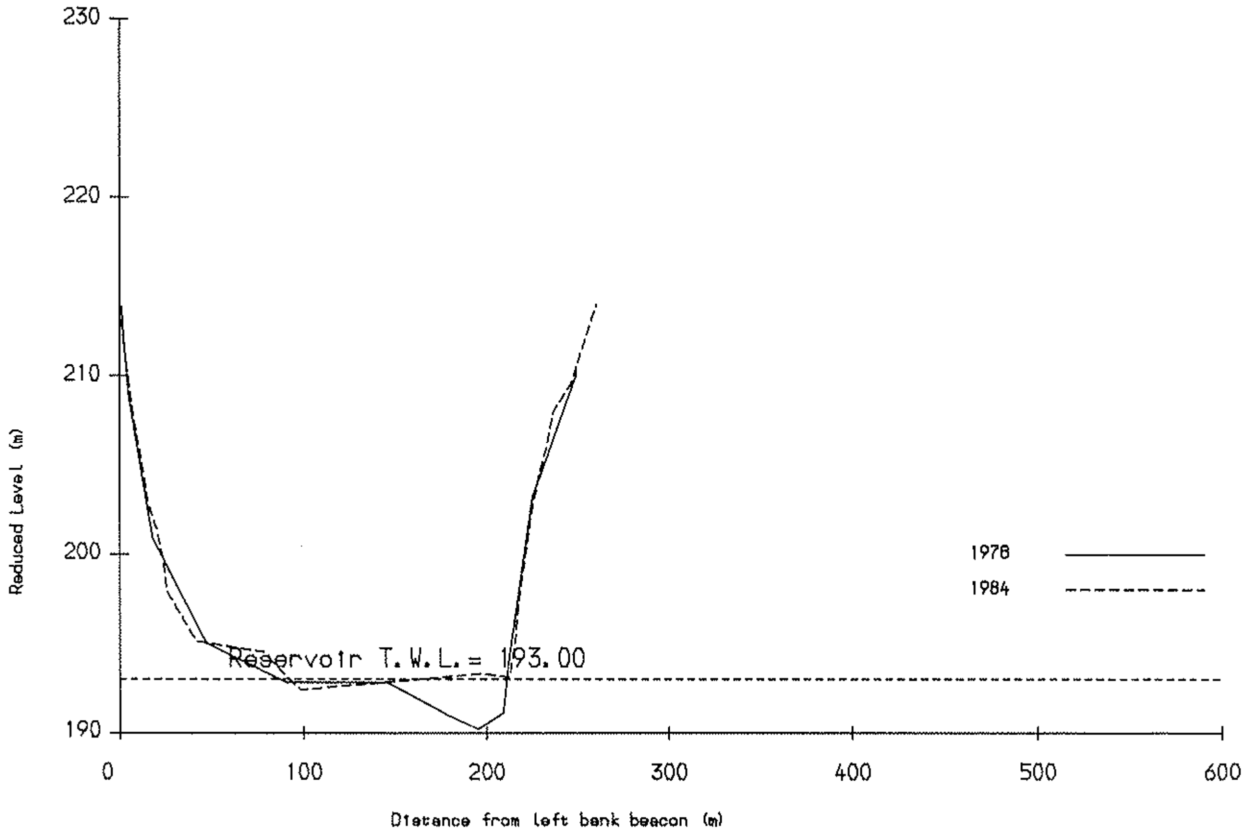
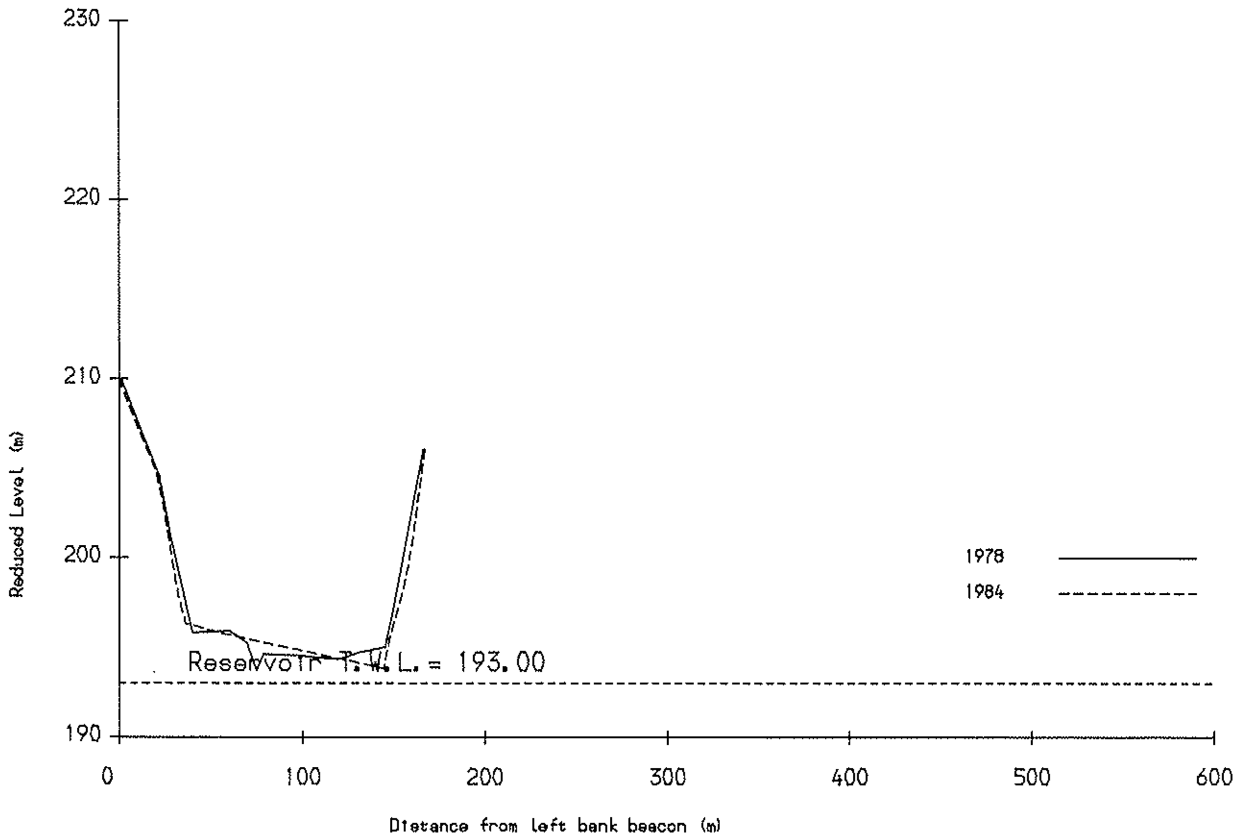
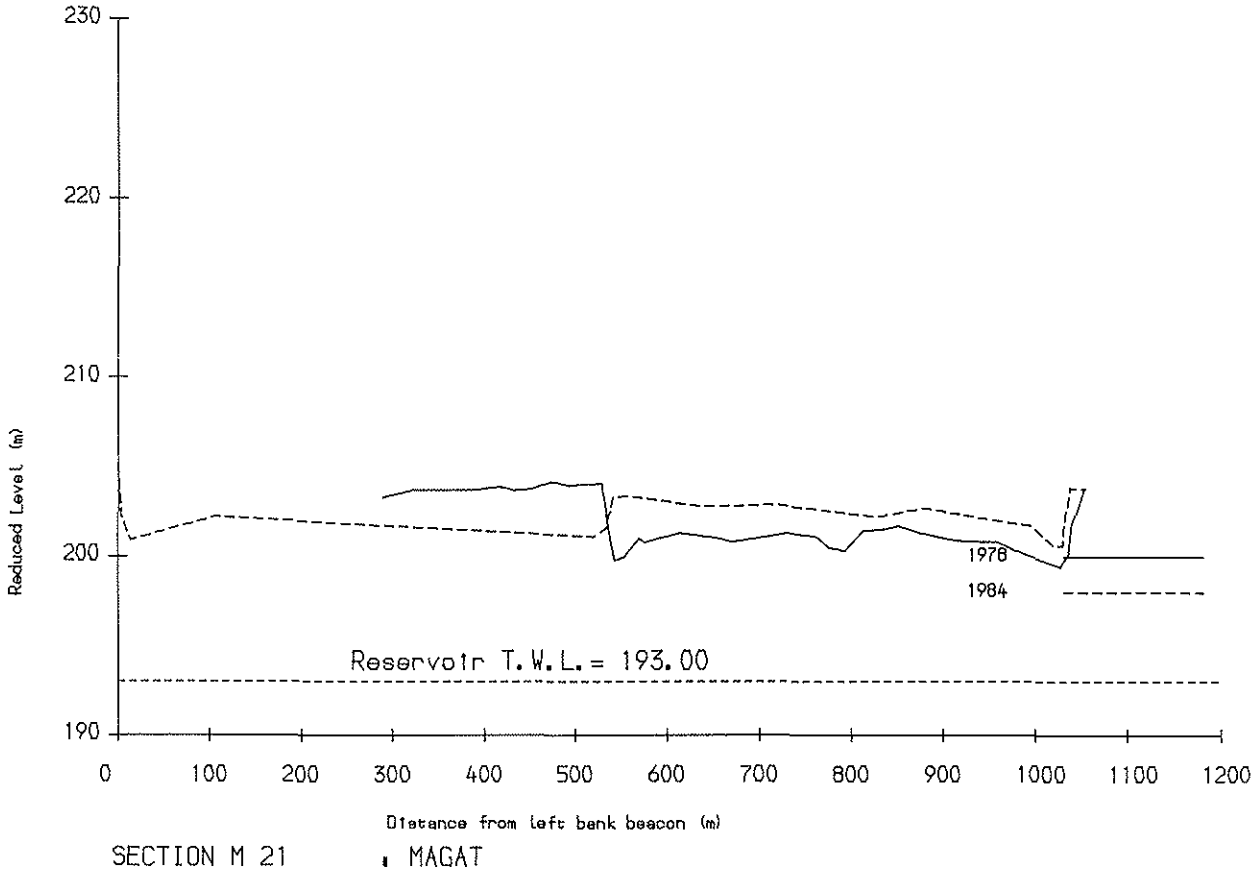


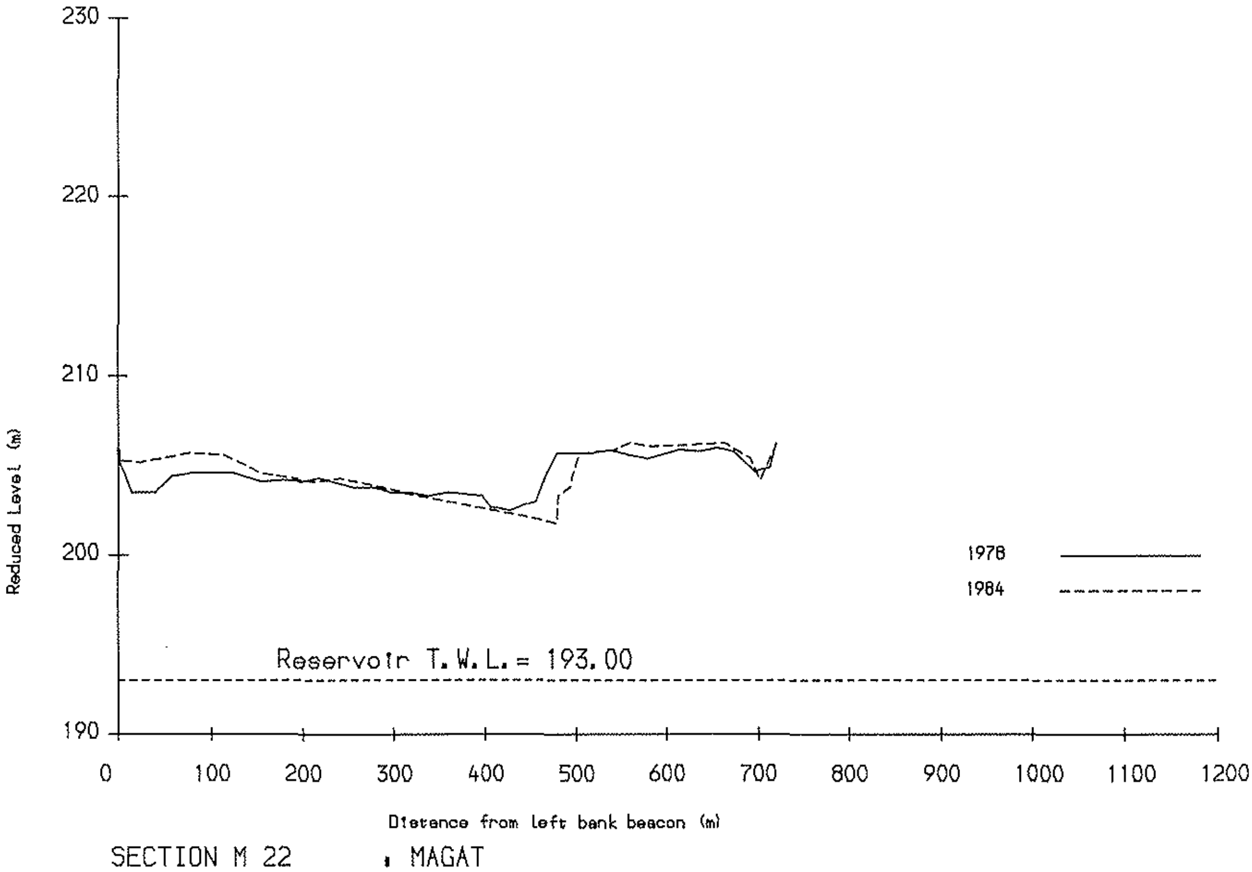
SECTION M 19 : MAGAT



SECTION M 20 : MAGAT

Fig 16 Section Nos. M19 and M20





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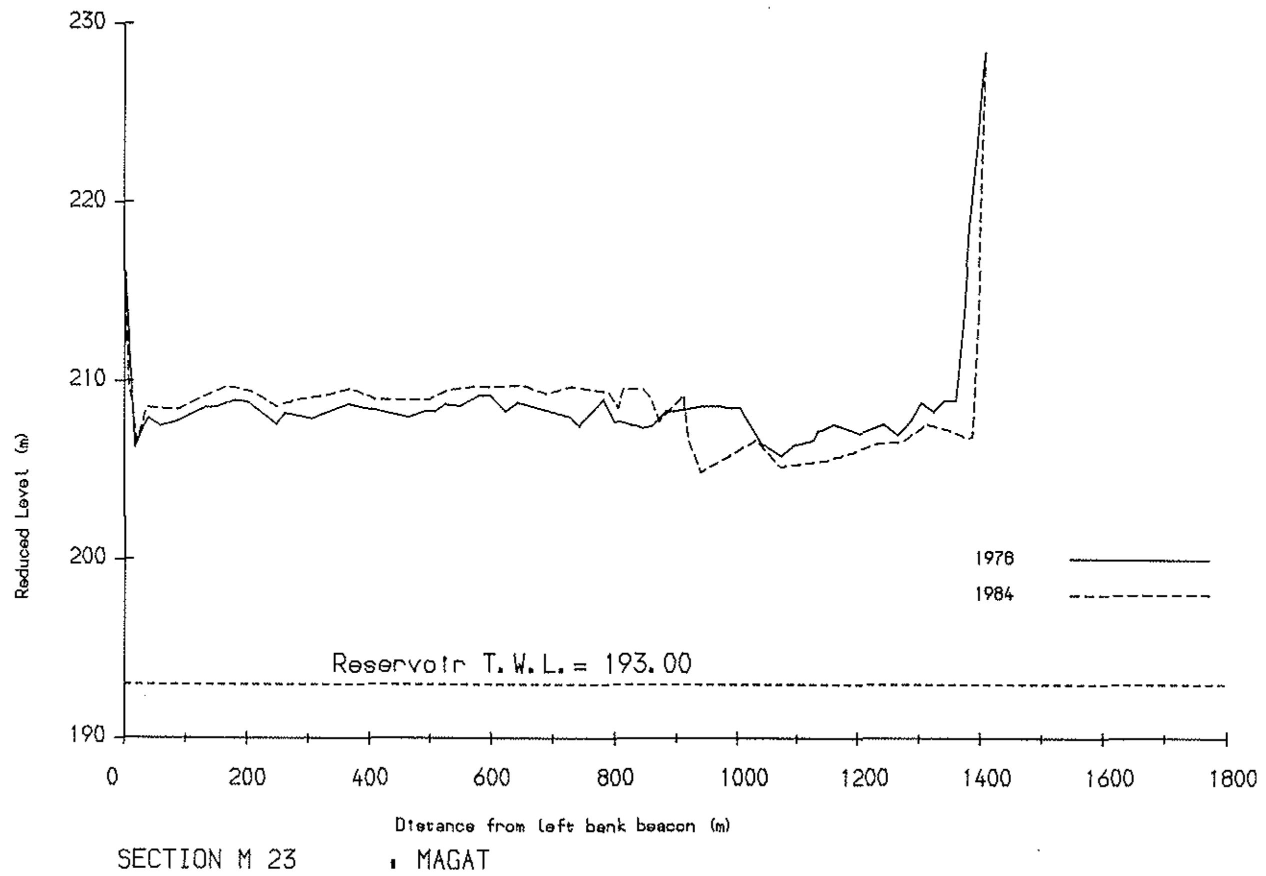

