Wallingford Water

Mutonga/Grand Falls Hydropower Project

Environmental Impact Assessment Feasibility Study

Draft Report EX 3375

Wallingford Water

This document contains the draft contributions from Wallingford Water with regard to:

Flood releases;
Morphological model studies; and
Water Quality studies

submitted for inclusion in the full report compiled by Acropolis.

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Mutonga/Grand Falls Hydropower Project
EIA Feasibility Study

Task 4.2.9 - Flood Release

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1 Introduction

This report describes the work performed under task 4.2.9 of the EIA Feasibility Study on the Mutonga/Grand Falls Hydropower Project. The objective and methods involved in this task are described below in accordance with the terms of reference set out in Acropolis Kenya Ltd and Otieno Odongo & Partners (1995).

Objective

To prepare a plan of reservoir operation which will allow for the provision of optimal flood release to the downstream river-dependent environments.

Methodology

(1) Working in conjunction with the Nippon Koei Hydrologist establish a consistent daily discharge set. Establish the normal flooding patterns at Garissa from this daily discharge set. Perform additional correlative assessment on selected daily flow at Garsen and/or Hola. Obtain and analyse any additional relevant meteorological (ie remote sensing) data corresponding to these flood periods. From these analyses determine the flood release required at Grand Falls to sustain the normal pattern of flooding at Garissa.

(2) Review all available information on previous artificial flood release schemes.

The current report concentrates on Task (1) above, as the findings of a literature review of previous schemes where artificial flood releases have been considered are incorporated into the separate report on flood and sediment releases from reservoirs.

The data and methods employed to establish a consistent daily discharge set for the Lower Tana are described in chapters 2 and 3. The detailed analysis of the discharge data to characterise the normal pattern of flooding at Garissa and corresponding floods at Grand Falls are described in chapter 4. Chapter 5 describes additional rainfall analyses performed to assist in the evaluating the relationship between flooding at the two sites. Following a discussion of the findings of the flood event and rainfall analyses in chapter 6. Chapters 7 and 8 comprise the conclusions and recommendations for further work.

2 Data

The consultants visited Nairobi in July 1995 and met with the Nippon Koei hydrologist and with staff of the Ministry of Water Development (MOWD), Kenya Meteorological Department (KMD) and the Tana and Athi Rivers Development Authority (TARDA). Following these discussions several visits were made to the MOWD in order to collect gauging and stage data for gauging stations on the lower Tana River. Stage data were provided by the Nippon Koei hydrologist for six stations; 4F13, 4G01, 4G06, 4G08, 4G09 and 4G10. No reference to station 4G06 can be found in any of the reports contained in the reference list and it is assumed that the stage data may in fact relate to station 4G04, Hola. Stage data for one further key station, 4G02 at Garsen, were subsequently collected from MOWD. The location of these gauging stations is shown on Figure 2.1.

Current mater data were provided by Nippon Koei for station 4F13, Grand Falls. Data for stations 4G01, 4G02, 4G08 and 4G10 were subsequently collected from MOWD. Details of the data collected are given in Table 2.1.

Table 2.1 Gauging and stage data collected from MOWD, July 1995

Station Number	Station Name	Period of Gaugings	Period of Stage Data
4F13	Grand Falls	07/62-01/81	1962 - 1993
4G01	Garissa	03/44 - 03/95	1933 - 1993
4G02	Garsen	03/46 - 11/91	1950 - 1985
4G04	Hola	None available from MOWD	
4G06	?	None available from MOWD	1966 - 1974
4G08	Nanigi	10/74 - 09/79	1973 - 1985
4G09	Ngao	None available from MOWD	1973 - 1985
4G10	Saka	02/84 - 05/85	1983 - 1985

Stage is observed manually either once or twice a day at each gauging station, with twice daily readings being more common in the two wet seasons. However, at all stations there are frequent gaps in the data, and there are only a few years with complete data. Figure 2.2 illustrates data availability at each station, with the figure showing the percentage of days in each year having at least one observed stage reading from which daily mean flow may be computed. Data availability is best at Garissa, perhaps because the station is close to a large town, and there are 11 complete years out of 61, with a further 21 having greater than 95 percent daily data available (equivalent to less than 18 days missing observed stages in any year). The key record at Grand Falls has only 3 nearly complete years out of 32 (i.e. greater than 95 percent daily data availability), and Garsen has only 4 nearly complete years out of 35, and 1970 is missing completely at this station. The earlier current meter data recorded at the gauging stations with longer records was provided in imperial units. This data were converted to metric format before proceeding with any analysis.