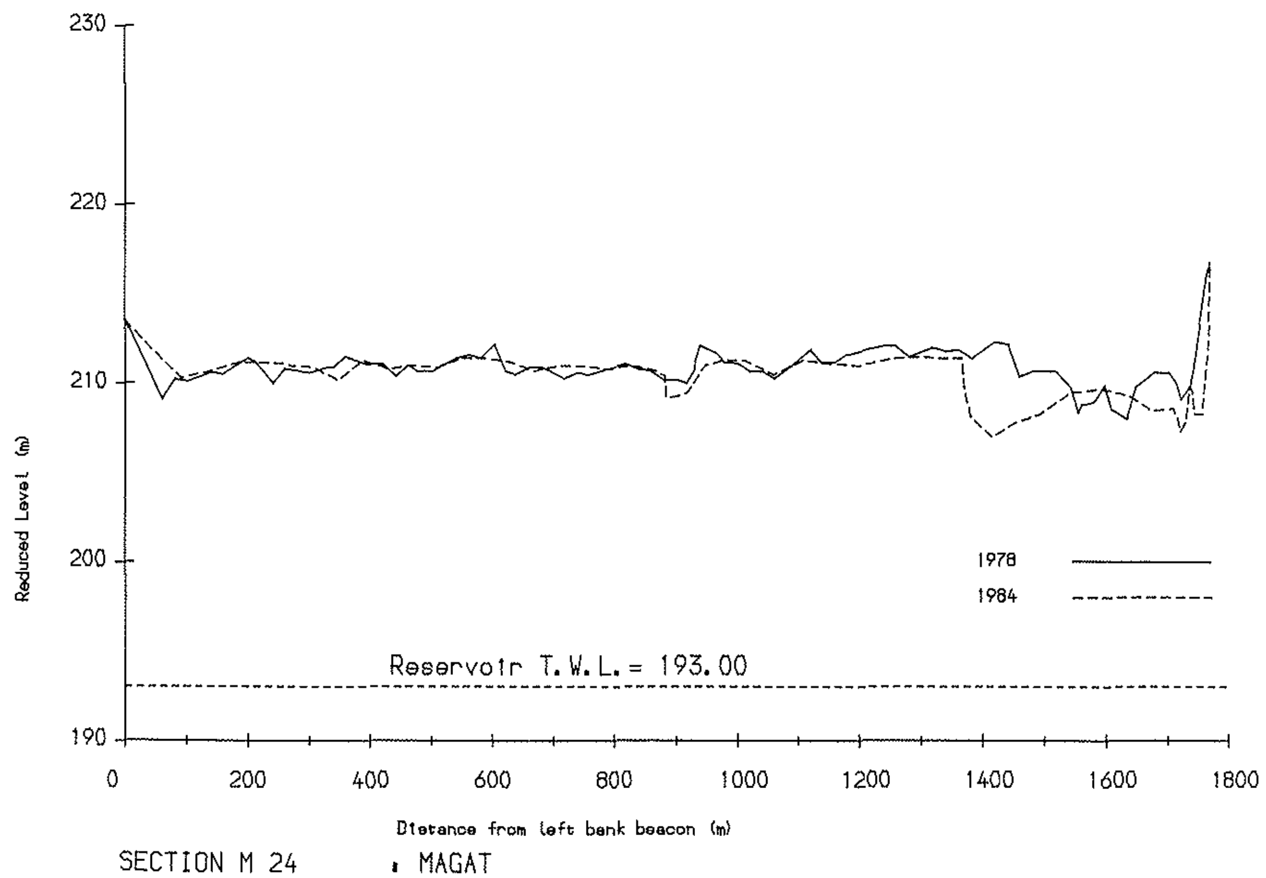

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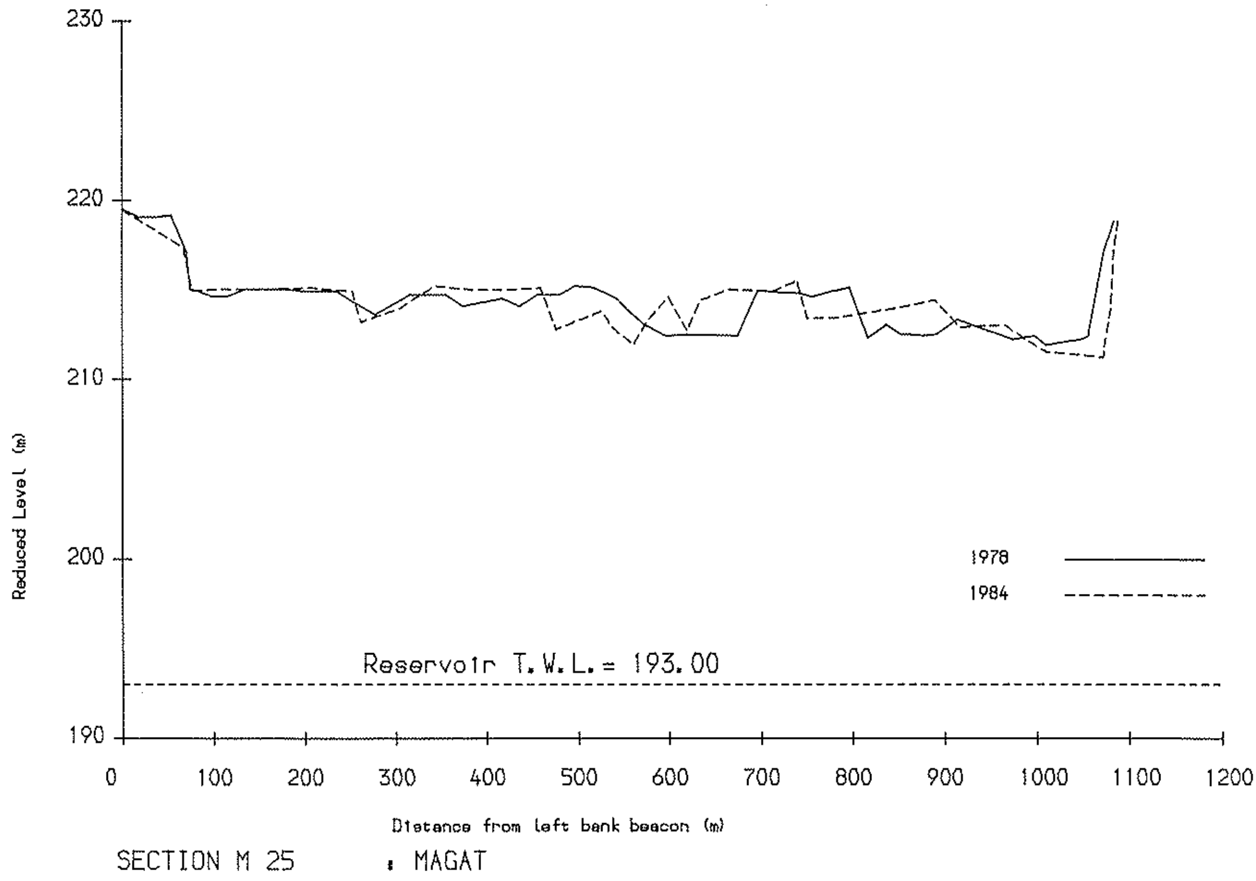


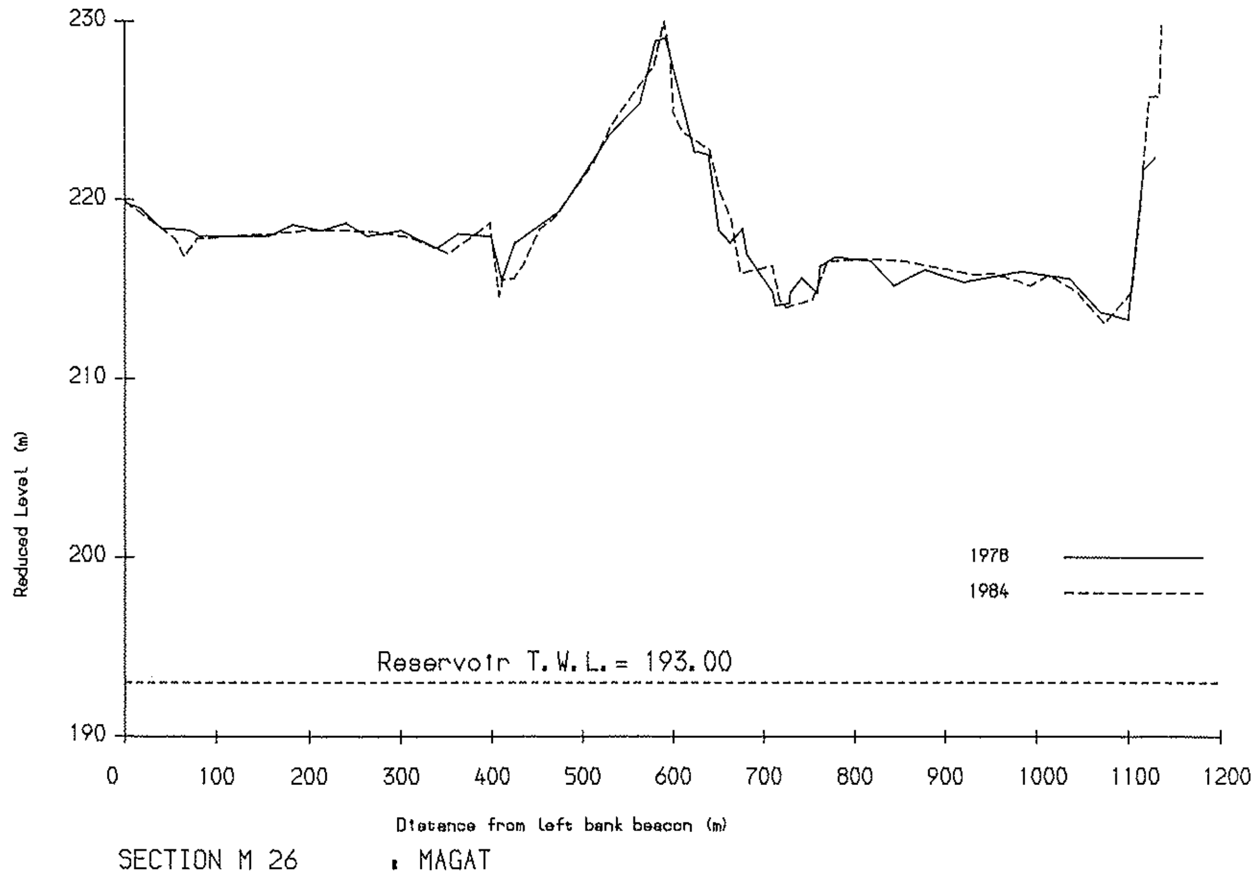
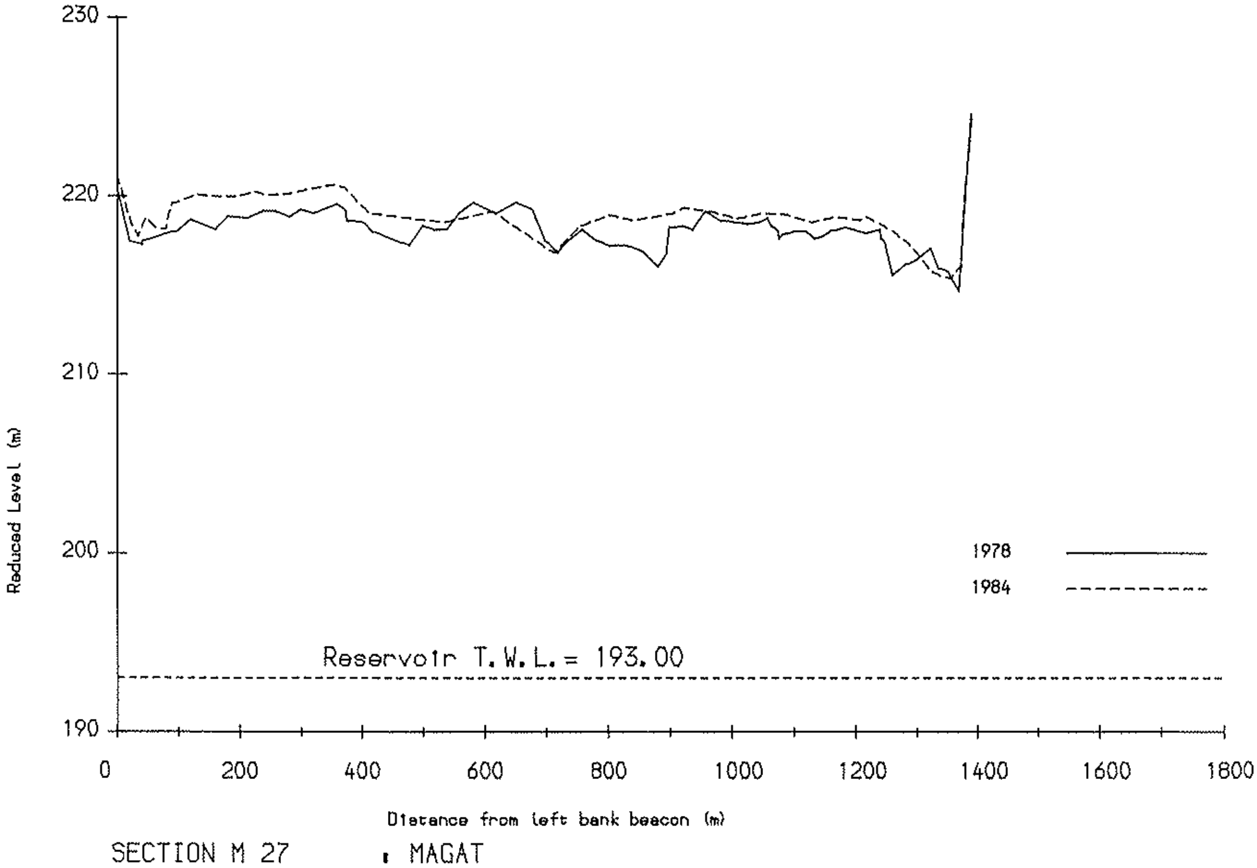


Fig 19 Section Nos. M25 and M26



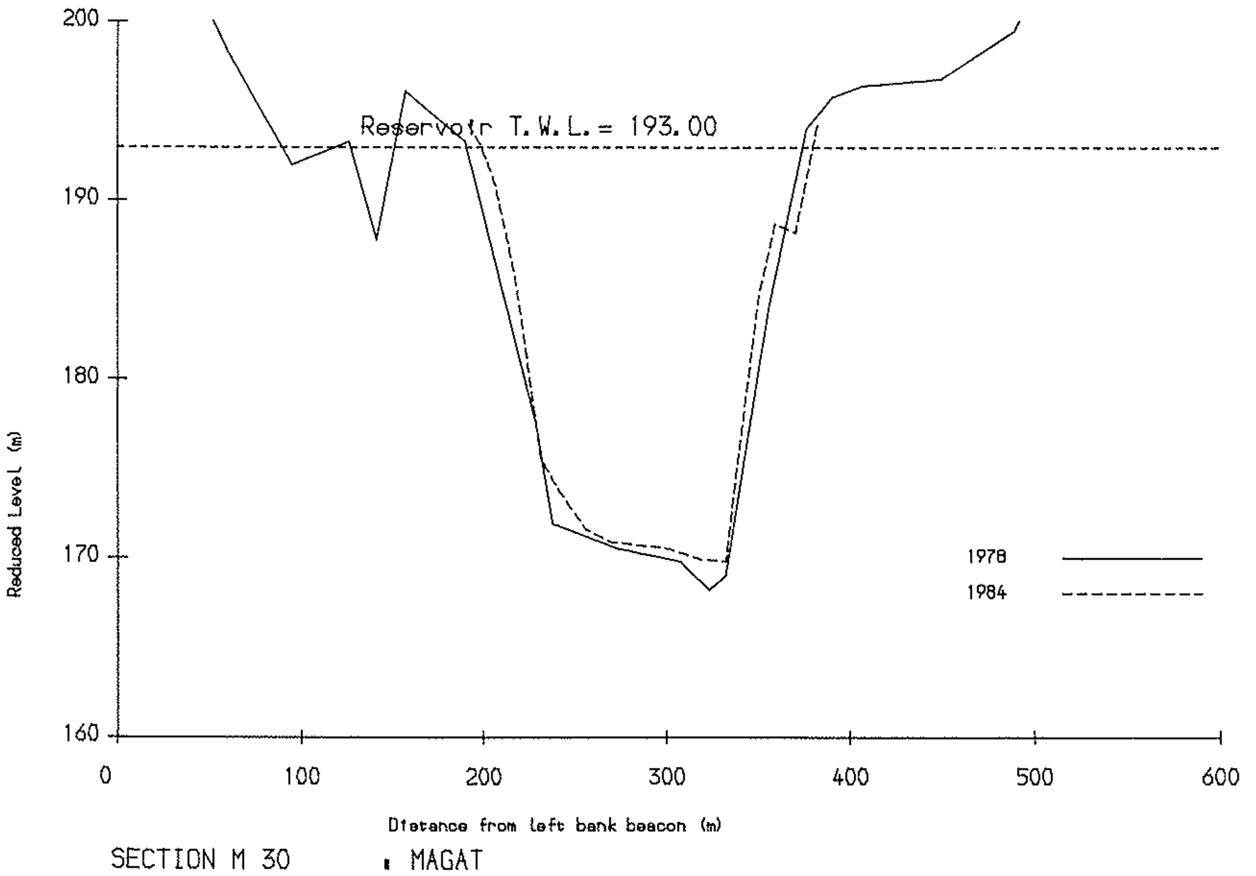
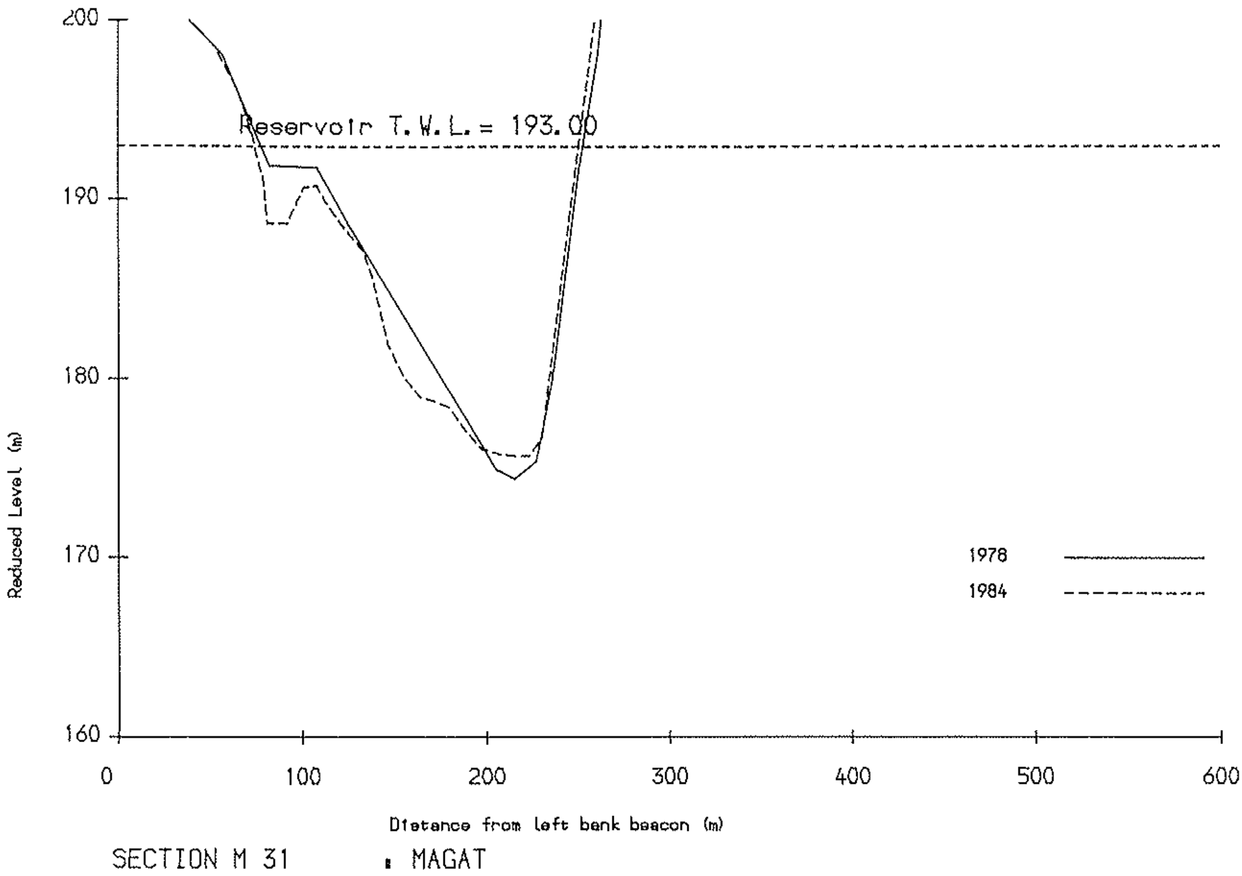


Fig 20 Section Nos. M27 and M30



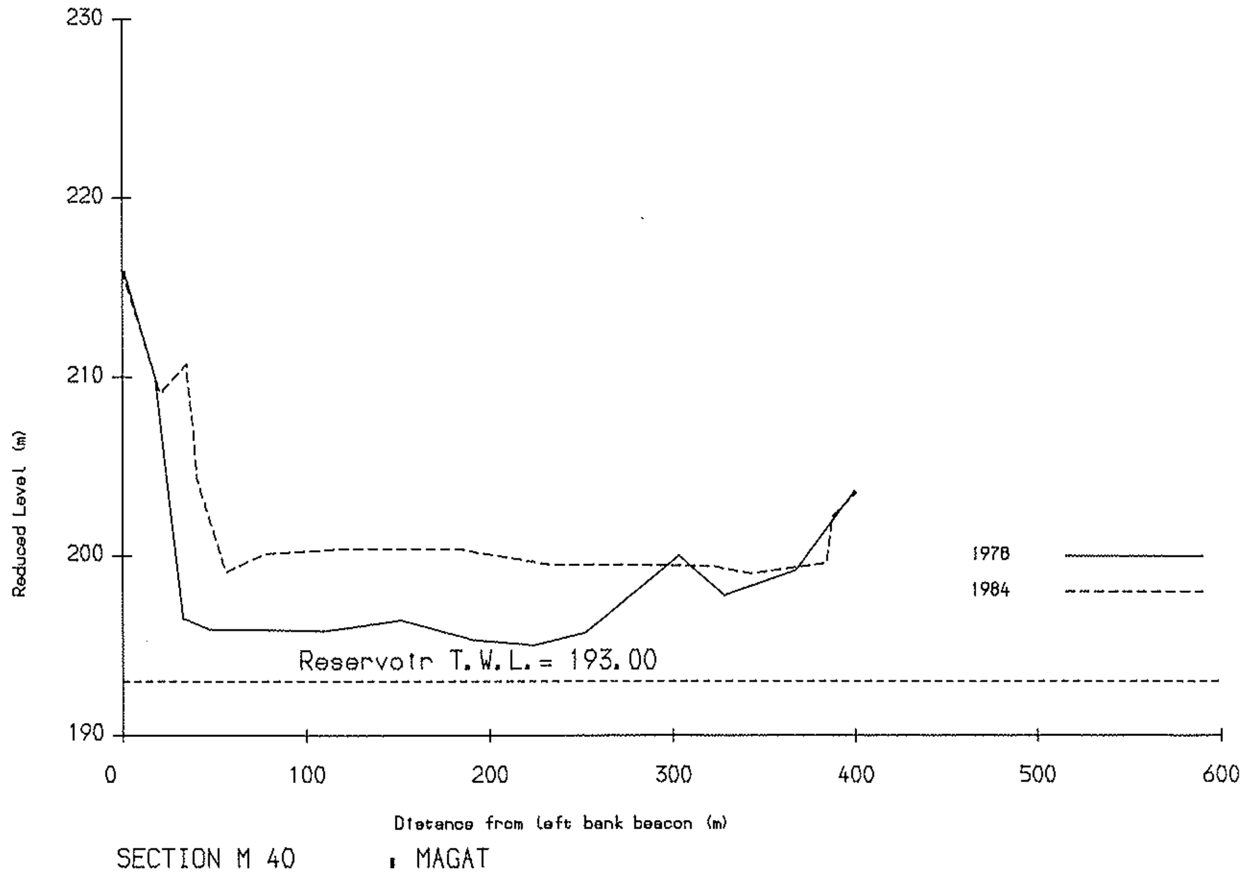
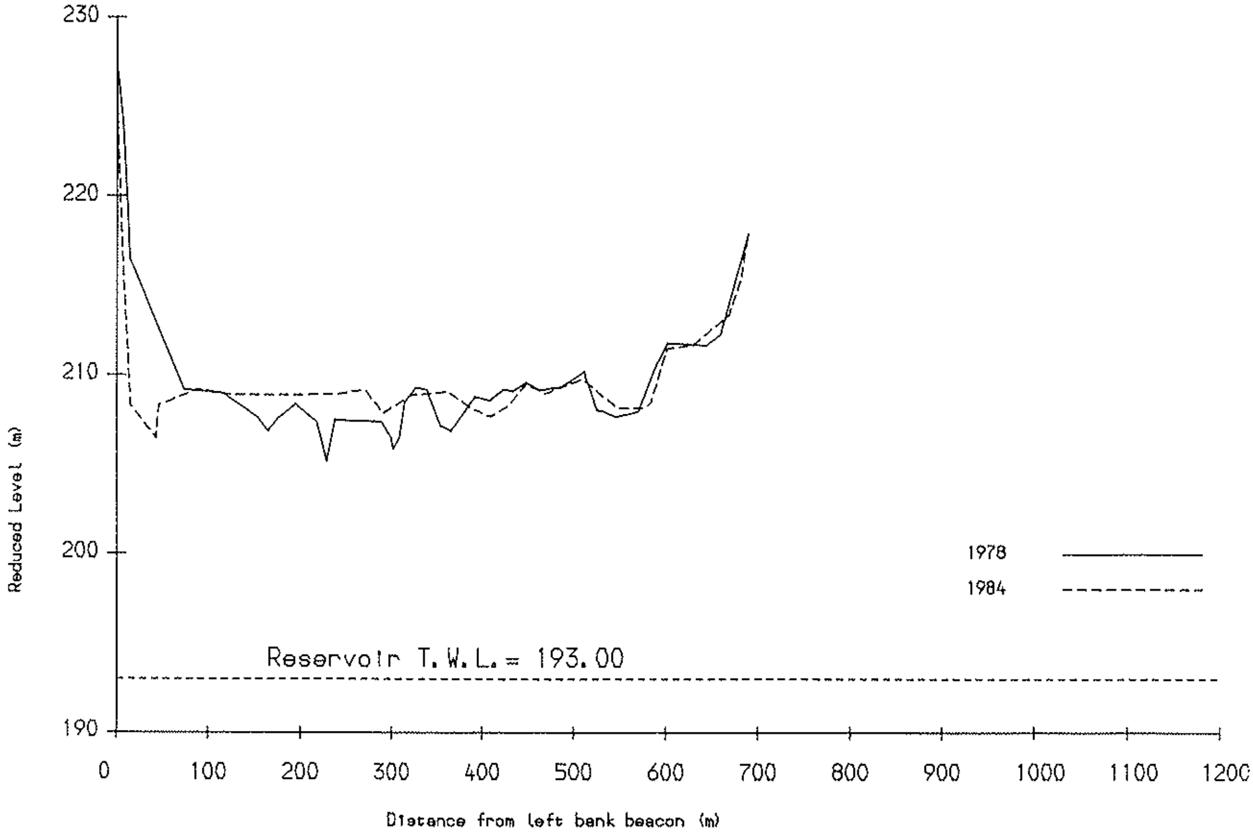
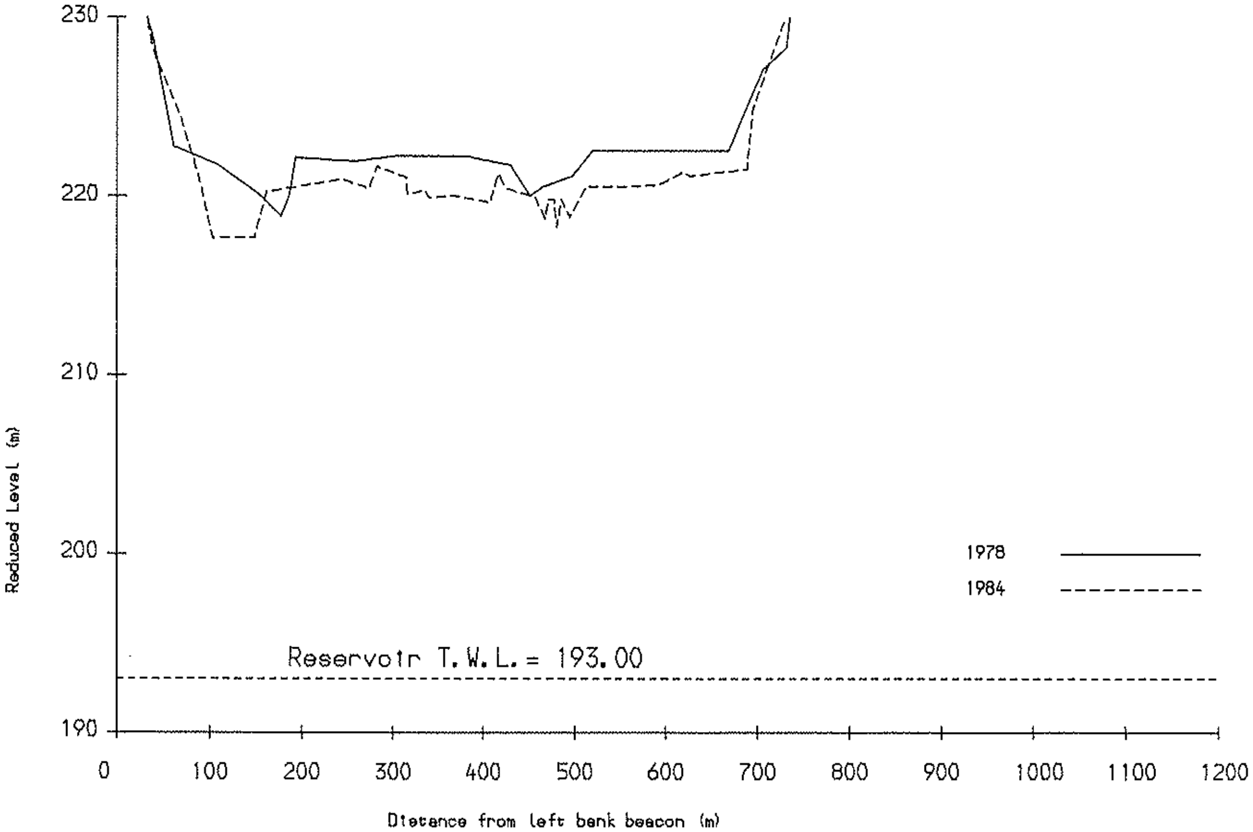