In addition to the stage and gauging data, daily rainfall records for approximately 200 to 300 stations in and around the Tana catchment collected by the KMD were provided by Nippon Koei to the consultants. These data were provided in several formats, some of which required processing before any analyses could be performed. Further details of the rainfall data used in the study are given in chapter 5.

3 Ratings and Discharge Conversion

3.1 Review and fitting of rating curves

The existing rating curves used to derive flow from stage at each of the five stations for which current meter gaugings were collected were reviewed through an assessment of the goodness of fit with the gauging data detailed in table 2.1. The ratings were taken from DHV (1986) and Nippon Koei (1995a) which, apart from minor discrepancies and difference in units, are broadly in agreement. These curves were fitted by MOWD except in the case of Saka for which curves were fitted by consultants involved in a previous study (DHV, 1986).

Following this review new ratings were fitted to the gauging data of each station. The gaugings were first assessed for any possible shifts in the relationship between stage and discharge and split into what appeared to be periods during which this relationship remained consistent. Outliers were inspected carefully to assess whether any errors may have occurred in the transcription of the data. Rating curves were then fitted to each of the periods of gauging data using the automatic fitting procedure on the Institute of Hydrology's HYDATA hydrological database and analysis software. Curves were fitted with between one and three parts with the goodness of fit judged partly by an automatically computed error function, and partly subjectively by an experienced hydrologist.

The new HYDATA ratings were plotted against the existing MOWD curves and the gauging data. For each station and each rating period the old and new curves were compared and a decision taken on which curve to use to convert the stage data to flows. In most cases the HYDATA rating curves appear to fit the gauging data provided more closely than the existing MOWD curves. In a minority of cases the HYDATA and MOWD curves are virtually identical. For consistency it was decided to select all the new HYDATA ratings for the conversion of stage data to discharge.

Details of the review, fitting and comparison of rating curves are given in Appendix A.

3.2 Conversion of stage to discharge

The stage data provided by MOWD were converted to discharges using the new HYDATA rating equations described in Appendix A. The conversion was made difficult by variations in the raw stage data, with some days having two stage readings, some just one and others none at all. A program was written to convert the raw stage data and to produce a single value of discharge for each day of record. On days with two stage readings each was converted to discharge and the mean taken. The resulting set of daily discharges are plotted in Appendix B.1.

The daily discharge series were carefully checked for any anomalies or suspected errors. Two types of anomaly were apparent. The first, single days of high or low values inconsistent with adjacent values, were easily checked by examining the stage data. In most cases the cause of these errors were obvious and could be amended. The second type of anomaly comprise periods of apparently constant discharge. In these cases examination of the raw stage data revealed that level had indeed been recorded as constant for a number of days. These periods of data were therefore not amended although suspected to be erroneous.

As a check on the daily discharges the values were summed to produce monthly totals and the mean monthly flow found. Complete months of record were compared with the values given as the 'reference streamflows' in Nippon Koei (1995a). This was only possible for the flow series for Grand Falls and Garissa. The two sets of data agree well with divergences as expected according to differences between the MOWD and HYDATA ratings. In most cases the discharge values estimated from the HYDATA ratings curves are slightly lower than those from the MOWD curves. Scatter plots comparing the monthly flows are presented in Appendix B.2.

4 Flood Event Analysis

4.1 Objective

The daily discharge series at Garissa was analysed in order to establish the characteristics of flooding at Garissa. Floods were characterised in terms of their duration, peak flow and total volume. The objective of this analysis was to produce an estimate of the 'normal' flood at Garissa. The daily discharge series at Grand Falls was also analysed in order to isolate the flow pattern corresponding with the normal flood downstream at Garissa. This flow is indicative of the release required from Grand Falls reservoir to sustain an acceptable pattern of flooding at Garissa.

The daily discharge series at Nanigi and Garsen were also analysed in order to examine the relationship between flooding at Garissa and that downstream.

4.2 Pattern of flooding at Garissa 1960 to 1993

The daily discharge series at Garissa from 1960 to 1993 was examined in order to establish the pattern of flooding. There is a marked seasonal pattern of river discharge with floods occurring in general during two distinct wet seasons in each year, the first during April and May and the second in November and December. Daily discharges between 1960 and 1969 are shown in figure 4.1 whilst those for the entire period are plotted in Appendix B.1.

In around half of the years between 1960 and 1993 floods greater than 500 m^3s^{-1} occurred in both wet seasons. In the majority of other years floods greater than 500 m^3s^{-1} occurred in one or other of the two wet seasons. However, in seven out of the 34 years there were no floods above this threshold and out of bank flow presumably did not occur. In probabilistic terms, and on the basis of this period of record, there is an 80% chance that a flood over 500 m^3s^{-1} will occur at least once in a year. The chance that floods will not occur in one or other of the two wet seasons is around 0.5 in any one year.

There appears to be a degree of clustering in the pattern of flooding between 1960 and 1993 (see figure 4.2). During the 1960s there were floods greater than 500 m^3s^{-1} in almost all of the wet seasons. In contrast floods were significantly lower during the early and mid 1970s. For four years between 1973 and 1976 there were no floods greater than 500 m^3s^{-1} at all. Following a period of higher floods in the late 1970s the pattern of flooding has become more erratic. Since 1981 floods greater than 500 m^3s^{-1} have occurred in only one season or not at all in 8 out of 13 years.

The pattern of flooding in the first wet season is slightly different to that in the second. There is a slight tendency for flood peaks to be greater in the first wet season, with this being the case in 22 out of the 34 years considered. This is supported by the flood frequency curves shown in figure 4.3 which show the return periods associated with recorded flood magnitudes separately for the two wet seasons. At low return periods (less than 2 years), in other words the most frequent occurrences, flood peaks are higher in the first wet season. However, the flood peaks of more infrequent events, with return periods of more than 2 years, are higher in the second wet season. The highest flood peaks recorded in each of the two seasons are extremely similar. Peak floods of around 1600 m^3s^{-1} occurred in April 1988 and in November of both 1961 and 1984.

4.3 Assessment of the 'normal' flood at Garissa

Prior to any analysis it was important to establish a definition to describe the 'normal' flood, or pattern of flooding, at Garissa. Ideally the flood should be defined in terms of a probability of occurrence, best described by a return period. The normal flood might, for instance, be selected as that which occurs on average once a year, with a return period of about 2 years.

Previous studies have preferred to describe the normal pattern of flooding at Garissa in terms of magnitude and duration. The consensus normal flood has a duration of 5 days during which mean daily discharge is over 500 m^3s^{-1}. This is assumed to represent the discharge required for out of bank flooding to occur at Garissa and to inundate the floodplain both upstream and downstream for a period sufficient to maintain the environment and level of economic activity currently supported by the river regime.

This definition, although strictly describing a requirement for flooding rather than a natural pattern, is useful because it places certain constraints on the assessment of the normal flood at Garissa. These are, firstly, that the flood results in out of bank flow at Garissa and, secondly, that the floodplain both upstream and downstream is inundated to an optimal extent and period of time.

In the present study it was assumed that these criteria must be satisfied by the normal flood at Garissa. Following a brief review of the work performed as part of previous studies the discharge value of 500m^3s^{-1} was accepted as the threshold above which out of bank flow is likely to occur at Garissa. This value was identified from a change in slope in the rating curve for Garissa gauging station and from a comparison of bank height and river water levels using the RIVMOR morphological model (Delft Hydraulics, 1994). It is also reported that this value agrees with local records (Nippon Koei, 1995b).

A check on the estimated threshold value of 500 m^3s^{-1} for out of bank flow was performed by comparing river water depths and channel cross sections published in DHV (1986). The results of a series of gaugings include the following water depths and discharges:

Date	Water Depth (m)	Discharge (m^3s^{-1})
17/05/85	3.83	490.0
23/05/85	4.85	683.0
27/05/85	4.01	539.0

The nearest channel cross section (at km 510, with Garissa at km 509) indicates that bankfull height is around 3.5-4.0 m. Given the above gaugings this appears to confirm that out of bank flooding will occur with a flow of around 500 m^3s^{-1} at Garissa.

A further check was performed in order to examine whether, given this threshold of 500 m^3s^{-1}, out of bank flooding is a 'normal' phenomenon. The annual maximum series of flood peaks (the largest flood peak recorded in each year) was extracted from the daily discharge series at Garissa and plotted against return period (see figure 4.4). The flood with peak of, or greater than, 500 m^3s^{-1} has a return period of around 1.3 years. Given that the out of bank flooding is likely to occur, on average, nearly once a year it is fair to describe this pattern of flooding as normal.