Fig 21 Section Nos. M31 and M40

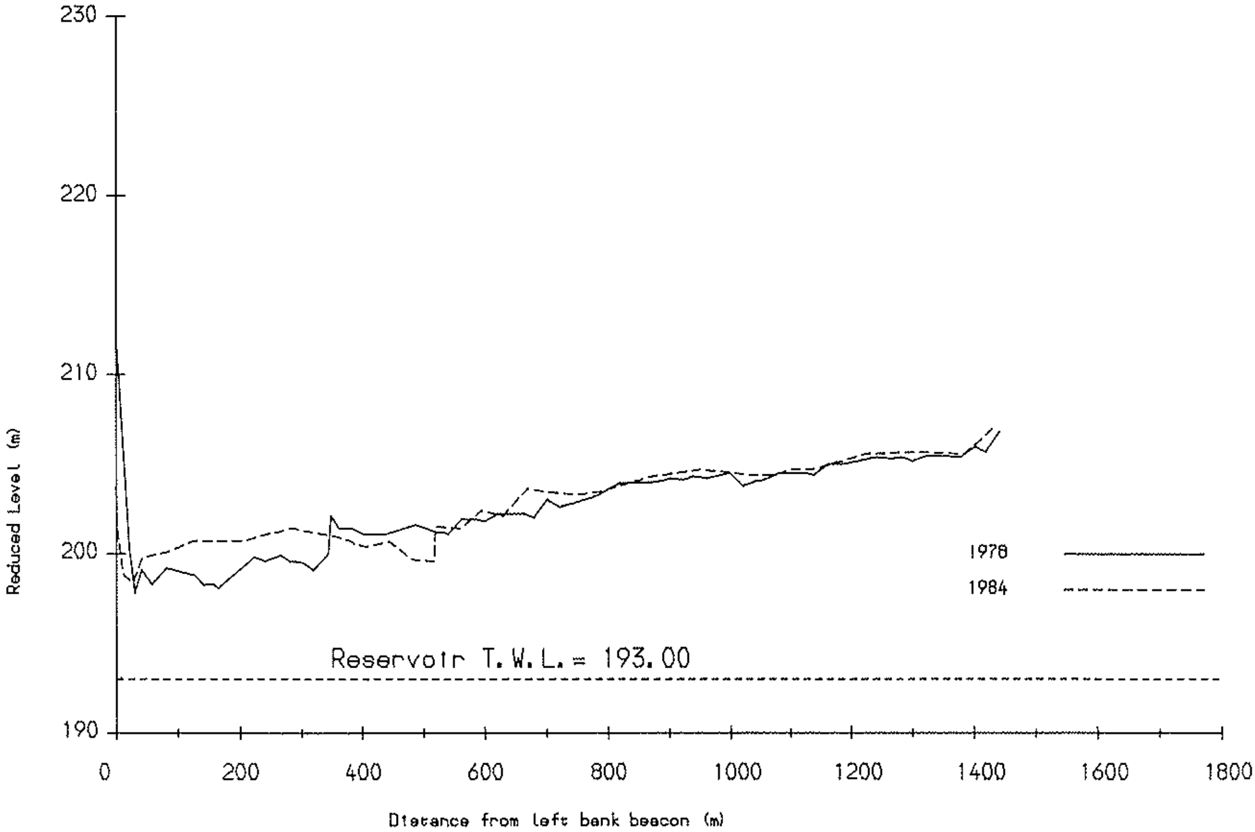


SECTION M 41 : MAGAT



SECTION M 42 : MAGAT

Fig 22 Section Nos. M41 and M42



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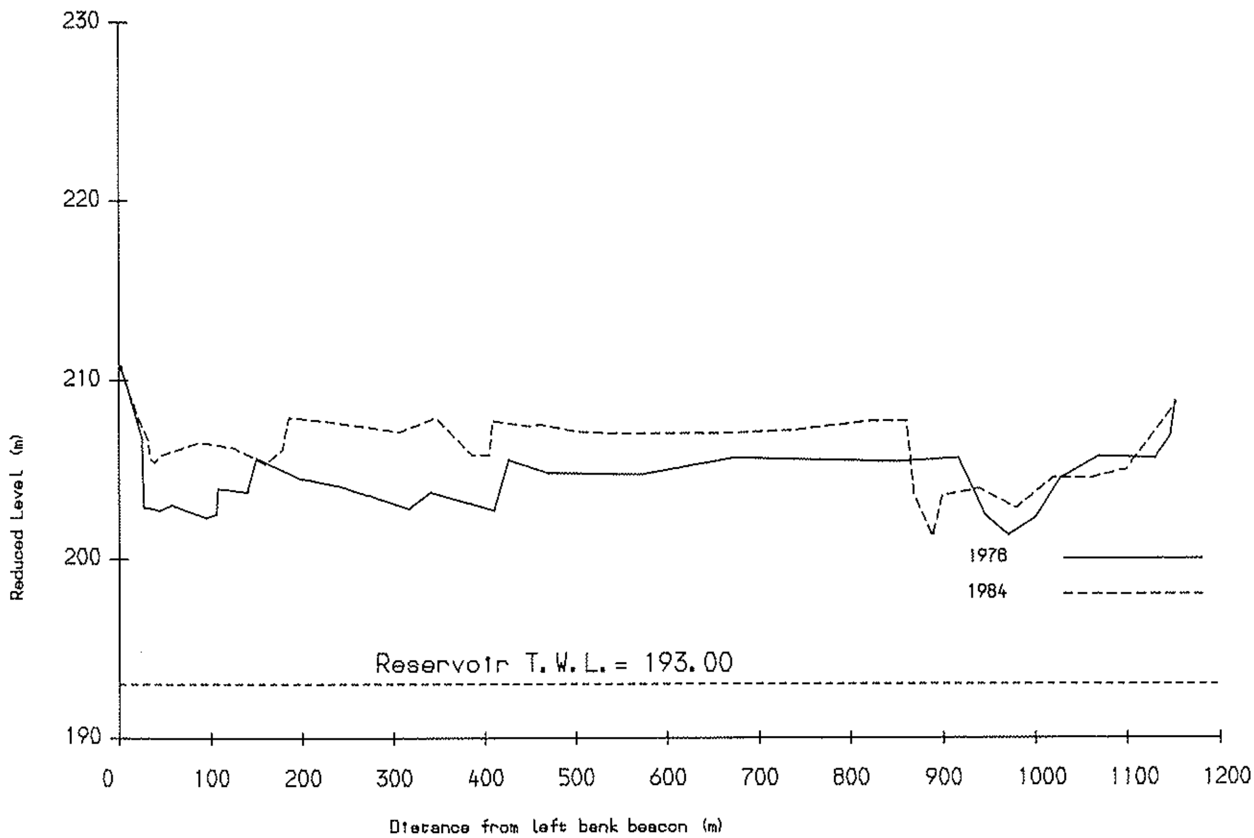