However, in order to characterise the range of out of bank flooding which occurs at Garissa it was necessary to take account of not just the minimum flood over the 500 m^3s^{-1} threshold but of all events with daily discharge above this value. This set of flood events is best characterised in terms of a median flood describing the middle value of flood duration, peak and total volume when these are ranked from largest to smallest. The median is an appropriate choice to represent the pattern of flooding because exactly half the events analysed are greater than it and exactly half are smaller. In probabilistic terms the median flood, with return period 2 years, has a 0.5 chance of occurring in any year. The mean flood is a poorer representation due to the skewed nature of the distribution of flood characteristics. It has an estimated return period of 2.33 years and is greater in magnitude than more than half of recorded events. The working definition of the normal flood assumed in this study is therefore given by:

The median flood of those events resulting in out of bank flooding at Garissa and which inundate the floodplain both upstream and downstream for a period sufficient to maintain the environment and level of economic activity currently supported by the river regime. The median of floods with at least one day's flow of over 500 m^3s^{-1}.

4.4 Estimation of the median flood at Garissa

The series of daily discharges at Garissa from 1963 to 1993 was analysed to isolate all flood events with at least one day of flow greater than 500 m^3s^{-1}. Given that it was important that concurrent flow records were also available for Grand Falls during each event the start date was determined by the availability of data for this latter station.

The discharge data extracted comprised all flood events with flow greater than 500 m^3s^{-1} at Garissa along with the ten days prior to the onset of the flood. Concurrent records were extracted for Grand Falls. Linear interpolation was used to infill a small number of single missing days of data at Garissa. Given the more incomplete state of the discharge data for Grand Falls periods of up to 3 days were infilled by the same method. Events with significant infilling or remaining missing days of data were not included in further analysis due to the high degree of uncertainty over the true daily discharge values. Where the daily discharge during a single event dropped slightly below 500 m^3s^{-1} these days were included in the analysis. Only 6% of all flows included in the analysis were less than 500 m^3s^{-1}.

Each flood event at Garissa was characterised in terms of its duration (number of days with flow greater than 500 m^3s^{-1}), peak flow and total flood volume. The characteristics of the 52 flood events examined are given in Appendix C.1 and are summarised in table 4.1.

Table 4.1 Summary characteristics of flood events at Garissa greater than 500 m^3s^{-1}

	Duration (days)	Peak Flow (m^3s^{-1})	Total volume (MCM)
Maximum	47.0	1631.5	3208.6
75% percentile	18.0	1007.6	1043.7
Median	6.5	784.8	394.2
25% percentile	3.0	667.8	184.7
Minimum	1.0	504.7	47.6

The median event from the 52 analysed has duration 6.5 days, peak flow of 784.8 m^3s^{-1} and total volume of 394.2 MCM. These characteristics were assumed to represent the 'normal' flood at Garissa. For comparative purposes it is worth noting the characteristics of the mean flood. This has duration 11.2 days, peak flow of 841.4 m^3s^{-1} and total volume of 708.6 MCM. The characteristics of the mean flood are higher than those of the median flood because of the skewed nature of the distribution of flood characteristics. The mean flood is less representative of the normal flood than is the median flood because it has a longer duration, higher peak and greater total volume than more than half of the events analysed.

The median flood resulting from this analysis compares well with the normal or required flood at Garissa specified in previous studies. The normal flood given in Nippon Koei (1995a) has duration 7 days, peak flow 600 m^3s^{-1} and total volume 345.6 MCM for the period during which discharge is greater than 500 m^3s^{-1}.

4.5 Comparison of floods at Garissa and Grand Falls

Having estimated the median flood at Garissa the next stage of the analysis involved comparing the concurrent discharge records of Garissa and Grand Falls in order to establish the relationship between flooding at the two sites. Of the 52 events analysed in the estimation of the median flood at Garissa only 34 were suitable for inclusion in this comparison, the remainder having insufficient or too much infilled data at Grand Falls. Some of the long duration floods at Garissa were disaggregated where it was clear that they represented a sequence of flood events that could be analysed separately.

The flow records at the two sites were compared graphically for each of the 34 flood events. From this comparison it was evident that the relationship between flooding at Grand Falls and that at Garissa is not constant. There appear to be four distinct types of flood, each one characterised by differences in the relationship between discharge at the two sites. Each of the four categories is illustrated graphically in figure 4.5 and summarised below.

A Flood attenuates as it moves downstream. Peak flows and total volume significantly less at Garissa than at Grand Falls.

B Massive flooding at Grand Falls with much greater attenuation than in type A. Flood at Garissa appears insignificant in comparison.

C Little change in flood as it moves downstream. Flood at Garissa very similar in terms of peak and/or volume to that at Grand Falls.

D Flood increases as it moves downstream. Peak flows and total volume significantly more at Garissa than at Grand Falls.

Of the 34 flood events analysed 11 were identified as type A, 5 as type B, 11 as type C and 6 as type D. The distribution of each type of event over the period 1963 to 1993 is shown in figure 4.6. It is noticeable that type B floods appear to have been confined to the 1960s and early 1970s. The apparent lack of other events in the 1980s and 1990s is due to the patchy nature of the flow records for Grand Falls over this period.

On the basis of this evidence it appears that type B floods are no longer a feature of the current flood regime of the Tana. There is also some doubt over the validity of these events. In one example (December 1963) losses between Grand Falls and Garissa were estimated to be 80%. Given this uncertainty, and given that flows at Garissa were less than 500 m^3s^{-1} for many type B events, these type B events were excluded from any further analysis.

The remaining 30 floods events at Grand Falls were characterised in terms of their duration, peak flow and total volume. The lag time between flooding at Grand Falls and Garissa was also estimated. These details are listed in Appendix C.2.

The events with characteristics at Garissa which were relatively similar to those of the median flood were selected in order to establish whether they were linked to a consistent pattern of flooding upstream at Grand Falls. No consistency was evident with three of these events falling into category A and two each into C and D. The most similar event to the median flood in each of the three cases was examined in order to isolate the different patterns of flooding at Grand Falls which could give rise to a median type-flood at Garissa. Details of these three events are given in table 4.2 and are shown in figure 4.7.

Table 4.2 Characteristics of events relating to median-type floods at Garissa

	Grand Falls				Garissa (median type floods)			
Type & date	Peak (m^3s^{-1})	Dur^n (days)	Volume (MCM)	Lag (days)	Peak (m^3s^{-1})	Dur^n (days)	Volume (MCM)	Losses
A 26/4/79	1306.2	8	518.8	1	835.4	8	461.8	11.0%
C 9/12/82	679.1	8	358.1	2	770.9	8	374.7	-4.6%
D 28/11/82	671.9	6	243.8	2	840.0	6	322.5	-32.3%

There is clearly no single flood at Grand Falls which will give rise to the normal flood at Garissa. The flood hydrograph may either attenuate, as in case A, be supplemented by additional runoff, as in case D, or undergo little change, as in case C. In order to improve the definition of these three relationships all events in each category were analysed and the median of each type estimated. The results of this analysis are presented in table 4.3.

Table 4.3 Median floods in each of types A, C and D

	Grand Falls				Garissa (median type floods)			
Type	Peak (m^3s^{-1})	Dur^n (days)	Volume (MCM)	Lag (days)	Peak (m^3s^{-1})	Dur^n (days)	Volume (MCM)	Losses
A	1460.1	10	717.3	2	1002.7	10	615.8	19.6%
C	1039.5	8	448.4	1	864.7	8	473.0	3.1%
D	671.9	8	358.1	1	840.0	8	387.3	-8.3%

The median events at Garissa for each of types A, C and D are larger than the overall median (or normal) event specified in section 4.3. This is due to the fact that many of the original 52 events excluded due to lack of data at Grand Falls were small magnitude, short duration events.

The information in table 4.3 allows the estimation of the flood at Grand Falls relating to the normal flood at Garissa for each of categories A, C and D. This is assumed to be a better estimate than relying on the relationship presented in table 4.2 which is based on a single flood event.

The normal flood at Garissa, having peak flow 784.8 m^3s^{-1}, duration 6.5 days and total volume 394.2 MCM, is estimated to correspond with the floods at Grand Falls specified in table 4.4 and presented graphically in figure 4.8. Peak flows are estimated from the ratio of peaks at the two sites and volumes from the losses between the two sites, both of which are specified in table 4.3. On the evidence of the events examined in this analysis the duration of flooding at both sites appears to be the same.

Table 4.4 Flood characteristics at Grand Falls corresponding to the normal flood at Garissa

Type	Peak (m^3s^{-1})	Duration (days)	Volume (MCM)
A	1145.8	6.5	490.3
C	943.4	6.5	406.8
D	627.7	6.5	364.0

The values listed in table 4.4 can be viewed as estimates of the release required from Grand Falls to ensure the normal flood at Garissa. Although these values are only estimates they are important in that they indicate that the release required at Grand Falls is not the only variable determining the flood response at Garissa but that other factors are involved. These other factors can apparently make a considerable difference between the release required at Grand Falls, with that estimated for type D flood conditions only 75% of the total volume of the release in a type A flood.

In flood types C and D it is evident that flow downstream of Grand Falls is supplemented by additional runoff from the Lower Tana catchment. The differences between runoff generation in each of the three flood types were investigated further through an analysis of rainfall. This is described in chapter 5.