SECTION M 51 : MAGAT

Fig 23 Section Nos. M50 and M51

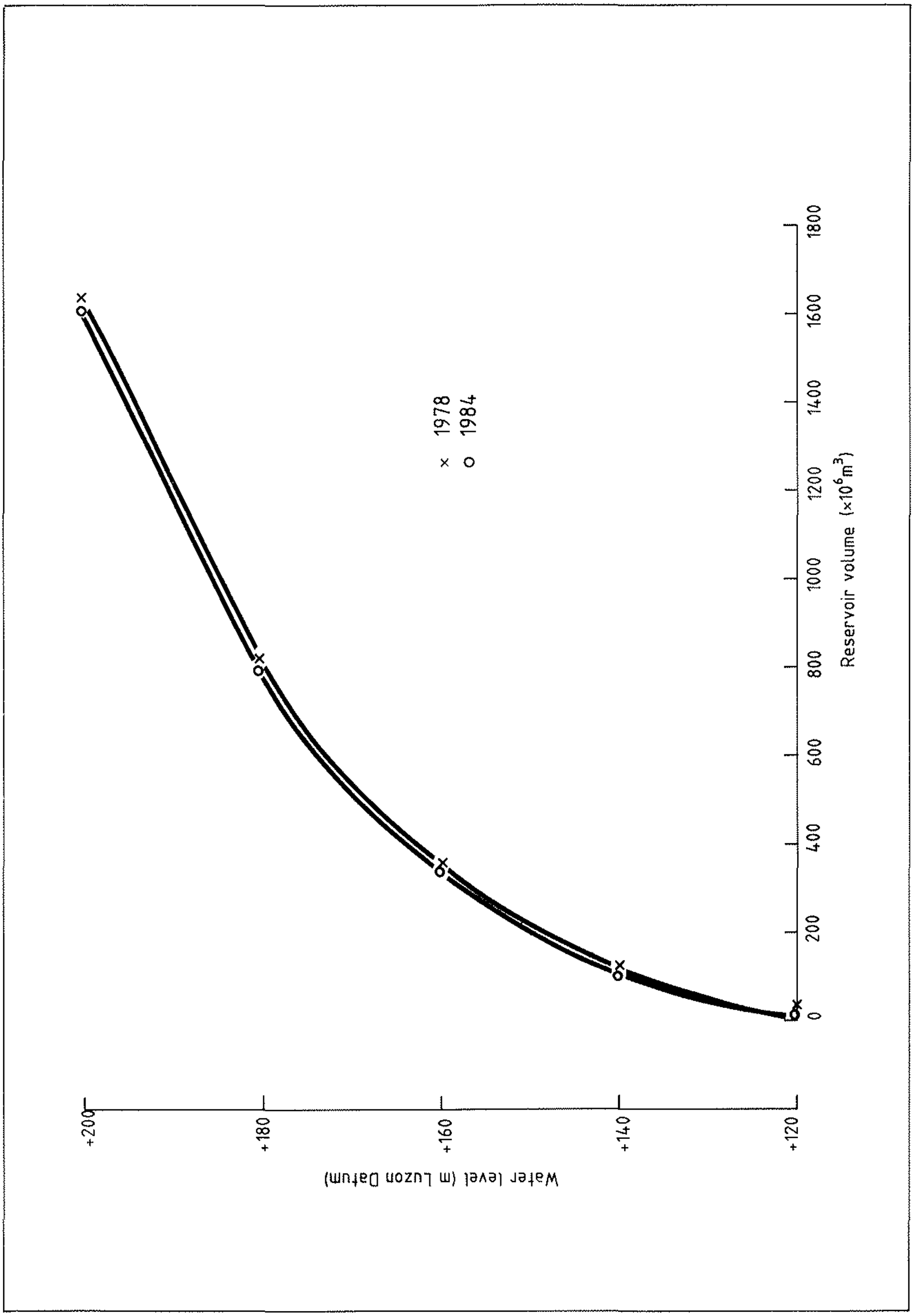

Fig 24 Magat reservoir stage/capacity curves

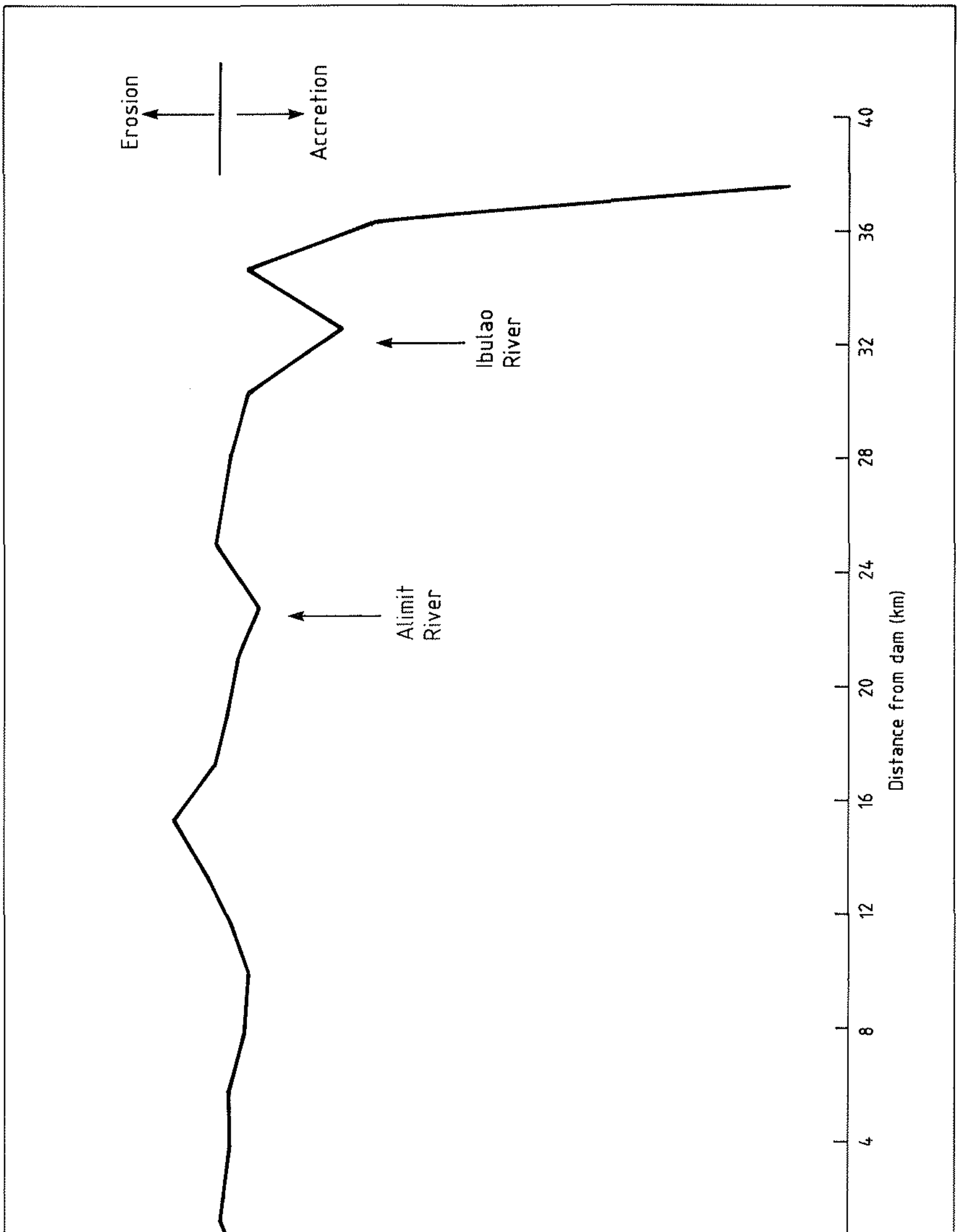

Fig 25 Longitudinal change in reservoir volume

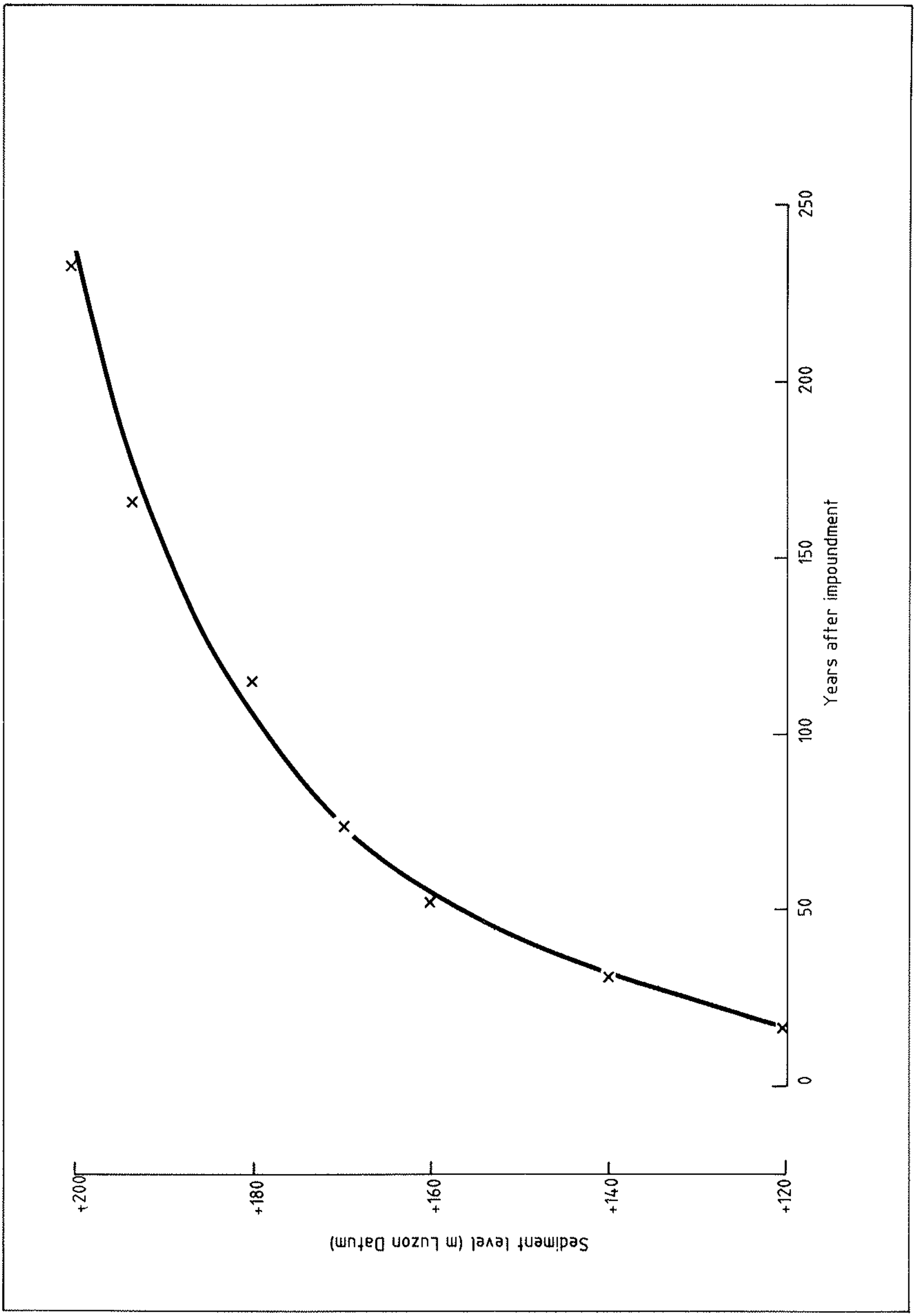

Fig 26 Magat reservoir sedimentation

Plates

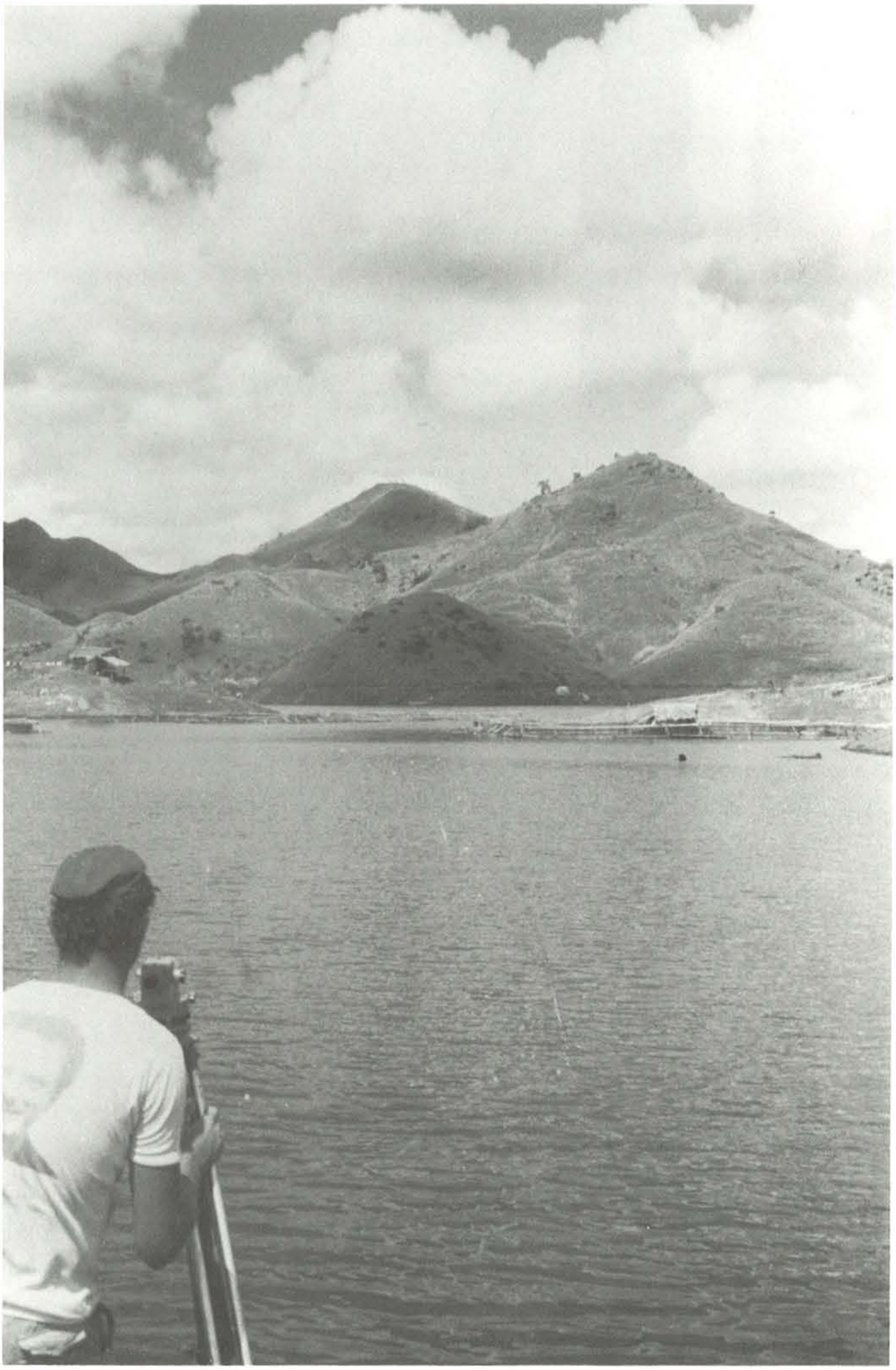

PLATE 1: Sighting across range line M3

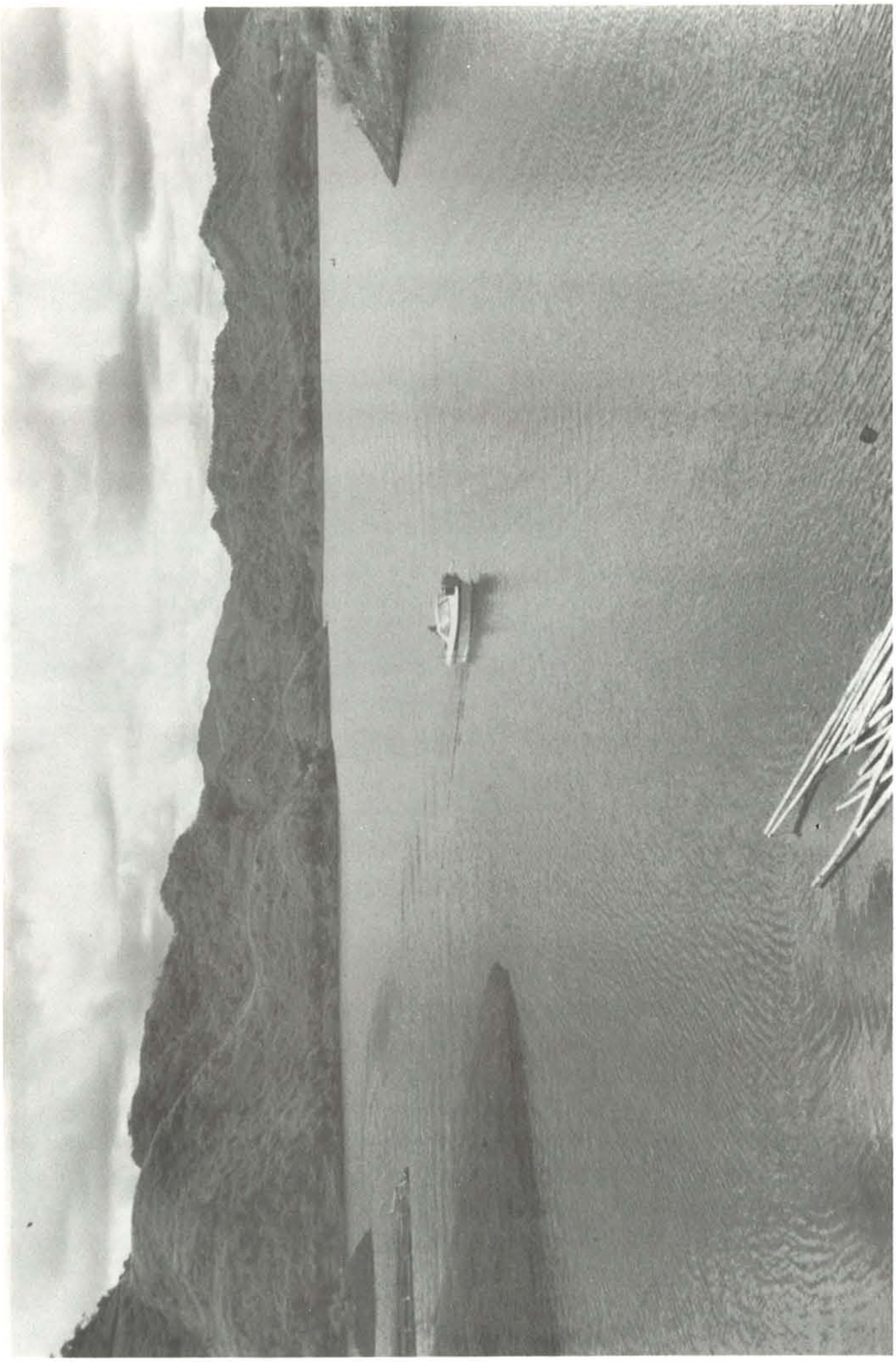

PLATE 2: Survey boat on range line M3

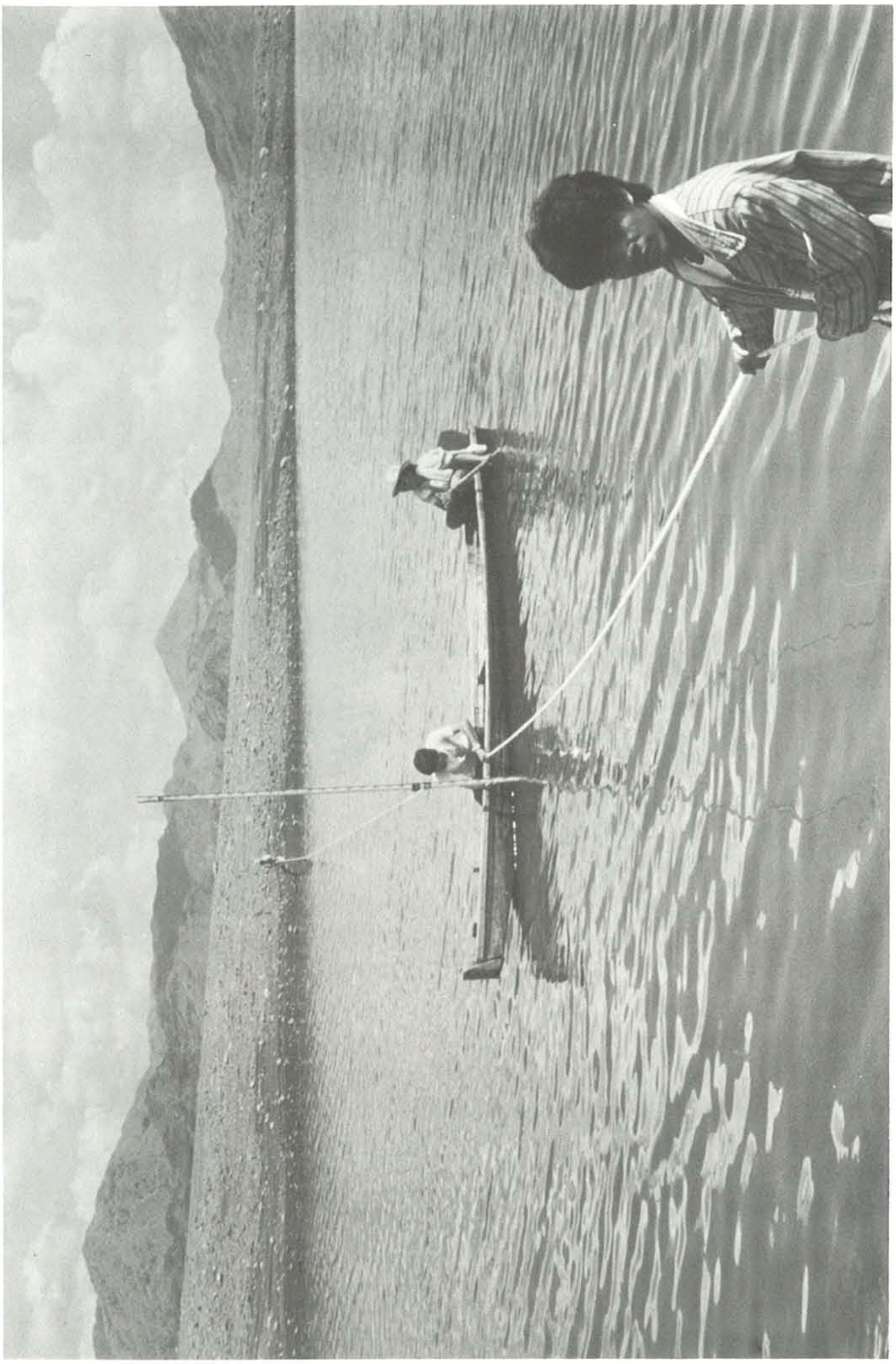

PLATE 3: Shallow water survey, range line M4

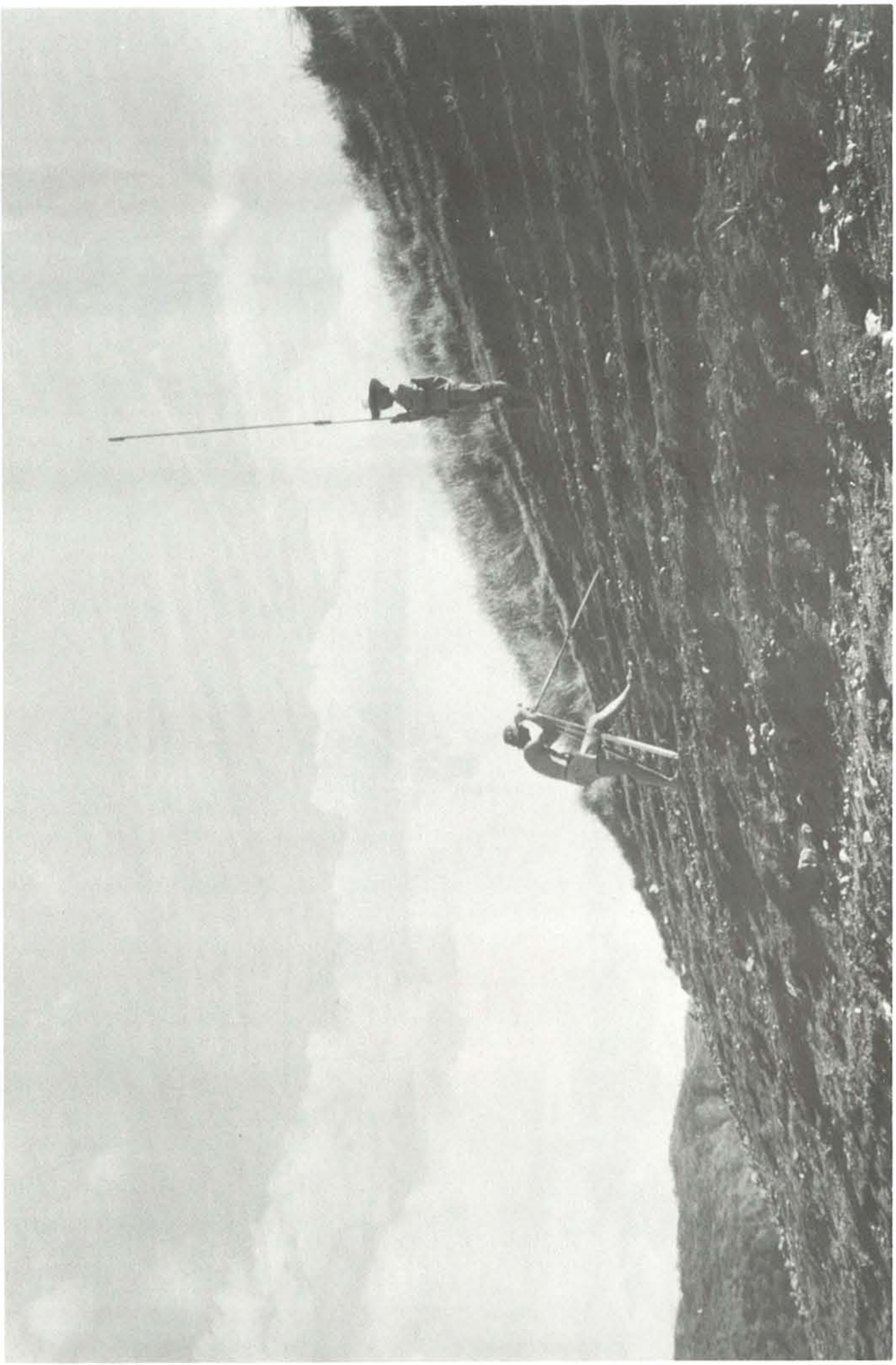

PLATE 4: Topographic survey at range line M9A

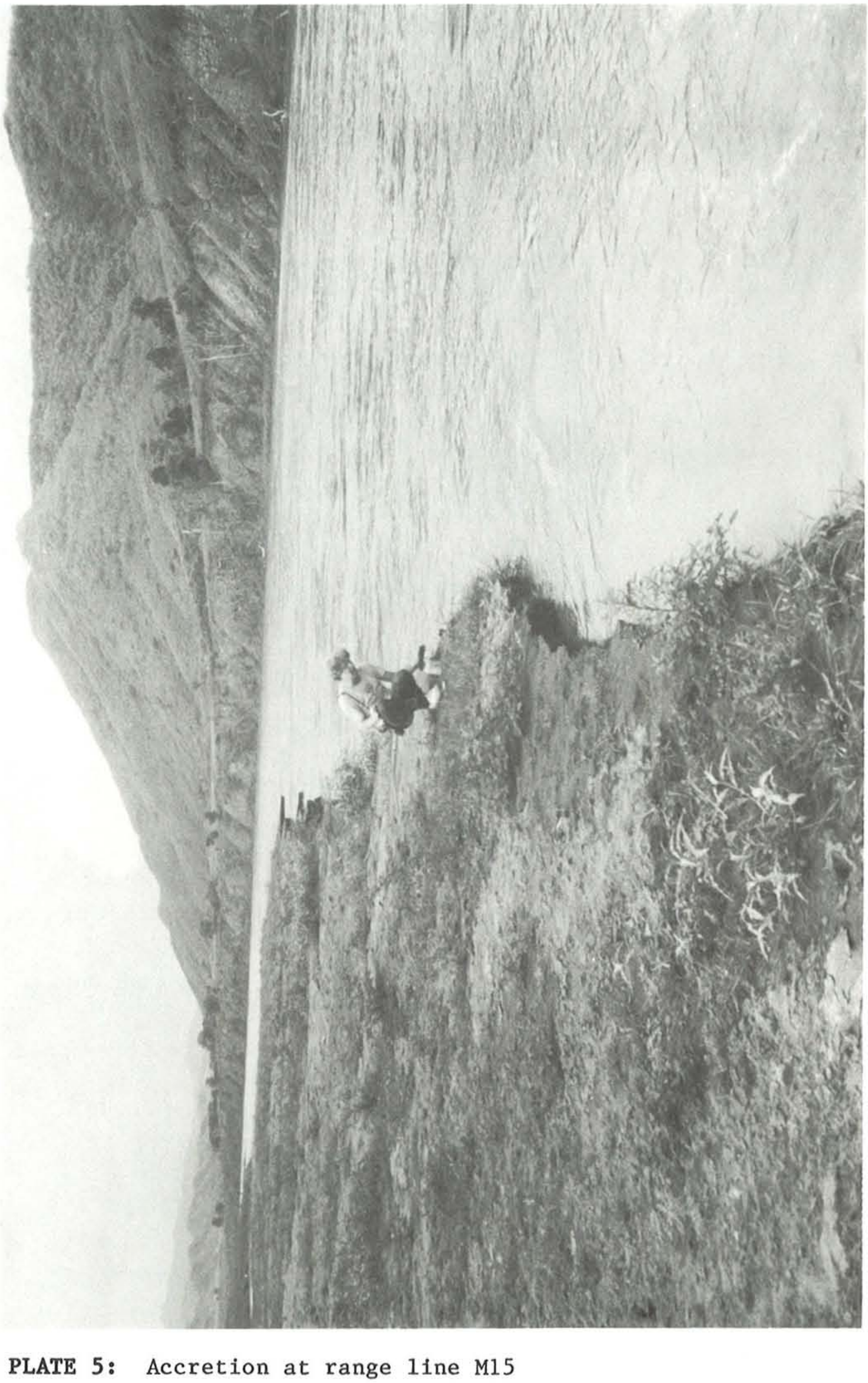

PLATE 5: Accretion at range line M15

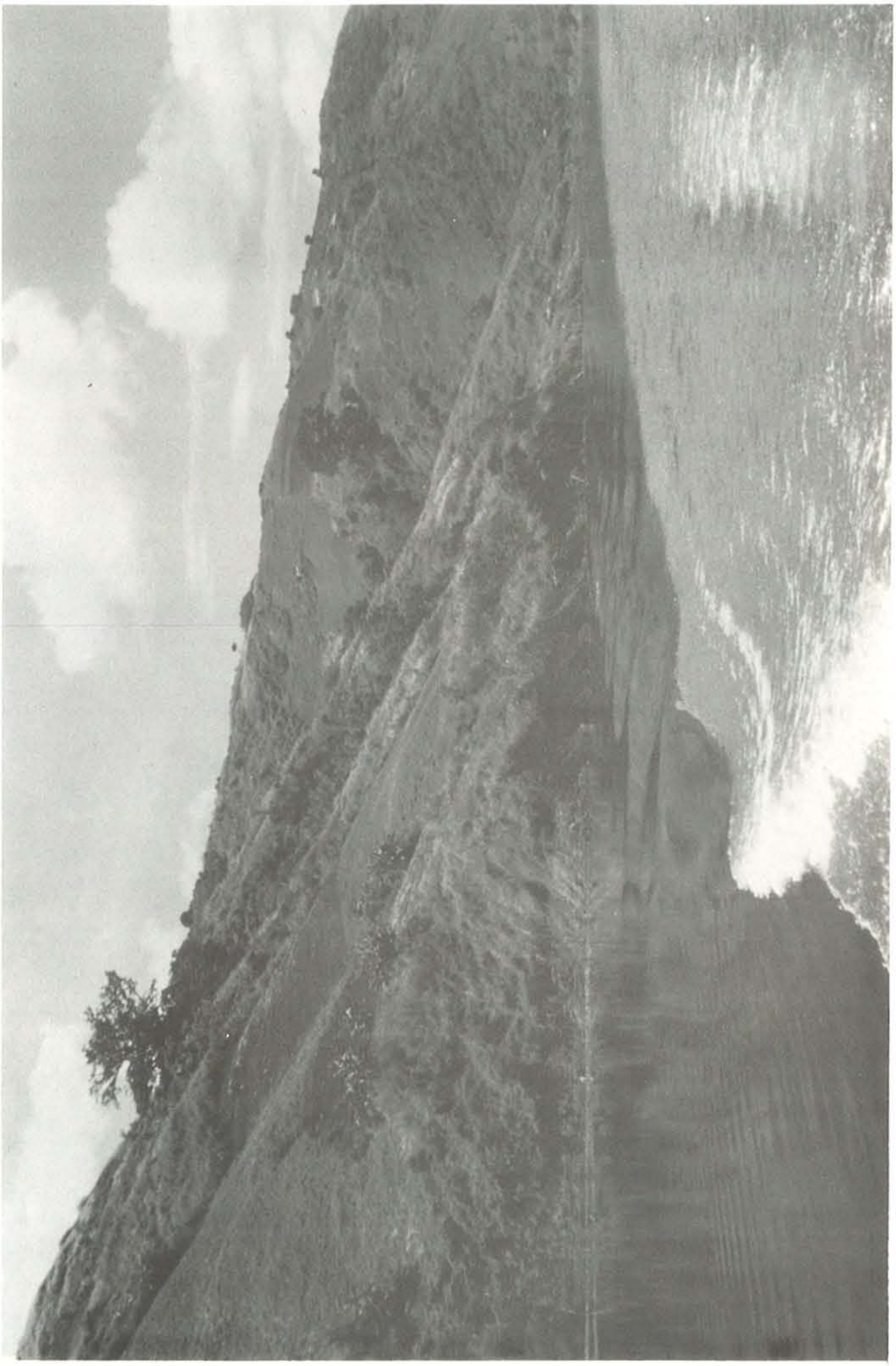

PLATE 6: Steep slope cultivation between range lines M15 and M16

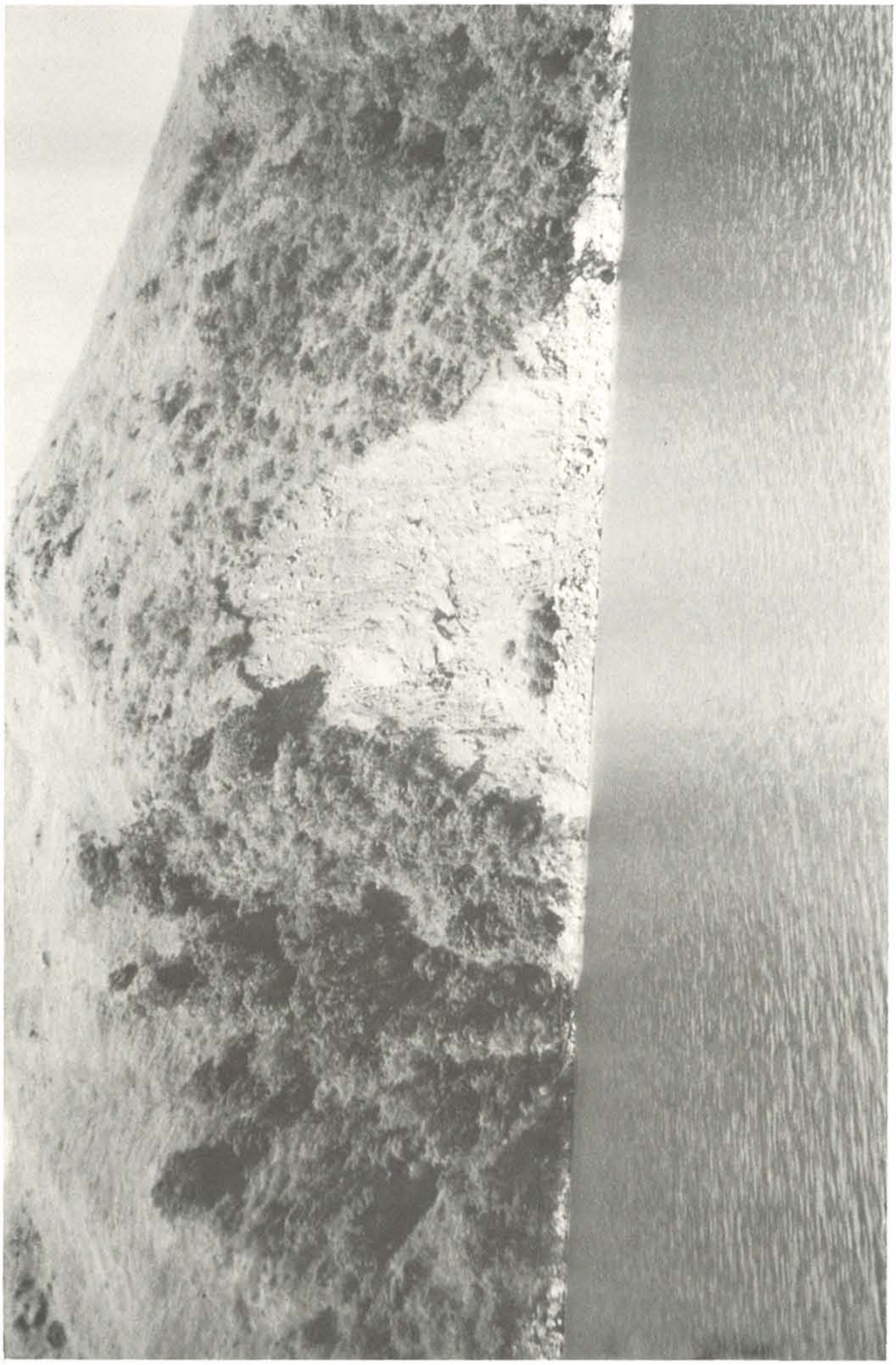

PLATE 7: Landslip between range lines M5 and M6

Appendices

APPENDIX 1

Procedures Used in Merging NIA and HR 1984 Survey Data

In June 1984 HR and NIA mounted a hydrographic survey to collect bed level data along the Magat Reservoir range lines. Details of the field survey techniques are described in Chapter 4 of this report. Echo-sounder data were collected along range lines M1-M3, M5-M17 and M30-M31, see Figure 4. At the time of the survey, the water levels were such that it was not possible for the survey boats to travel upstream beyond section M17 (sections M30 and M31 are on a tributary, the Alimit River, which joins the Magat River between sections M13 and M14). Later in 1984, an NIA field team carried out a topographic survey of sections M18-M27, M40-M42, M50-M51; they also surveyed most of the remaining range line from at least one beacon to the water's edge.