4.6 Pattern of flooding downstream of Garissa

The analysis of flooding downstream of Garissa was based on fewer events due to the scarcity of data for gauging stations on the lower Tana. Events were examined where reasonably complete daily discharge series were available for the gauging stations at Nanigi and Garsen. The short daily discharge series for Saka does not contain concurrent data with any of the flood events analysed at the other stations and was not included in this analysis.

Despite the shortage of data the analysis was able to reveal the general pattern of flooding at Nanigi and Garsen. Flood hydrographs show significant attenuation as the flood moves downstream from Garissa (see figure 4.9). The recorded peak flows and total volumes are lower at Nanigi, 79 km downstream of Garissa, and still less at Garsen, a further 300 km downstream. The lag time between the onset of flooding at Garissa and Nanigi is less than one day but appears to be at least four or five days from Nanigi to Garsen.

Flood discharges at Nanigi typically peak at 400-550 m^3s^{-1} and remain at this level for an extended period rather than receding quickly as do flood peaks upstream at Grand Falls and Garissa. Losses between

Garissa and Nanigi during flood events are in the range 20-50% with a mean of 37%. Flood hydrographs at Garsen are further attenuated with an extremely gradual rise to peak flows which level out at around 200-300 m^3s^{-1}. Losses between Garissa and Garsen are in the range 40-70% with a mean of 60%.

Given these figures the normal or median flood at Garissa may be expected to give rise to a flood downstream at Nanigi with peak of around 400 m^3s^{-1} and total volume of 250 MCM. The flood at Garsen would have a peak of around 200 m^3s^{-1} and an estimated total volume of 150 MCM. It was not possible to examine the actual response at Nanigi and Garsen following a median-type event at Garissa due to the lack of concurrent data for any such event. These estimates are therefore extremely speculative and should be treated with caution.

The pattern of flooding at Nanigi and Garissa does not appear to be affected by the relationship between flooding at Garissa and Grand Falls. The attenuation of floods downstream of Garissa appears to occur in a similar fashion irrespective of whether a flood is classed as type A, C or D upstream.

5 Rainfall Analysis

5.1 Objective

Daily rainfall data from selected stations were analysed in order to assess the extent to which variations in the relationship between floods at Grand Falls and Garissa relate to runoff generated by rainfall in the Tana catchment below Grand Falls. The rainfall preceding flood events of type A, C and D was examined in an attempt to characterise the rainfall corresponding with each type.

5.2 Selection of rainfall data

As described in chapter 2 rainfall data was provided for between 200 and 300 stations in and around the Tana catchment. The vast majority of these lie in the headwaters of the catchment upstream of Grand Falls or in areas draining through lagas to the Tana downstream of Garissa. Only a small number of stations lie in the area of interest draining to the river between Grand Falls and Garissa. Daily rainfall data was extracted for 14 stations lying in this area of the Tana catchment. The stations are listed in table 5.1 whilst their locations are shown in figure 5.1.

Table 5.1 Details of rainfall data used in the analysis

No	ID	Name	Area	Alt (m)	Long	Lat	Period
10	8937041	Lare, Meru	NH	2796	37.93 E	0.33 N	1957-90
12	8937059	Maua Nyambene Hills	NH	1738	37.93 E	0.23 N	1959-90
13	8937060	Meru Mucii Mukuru	NH	2050	37.85 E	0.18 N	1960-90
24	8937086	Atheru Gaiti Coffee	NH	1410	37.97 E	0.20 N	1974-90
25	8937089	Kathanga Primary School	NH	1935	37.98 E	0.43 N	1974-90
26	8937091	Akachiu Chief's Camp	NH	1542	37.95 E	0.18 N	1974-90
27	8937092	Atheru Ruujine Coffee	NH	1410	37.97 S	0.37 N	1974-90
30	8938001	Kinna Scheme Isiolo	NF	754	38.20 E	0.32 N	1957-90
31	8938005	Rapsu Scheme	NF	722	38.22 E	0.28 N	1973-87
223	9038020	Usueni Dispensary, Kitui	ds GF	443	38.20 E	0.15 S	1974-87
225	9038024	Nzanzeni Primary School	ds GF	508	38.20 E	0.22 S	1974-87
227	9038026	Kaivirya Primary School	ds GF	607	38.15 E	0.32 S	1974-87
233	9039000	Garissa Met Station	Gar	138	39.63 E	0.48 S	1957-90
234	9039001	Garissa Balambala Police	us Gar	205	39.07 E	0.03 S	1982-90

Key to areas: NH - Nyambene Hills, NF - Nyambene foothills, ds GF - downstream of Grand Falls, Gar - Garissa, us Gar - upstream of Garissa

Daily rainfall was extracted for each of the flood events analysed previously. This included rainfall during and for a ten day period before each event. During most of the events the rainfall records of one or more stations was missing. For ease of comparison the rainfall stations were put into one of five groups according to their location; Nyambene Hills, Nyambene foothills, in the Tana valley downstream of Grand Falls, Garissa, and on the Tana upstream of Garissa. There was only a single station in each of the latter two groups. In the other three groups the mean daily rainfall of the individual sites was found and assumed to be representative of those areas.

The daily rainfall of 28 events was examined. Only two of these events had rainfall records for all of the five areas. This was largely due to the unavailability of records for station 9039001, the site upstream of Garissa. This site was largely excluded from the analysis described below. Half of the events had complete records for the other four sites whilst the remainder had data only for the Nyambene Hills and Garissa.

5.3 Analysis of rainfall events

The rainfall events were characterised in terms of their duration, total rainfall, mean daily rainfall and maximum daily rainfall. Events were grouped according to the flood types they correspond with. A list of the characteristics of the events analysed is given in Appendix D.

The median characteristics of rainfall events in each area for each type of flood were estimated. The median was estimated firstly only from those events for which data was available for each of the four areas ('common' events). Unfortunately this halved the number of events under analysis. In particular the number of type C and D events was dramatically reduced so the decision was made to examine the rainfall of these two groups together. In order to examine whether there were differences between the rainfall of type C and D flood events it was therefore necessary also to estimate the median characteristics from all the available data for each site, although no longer comparing like with like.

The characterisation of rainfall events in this way resulted in a large array of summary statistics. The median characteristics for each area of the catchment during each type of flood event are given in Appendix D.2. A descriptive summary is provided below.

Type A floods are characterised by heavy rainfall on the Nyambene Hills, with median daily rainfall of around 35 mm and total rainfall of around 200 mm. Rainfall on the foothills and in the valley downstream of Grand Falls is low, with daily rainfall of 4-8 mm and totals during the event of around 15-20% of that falling on the Nyambene Hills.

Type C/D flood events have a lower median rainfall on the Nyambene Hills by 50 mm compared with type A. Daily rainfall intensities are also less with a median of under 30 mm/day. Rainfall in the river valley below Grand Falls is higher being around 50% of that on the Hills and with daily intensities of 15 mm/day. Rainfall on the Nyambene foothills is also slightly higher than during type A events, with total event rainfall of 20-30% of that falling on the Hills themselves.

There are also differences between the rainfall of events of types C and D (although it should be noted these results are not based entirely on 'common' rainfall data). During type D events rainfall is heavier at all sites than during type A events. Median total rainfall downstream of Grand Falls and on the Nyambene foothills is 60% and 35% respectively of that falling on the Nyambene Hills. Daily rainfall is 12-25mm at these sites during these events but is relatively low at 32mm on the Hills themselves. Type C events show less extreme patterns of rainfall than during type D events, but rainfall is still heavier downstream of Grand Falls and lower on the Nyambene Hills than during a type A event.

These differences between the median rainfall characteristics of rainfall events associated with flood types A, C and D are also borne out by an examination of the range of rainfall (total rainfall and mean daily intensities) in events of each type. Figure 5.2a shows the range (maximum to minimum) and median of total rainfall in each area during common events of type A and types C/D. Figure 5.2b shows the pattern of mean daily rainfall in the same fashion. The ranges of both total and mean daily rainfall are higher during type C/D events than type A events in all areas other than the Nyambene Hills. In contrast, the range of mean daily rainfall in the Nyambene Hills is significantly higher during type A events whilst the total rainfall in this area covers a wider range in type A events than in type C/D events.

This general pattern of rainfall variations during the different types of event is shown in figures 5.3a-c which present the rainfall and flow during examples of each of a type A, C and D event. In the event during April and May 1977 (type A) over 200 mm of rain fell in the Nyambene Hills. The rainfall on the foothills and downstream of Grand Falls was only 12% and 19% of this total respectively. During the type C event shown in November 1977 rainfall on the Nyambene Hills was over 300mm. The proportion of this rainfall falling elsewhere in the catchment was 15% on the foothills, 28% downstream of Grand Falls and 10% at Garissa. Rainfall in these areas relative to that on the Hills was even higher during the event of November 1984 (type D). During this event 350 mm of rainfall fell on the Nyambene Hills with 15% of this total falling on the foothills, 40% downstream of Grand Falls and at 26% Garissa.