To help with merging these two sets of data, they were each plotted separately on translucent paper so that the two sections could be overlaid and moved relative to each other. When making the comparison, it was assumed that levels and slopes above the top water level had not been changed as a result of the pre-impoundment clearing or as a result of the dam closure. If the two data sets had to be merged below the top water level, the ground slopes were compared and, in some cases, the total range line length was used to define their relative positions.

In the following notes the usual convention has been used whereby the directions are taken looking downstream.

Section M1

1. Left end - merged at last NIA point.
2. After L+1031m, 43m was added to all HR distances. At this point, some confusion occurred in the field booking and comparisons of the 1978/1984 sections show that such an addition was necessary.
3. Right end - last six NIA points added to HR data.

Section M2

1. Left end - added level of monument at zero metres.
2. Right end - added NIA 1984 survey data from distances 3325m.

This gave a total section length of 3880m which compared well with the 1978 NIA survey length of 3893m.

Section M3

1. HR survey changed targets at distance 1972m. From this point, add 65m to all distances.

2. Survey stopped below top water level. Merged 1978 NIA data from end of HR survey data to close section.

Section M4

Not surveyed.

Section M5

1. Left end - deleted first eight HR survey points and replaced with all NIA points.

2. Right end - deleted last five HR points and added last twenty NIA points.

3. Levels recorded between 487m and 579m did not have 'fix' marks but peak should obviously be there. Point 540, 184.4 added to give more correct representation.

Section M6A

1. Left end - variation in bank slope between NIA and HR surveys made assimilation very difficult and therefore worked on HR data only.

2. Right end - added all NIA points starting at distance 988m.

The section was too short by 69m when compared with NIA 1978 survey. Section therefore plotted assuming that:

(a) right bank levelling was correct;
(b) left bank slope was unchanged between 1978 and 1984. Hence section was 'stretched' to fit.

Section M6B

1. Left end - add NIA data with first point at zero.

2. Right end - add NIA points from distance 991m and delete HR points from distance 1022m.

In the HR data, fix 10 may have been incorrectly booked to indicate a 'bank' at 720m, but there is no proof, and so the distance has not been changed.

Section M7A

HR section moved 33m right to match the main features. One point taken from the 1978 survey was added to the right end to take the section above top water level.

Section M7B

HR section moved 159m right to match the main features. One point added to the left end to take the section above top water level.

Section M8

Section plotted as measured. One point from 1978 data added to right end to complete the section.

Section M9A 1984 section moved 39m right to match main features. One point from 1978 data added to left end to complete the section.

Section M9B

1. Left end - HR and NIA data agree.

2. Right end - added three NIA data points.

1984 section moved 56m right to match main features. Channel in right bank confirmed by two data points. In pre-impoundment data set it was located by Certeza but omitted by NIA.

Section M10

1. Left end - HR and NIA survey data points coincide.

1984 section moved 36m right to match main features.

Section M11 1984 survey moved 375m right to conform to 1978 profile. One point from 1978 survey added to right end to complete section.

Section M12

1. Left end - very good comparison between surveys.

2. Right end - vertical face in 1978 suggests that 1984 slope cannot be correct. 1984 line modified to fit.

Section M13 1984 section moved 76m right to match main features.

Section M14

1. Left end - added NIA points up to 177m from beacon.

2. Right end - added NIA points from 632m; last HR point deleted.

1984 section moved 176m right to match main features.

Section M15 1984 section moved 46m right to match main features. One point added from 1978 survey to right end to bring section above top water level.

Section M16

1. Left end - added NIA points up to 134m from beacon; erased first HR point.

2. Right end - added NIA points.

1984 section moved 120m right. This closely matched left end but section looks too wide when compared with 1978 data. However, wider section is as plotted by NIA so no further changes have been made.

Section M17

1. Left end - added NIA points up to 52m from beacon.

2. Right end - added NIA points from +210m.

1984 section moved 50m right to match main features.

APPENDIX 2

Sediment Volume Program SVPRO3

This computer program has been designed to run on an ICL 2972 computer using Fortran 77. Each line of the listing is numbered and these numbers are used as references for the following notes.

Line 105	If SWIT is greater than zero then the program monitor file is printed on channel 6 - this is only used during the development stage to detect errors.
Lines 136-139	Initialise CVOL to ensure that all elements of the array contain zero.
Lines 147-152	Initialise cross-section area variables to zero.
Lines 161-280	New values of reservoir are calculated for each survey using constant factors CFAC previously calculated.
Line 169	Cross-section co-ordinates are read in pairs for each section starting with 0,0 at the left end; the READ will continue for each section until a non-numeric character set (eg END) is found.
Line 171	The final co-ordinate pair should, however, whenever possible be the right-hand beacon.
Lines 173-176	Find the lowest level in the current section.
Lines 177-182	Calculate the maximum water depth and number of sub-segments (contour slices) in the current section: default value = 1.
Lines 198-201	In any given section, the top vertical distance is WLCINC (see Line 131) and the remaining vertical distances are CINCRE (see Line 129).
Lines 206-266	Each consecutive pair of co-ordinates, are examined in turn and the area contained by these two points and the next highest contour - or the water surface - are calculated. The eight possible configurations are defined as:
Lines 214-218	H(I) and H(I+1) are both between the same pair of contours.
Lines 219-223	H(I) is above the water surface and H(I+1) is below the water surface but above the next highest contour.
Lines 224-230	H(I) is above the water surface and H(I+1) is below the next highest contour.
Lines 231-239	H(I) is between the water surface and the next contour, H(I+1) is below the next contour.

Lines 240-245	H(I+1) is above the water surface and H(I) is below the water surface but above the next highest contour.
Lines 246-253	H(I+1) is above the water surface and H(I) is below the next highest contour.
Lines 254-261	H(I+1) is between the water surface and the next contour, H(I) is below the next contour.
Lines 262-265	Both pairs of co-ordinates are contained between two given levels.
Lines 270-276	Maintaining running totals of contour slice end areas and set up sub-segment levels for repeat of lines 206-266.
Lines 287-407	Calculate constant factors from pre-impoundment survey and contour data.
Lines 293-294	Check if current range line is at upstream or downstream limit and if a contour appears upstream of the first line or downstream of the last line.
Lines 310-313	Read original contour data with SAUPP containing the surface area of the upper contour.
Lines 316-318	Set up the level of the lower contour for each sub-segment (contour slice).
Lines 330-348	Re-arrange stored data to match up contour areas and vertical increment to each sub-segment.
Lines 352-358	Sum consecutive pairs of cross-section areas: if contours are drawn before the most upstream section, then an imaginary section with zero area is included; if the dam is downstream of the last section, then it is assumed to have the same cross-section area as the last section.
Line 360	Sub-segment volume is calculated as the produce of the mean of the contour areas and the contour increment.
Line 361	The constant factor CFAC is the sub-segment volume divided by the sum of the end areas.
Lines 388-392	Summation of end area data for most recent hydrographic survey.
Lines 399-402	Obtain new reservoir segment and total volumes using CFAC calculated above.
Lines 412-480	Re-arrange data in files and print table of results.

```
      PROGRAM SVPRO3
C
C       ******************************************************************
C       *                                                                *
C       *          Hydraulics Research Ltd,Wallingford,Oxon.             *
C       *             Program begun by C.R.Talbot,continued              *
C       *               by Tony G.    1984                               *
C       *                                                                *
C       ******************************************************************
C
C     A program to read survey data in the form of X and  Y coordinates
C     (i.e distances and reduced levels) along reservoir X-sections.The
C     program calculates the X-sectional areas using the Trapezium Rule
C     and,after calculating initial"Constant Factors" for the sections,
C     new volumes of each  segment and  the  complete   reservoir  are
C     calculated using the new survey data.
C
C     The program has two main parts.The first part reads in  survey
C     data and calculates X-sectional areas for each section.This is
C     done for both the original and recent surveys.Constant factors
C     and design volumesare calculated in the second part and finally
C     new volumes are calculated.
C
C     The program can deal with reservoirs containing any specified no.
C     of limbs.This is specified (as 'NLIMBS'), and each limb is consid
C     -ered separately, starting with the main limb, which will include
C     the segment between the final (downstream) section and the dam.
C     Care in defining'upstream' and'downstream'is required,the program
C     assumes upstream values to be input before downstream.
C
C     It is assumed the user has a knowledge of the ' Constant Factor '
C     method for calculating reservoir volumes.
C
C     **************** Glossary of Variable names ******************
C
C     (r) read in
C     (c) calculated
C
C            AO   (C)    =   Sum of end areas of segment.
C            AREA (c)    =   Area of trapezium within sub-section,defined
C                            by XCOORD's and YCOORD's.
C            CFAC (r)    =   Constant Factor.AO/VO
C          CINCRE (r)    =   Increment between contours.(Area calcs)
C          CONT   (r)    =   Higher contour in sub-segment
C          CONTL  (c)    =   Lower  contour in sub-segment
C          DSTRM  (r)    =   Is program to include volume of segment d/s
C                            of final section? (YES/NO)
C            DMAX (c)    =   Maximum depth along a defined section.'DMAX'
C                            is calculated using 'XSMALL'.
C               H (c)    =   Height of  water level/upper contour  above
C                            reduced level of bed at point 'XCOORD'.
C            INC  (c)    =   Increment between contours.(Vol calcs)
C            NFIX (c)    =   No of fixes(ie XCOORD's and YCOORD's) along
C                            a defined section.
C          NLIMBS (r)    =   No of limbs in reservoir.
C           NSECT (r)    =   No of sections in reservoir/reservoir limb.
C           NSUBS (c)    =   No of sub-sections in a defined section.
C           NQUAT (c)    =   A number,written out to monitor file, which
C                            indicates which equation was used to calcul
C                            -ate the area of a defined trapezium.Useful
C                            for checking against possible data errors.
```

```
C           REFNAM (r)    =   Reference name of section/segment.
C            SAREA (c)    =   Area of a defined sub-section.
C              SED (r)    =   Volume of defined sub-segment(previous sur-
C                             vey)
C           SEDSUM (r)    =   Volume of defined segment(previous survey)
C             SEDX (c)    =   Present volume of defined sub-segment.
C            SEDXM (c)    =   Present volume of defined segment.
C           SUMSEG (c)    =   Total reservoir volume (at design).
C            SUMVO (r)    =   Volume of defined segment (at design).
C           TOTSED (c)    =   Total reservoir volume (previous survey).
C           TSEDXM (c)    =   Present Total reservoir volume.
C           UPSTRM (r)    =   Is program to include volume of segment u/s
C                             of first section? (YES/NO)
C               VO (r)    =   Volume of a defined sub-section (at design).
C            WIDTH (r)    =   Width of defined section (beacon to beacon).
C           XSMALL (c)    =   see 'DMAX'.
C           XCOORD (r)    =   Distance(m) of fix from left bank beacon.
C           YCOORD (r)    =   Reduced level of bed at 'XCOORD'.
C               WL (r)    =   Water level.
C           WLCINC (r)    =   Increment between 'WL', and contour which
C                             defines lowest part of uppermost sub-sect
C                             -ion in the reservoir.
C
C      The program creates two files; a results file (channel 3),and
C      a monitor file (channel 6) to which are written intermediate
C      values whilst the program is running.This is useful for detect
C      -ing data errors.
C
C    ***************************************************************
C    ***************************************************************
C
      CHARACTER*80 REFNAM,TEST,LINST,UPSTRM*5,DNSTRM*5,TITLE*120,
     1NAME*25
      DIMENSION XCOORD(300),YCOORD(300),H(300),SAREA(25,100,5),
     1 SED(25),VO(25),SEDX(25),AOSEDX(25),NSUBS(25),CONTH(25),
     2 SAUPP(25),SALOW(25),AO(25),CONTL(25),INCRE(25),NDATE(25),
     3 CONT(25),INC(25),RSALOW(25),RSAUPP(25),NCHANN(25),CFAC(25),
     4 TOAREA(100,5),CVOL(25,5),DSAREA(25),USAREA(25)
      INTEGER DS,US,DATE
      REAL INC,INCRE
      LOGICAL XXX
C
      READ(4,*)SWIT
      READ(4,*)DATE
      READ(4,*)NSEGS
      READ(4,*)MCONTS
      READ(4,*)(CONT(M),M=1,MCONTS)
C
C          Initialisation
C
      XXX = .FALSE.
      SUMSEG = 0.0
      TOTSED = 0.0
      TSEDXM = 0.0
      MNCONT = 1.0
C
C
C          Read in general parameters (channel 1)
C
          READ(1,350)NAME
          READ(1,*)NYEARS
          READ(1,*)NLIMBS
          READ(1,*)NSECT
```

```
            READ(1,350)UPSTRM
            READ(1,350)DNSTRM
            READ(1,340)
            READ(1,*)CINCRE
            READ(1,*)WL
            READ(1,*)WLCINC
      DO 5 N = 1,NYEARS
            READ(1,*)NDATE(N),NCHANN(N)
    5 CONTINUE
C
         DO 2  I=1,25
          DO 2 K=1,NYEARS
            CVOL(I,K)=0.0
    2 CONTINUE
C
      III = NLIMBS
C
C           If more than one limb exists,XXX is set to 'TRUE'
C
   33 IF(III.GT.1) XXX = .TRUE.
C
      DO 18 J = 1,100
         DO 18 I = 1,25
         DO 18 K=1,NYEARS
         SAREA(I,J,K) = 0.0
         TOAREA(J,K) = 0.0
   18 CONTINUE
      WRITE(6,*)NSECT,CINCRE,WL
C
C
C           ********************************************************
C           This first part reads in the new survey data and calculates
C           X-sectional areas for each section.
C           ********************************************************
C
      DO 101 K=1,NYEARS
      DO 100 MSECT = 1,NSECT
      WRITE(6,920)MSECT
         READ(NCHANN(K),350)REFNAM
         READ(NCHANN(K),*)WIDTH
C
C           'REFNAM' is the reference name of the section
C
    3    READ(NCHANN(K),*,ERR=4)(XCOORD(LL),YCOORD(LL),LL=1,300)
    4 NFIX = LL-1
      XCOORD(NFIX+1)=WIDTH
C
      XSMALL = 99999.0
         DO 6 I = 1,NFIX
         IF(XSMALL.GT.YCOORD(I))XSMALL = YCOORD(I)
    6    CONTINUE
      DMAX = (WL-XSMALL)
       IF((DMAX-WLCINC).LE.0.0)THEN
             NSUBS(MSECT)=1
       ELSE
             NSUBS(MSECT) =((DMAX-WLCINC)/CINCRE)+1.9999
       ENDIF
C
C           Note above equation.0.9999 is added to left-hand side to ensure
C           that rounding is always (in effect) upwards to nearest integer.
C
      WRITE(6,600)REFNAM
      WRITE(6,*)XSMALL,NFIX,XCOORD(NFIX+1)
```

```
C
C          Calculate 'H(I)' i.e the depth of reservoir at each fix.
C
      DO 7 I=1,NFIX
      H(I) = WL-YCOORD(I)
    7 CONTINUE
C
      STORE = CINCRE
C
      DO 10 J = 1,NSUBS(MSECT)
      IF(J.EQ.1) CINCRE = WLCINC
      IF(J.GE.2) CINCRE = STORE
      WRITE(6,405)CINCRE
C
C          This section defines each trapezium and decides how to calculate
C          the area of that trapezium.
C
      DO 25 I = 1,NFIX
      H(NFIX+1) = 0.0
         IF(H(I).LE.0.0.AND.H(I+1).LE.0.0)GO TO 25
C
C          Note 'NQUAT' is set to an integer value,in the range 1 to 8
C          depending on which equation is used to calculate 'AREA' for
C          each trapezium.
C
      IF(H(I).GE.CINCRE.AND.H(I+1).GE.CINCRE)THEN
         AREA = CINCRE*(XCOORD(I+1)-XCOORD(I))
         NQUAT = 3
         GO TO 20
      ENDIF
C
      IF (H(I).LT.0.0.AND.H(I+1).GT.0.0)THEN
         X = ((XCOORD(I+1)-XCOORD(I))*H(I+1))/(H(I+1)-H(I))
         AREA = (H(I+1)/2.0)*X
         NQUAT = 4
            IF(H(I+1).GT.CINCRE)THEN
               X2 = ((XCOORD(I+1)-XCOORD(I))*(H(I+1)-CINCRE))
     1         /(H(I+1)-H(I))
               AREA2 = ((H(I+1)-CINCRE)/2.0)*X2
               AREA = AREA - AREA2
               NQUAT = 1
            ENDIF
         GO TO 20
      ELSEIF(H(I+1).GT.CINCRE.AND.H(I).LT.CINCRE)THEN
         X = ((XCOORD(I+1)-XCOORD(I))*(H(I+1)-CINCRE))
     1   /(H(I+1)-H(I))
         AREA = (((H(I)+H(I+1))/2.0)*(XCOORD(I+1)-XCOORD(I)))-
     1   ((H(I+1)-CINCRE)/2.0)*X
         NQUAT = 5
         GOTO 20
      ENDIF
C
      IF(H(I).GT.0.0.AND.H(I+1).LT.0.0)THEN
         X = (((XCOORD(I+1)-XCOORD(I))*(H(I))))/
     1   (H(I)-H(I+1))
         AREA = (H(I)/2.0)*X
         NQUAT = 6
           IF(H(I).GT.CINCRE)THEN
              X2 = ((XCOORD(I+1)-XCOORD(I))*(H(I)-CINCRE))
     1        /(H(I)-H(I+1))
              AREA2 = ((H(I)-CINCRE)/2.0)*X2
              AREA = AREA - AREA2
              NQUAT = 2
```

```
            ENDIF
         GO TO 20
      ELSEIF(H(I).GT.CINCRE.AND.H(I+1).LT.CINCRE)THEN
         X = ((XCOORD(I+1)-XCOORD(I))*(H(I)-CINCRE))
     1   /(H(I)-H(I+1))
         AREA = (((H(I)+H(I+1))/2.0)*(XCOORD(I+1)-XCOORD(I)))-
     1   ((H(I)-CINCRE)/2.0)*X
         NQUAT = 7
         GO TO 20
      ENDIF
C
      AREA = ((H(I)+H(I+1))/2.0)*(XCOORD(I+1)-XCOORD(I))
      NQUAT = 8
C
   20 CONTINUE
C
      IF(AREA.LT.0.0)AREA = 0.0
C
      SAREA(J,MSECT,K) = SAREA(J,MSECT,K)+AREA
   25 CONTINUE
      WRITE(6,750)SAREA(J,MSECT,K),NQUAT
        DO 21 L = 1,NFIX
        H(L) = H(L) - CINCRE
   21 CONTINUE
      TOAREA(MSECT,K)=TOAREA(MSECT,K)+SAREA(J,MSECT,K)
   10 CONTINUE
      WRITE(6,760)TOAREA(MSECT,K)
  100 CONTINUE
  101 CONTINUE
C
C          **********************************************************
C          This second main part reads in contour data and calculates
C          Constant Factors' using previously calculated Xsectn areas.
C          **********************************************************
C
      WRITE(3,300)DATE
      WRITE(3,310)
      WRITE(3,340)
      WRITE(3,320)
      NSECT = NSECT + 1
      DO 228 MSECT = 1,NSECT
      IF(UPSTRM.EQ.'NO'.AND.MSECT.EQ.1)GO TO 228
      IF(DNSTRM.EQ.'NO'.AND.MSECT.EQ.NSECT)GO TO 228
C
C     As each end area may(eg if UPSTRM=YES)require an extra set of
C     contour data,the assumed value of UP/DOWNSTRM is YES and the
C     extra'read in'is operated unless NO is specified.
C
C
C           SET K=1 I.E. USE ORIGINAL SURVEY DATA FOR CALCULATING CFAC
C
      K=1
      SUMVO = 0.0
      SEDSUM = 0.0
      SUMSIL = 0.0
C
  104 READ(5,350)LINST
      IF(LINST.EQ.' ')GO TO 104
C             READ IN ORIGINAL RESERVOIR DATA
      READ(5,*) NCONTS
      READ(5,*) BINCRE
      READ(5,*)(SAUPP(J),J=1,NCONTS)
C
```

```
C
      DO 108 M=1,NCONTS
      IF(M.EQ.NCONTS)GO TO 109
      CONTL(M) = CONT(M+1)
C
C              Incre could be activated if contours are unevenly spaced
C              this would require further program modification.
C     INCRE(M) = CONT(M)-CONTL(M)
C
      GO TO 108
  109 CONTL(NCONTS) = CONT(NCONTS) - BINCRE
  108 CONTINUE
C
C         Assign top and bottom areas for each contour slice
C
      DO 118 L = 1,NCONTS
      IF(L.EQ.NCONTS)GO TO 119
      SALOW(L) = SAUPP(L+1)
      GO TO 118
  119 SALOW(NCONTS) = 0
  118 CONTINUE
C
C       Assign vertical increments between cotours,water level and bottom
C
      DO 122 N = 1,NCONTS
        IF(N.EQ.1)THEN
          INC(N) = WLCINC
        ELSEIF(N.EQ.NCONTS)THEN
          INC(N) = BINCRE
        ELSE
          INC(N) =CINCRE
        ENDIF
  122 CONTINUE
      IF(NCONTS.GE.MNCONT)MNCONT=NCONTS
C
C       Calculate Original Volumes and hence Constant Factors
C
      DO 129 J = 1,NCONTS
      IF(MSECT.EQ.1)THEN
          AO(J)=SAREA(J,MSECT,K)
      ELSEIF(MSECT.GT.1.AND.MSECT.LT.NSECT)THEN
          AO(J)=SAREA(J,MSECT,K)+SAREA(J,MSECT-1,K)
      ELSEIF(MSECT.EQ.NSECT)THEN
          AO(J)=SAREA(J,MSECT-1,K)*2
      ENDIF
      VO(J)=((SAUPP(J)+SALOW(J))/2)*INC(J)
      CFAC(J)=VO(J)/AO(J)
      SUMVO = SUMVO+VO(J)
C
      CVOL(J,K)=CVOL(J,K)+VO(J)
  129 CONTINUE
C
C        Optional Info to moniter file
C
      IF(SWIT.EQ.0.0)GO TO 111
      WRITE(6,210) LINST
      WRITE(6,620)
      WRITE(6,230)(CONTH(J),CONTL(J),SAREA(J,MSECT,K),
     1SAREA(J,MSECT-1,K),AO(J),SAUPP(J),SALOW(J),VO(J),CFAC(J),
     2J=1,NCONTS)
      WRITE(6,240)SUMVO
  111 CONTINUE
C
```

```
C
      DO 199 K = 2,NYEARS
C     Normally there will only be 2 years data processed simultaneously
C
      SEDXM=0.0
C
      DO 117 J = 1,NCONTS
C
C         Calculate sum of end areas 'AOSEDX'
C
      IF(MSECT.EQ.1)THEN
          AOSEDX(J) = SAREA(J,MSECT,K)
      ELSEIF(MSECT.GT.1.AND.MSECT.LT.NSECT)THEN
          AOSEDX(J) = SAREA(J,MSECT,K)+SAREA(J,MSECT-1,K)
      ELSEIF(MSECT.EQ.NSECT)THEN
C
          AOSEDX(J) = SAREA(J,MSECT-1,K)*2
      ENDIF
C
C         Multiply 'AOSEDX' by Constant Factor 'CFAC'.
C
      SEDX(J) = CFAC(J)*AOSEDX(J)
      SEDXM = SEDXM + SEDX(J)
C
      CVOL(J,K)=CVOL(J,K)+SEDX(J)
C
  117 CONTINUE
C
      PCENT = 100.0-((SEDXM/SUMVO)*100.0)
      SEDSUM=SUMVO-SEDXM
C
C       Write to results file(channel 3)
C
C
      WRITE(3,340)
      WRITE(3,250)LINST
C
      DO 138 J = 1,NCONTS
         IF(MSECT.EQ.1)THEN
         NSLAST = 0.0
         ELSE
         NSLAST = INT(SAREA(J,MSECT-1,K))
         ENDIF
      IF (MSECT.EQ.NSECT) THEN
      NSAREA=NSLAST
      ELSE
      NSAREA=INT(SAREA(J,MSECT,K))
      ENDIF
      SVO=VO(J)-SEDX(J)
      F6=1.0/(10.**6)
      VJ6=VO(J)*F6
      SE6=SEDX(J)*F6
      SV6=SVO*F6
      WRITE(3,150)CONT(J),CONTL(J),NSAREA,NSLAST,AOSEDX(J),
     1CFAC(J),VJ6,SE6,SV6
  138 CONTINUE
C
      WRITE(3,340)
      SVO6=SUMVO*F6
      SXM6=SEDXM*F6
      SDM6=SEDSUM*F6
      WRITE(3,200)SVO6,SXM6,SDM6,PCENT
C
```

```
  199 CONTINUE
C
      SUMSEG = SUMSEG+SUMVO
      TOTSED = TOTSED+SEDSUM
      TSEDXM = TSEDXM+SEDXM
C
  228 CONTINUE
C
C          Check whether there are any further limbs in reservoir to be
C          considered.If 'yes' then return to read more survey data.
C
         IF(XXX)THEN
           III = III - 1
           XXX = .FALSE.
           READ(1,*)NSECT
           READ(1,350)UPSTRM
           READ(1,350)DNSTRM
           GO TO 33
         ENDIF
C
      TPCENT = 100.0-((TSEDXM/SUMSEG)*100.0)
      WRITE(3,340)
      SMSG6=SUMSEG*F6
      TSXM6=TSEDXM*F6
      TOED6=TOTSED*F6
      WRITE(3,340)
      WRITE(3,403)SMSG6,TSXM6,TOED6,TPCENT
C
C       Sum the reservoir volumes below each contour
C
      DO 238 K=1,NYEARS
C
      RUNTOT=0.0
C
             DO 238 J=MNCONT,1,-1
              RUNTOT=RUNTOT+CVOL(J,K)
              RTOT6=RUNTOT*F6
              WRITE(3,780)NDATE(K),CONT(J),RTOT6
  238        CONTINUE
      STOP
C
  110 FORMAT(A119)
  120 FORMAT(A116)
  130 FORMAT(A120)
  150 FORMAT(14X,F7.2,2X,F7.2,3X,I6,3X,I6,4X,F8.1,3X,F8.1,1X,
     1F11.4,3X,F11.4,2X,F11.4)
  200 FORMAT(73X,F10.4,1X,F13.4,F13.4,2X,F6.2)
  250 FORMAT(/1X,A)
  340 FORMAT()
  341 FORMAT(///)
  350 FORMAT(A)
  402 FORMAT(16X,F11.1,2X,F11.1,2X,F11.1)
  403 FORMAT(56X,'TOTAL RESERVOIR ',F12.4,2X,F11.4,3X,F12.4,2X,F6.2)
  405 FORMAT(/5X,'CINCRE = ',F5.3)
  600 FORMAT(/5X,'REFNAM = ',A)
  660 FORMAT(/5X,'H(L) = ',5(F6.3,1X))
  700 FORMAT(5X,'AREA = ',F10.4)
  750 FORMAT(5X,'SAREA( RUNNING TOTAL ) = ',F11.4,6X,I2)
  760 FORMAT(5X,'TOTAL XSECTN AREA  = ',F11.2)
  920 FORMAT(/2X,'MSECT = ',I3)
  930 FORMAT(/2X,'J = ',I3)
  300 FORMAT(1H1,'  SECTIONS        UPPER    LOWER        END AREAS          SU
     1M OF     CONSTANT        DESIGN          ',I4,'    CHANGE IN    '% LOSS'
```

```
     1)
 310 FORMAT(1X,'  U/S    D/S    CONTOUR    CONTOUR     D/S      U/S       END
    1 AREAS    FACTOR       CAPACITY     CAPACITY    VOLUME        OF')
 320 FORMAT(33X,'[SQ.M]    [SQ.M]      AO [SQ.M]      [C]        [MCU.M]
     1  [MCU.M]       [MCU.M]     CAPACITY')
 220 FORMAT(/)
 210 FORMAT(/1X,A)
 620 FORMAT(1H1///4X,'UPPER         LOWER         END AREAS           SUM OF
     1          CONTOUR SURFACE AREAS        CAPACITY        CONSTANT')
 630 FORMAT(3X,'CONTOUR     CONTOUR       D.S       U.S        END AREAS
     1  UPPER              LOWER             VO               FACTOR')
 640 FORMAT(5X,'[M]           [M]         [SQ.M]    [SQ.M]     AO [SQ.M]          [S
     1Q.M]            [SQ.M]       [CU.M]              [CFAC]')
 240 FORMAT(/56X,'VOLUME OF SEGMENT [CU.M] = ',F12.1)
 230 FORMAT(4X,F7.2,4X,F7.2,3X,I5,4X,I5,6X,I5,7X,I7,9X,I7,5X,F10.1,7X,I
     14)
 780 FORMAT(/5X,I5,' VOLUME BELOW ',F7.2,' = ',F12.4,' MCU.M')
      END
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