6 Discussion

6.1 Explanation of flood types

The analysis of flood events described in chapter 4 showed that the relationship between floods at Grand Falls and those at Garissa is not constant but varies in one of four ways. During type A events the flood attenuates as it moves downstream having a lower peak and total volume at Garissa than at Grand Falls. These floods might be thought of as 'classical' events. In contrast, the flood hydrograph appears to undergo little attenuation as it moves downstream during type C floods. The pattern of flooding during type D events is the reverse of that during type A events with higher flood peaks and volumes at Garissa than at Grand Falls. Type B events, during which massive attenuation occurs between Grand Falls and Garissa, were excluded from detailed analysis as they do not appear to be a current feature of the flood regime of the river. The validity of these events is somewhat uncertain.

The rainfall analysis described in chapter 5 identified variations in the pattern of rainfall corresponding with each of event types A, C and D. These differences in rainfall are important in determining the additional runoff to the Tana between Grand Falls and Garissa and so directly influence not only the change in the characteristics of a flood as it moves downstream between the two sites, but also in consequence the volume of flood release which would be required from Grand Falls dam. Figure 6.1 illustrates these differences.

During a type A event heavy rainfall falls on the Nyambene Hills, the highest land in the Tana catchment downstream of Grand Falls. Rainfall on the lower slopes of these Hills and in the Tana valley downstream of Grand Falls is relatively insignificant. Runoff from the Nyambene Hills is carried to the Tana via several tributaries, most of which appear to be ephemeral lagas, such as the Ura and the Rojewero. As flow down the tributaries is not supported by further rainfall at lower elevations transmission losses are relatively large and the inflow to the Tana is greatly diminished. With relatively low inflow from its tributaries the flood flow in the Tana attenuates as it travels downstream to Garissa.

The pattern of rainfall during a type C or D event differs from that during a type A event. Rainfall is distributed over a wider area of the catchment with significant amounts falling on the foothills of the Nyambene Hills and in the Tana valley. The wider distribution of rainfall means that, although still heaviest on the Nyambene Hills themselves, rainfall intensities here are lower than during the more concentrated type A rainfall. With a greater area of the catchment contributing runoff losses from tributary inflows are proportionately less than in type A events (as mean travel time from the runoff source to inflow into the main river is reduced). The runoff from these areas of the catchment therefore represents an important component of total flow in the Tana and offsets the transmission losses and evapotranspiration occurring between Grand Falls and Garissa. The difference between type C and D events appears to be one of scale. During type C events losses from the Tana are balanced by tributary inflows whilst during type D events the inflows are significantly greater than the losses. During some type D flood events it is also likely that local heavy rainfall at Garissa and in the river stretch upstream can further supplement flow in the Tana with the result that fairly minor events at Grand Falls become much more significant at Garissa.

According to this explanation the critical factor influencing the characteristics of flooding on the lower Tana is the pattern of rainfall in the top end of the catchment downstream of Grand Falls. Inflow from lagas further downstream towards Garissa is assumed to play a less significant role. This assertion is supported by two pieces of evidence. The first is the map of mean annual rainfall in the catchment (see figure 6.2). This clearly shows the Nyambene Hills and the surrounding areas to be the most important areas of rainfall, and hence runoff generation, in the lower Tana catchment. Mean annual rainfall is at a maximum of over 2400 mm on the Nyambene Hills and decreases through a steep rainfall gradient to around 600 mm on the lower foothills and in the Tana valley downstream of Grand Falls. Mean annual rainfall further downstream towards Garissa falls below 300 mm.

The second piece of evidence relates to the pattern of flooding downstream of Garissa. The analysis of flooding at Nanigi and Garsen, described in section 4.6, found a consistent attenuation of floods in the lower reaches of the Tana. This pattern of attenuation occurs irrespective of whether the relationship between flooding at Grand Falls and Garissa is of type A, C or D. In general it appears that inflow from lagas in these reaches of the river is not significant in relation to variations in runoff generation in the top end of the lower Tana catchment.

6.2 Implications for flood release

The normal flood at Garissa estimated from the analysis of flood events with discharge greater than 500 m^3s^{-1} (section 4.4) has a total volume of 394 MCM. The corresponding flood volume at Grand Falls was estimated to be 490 MCM during a type A event, 406 MCM during a type C event and 364 MCM during a type D event. These values may be assumed to represent the release, and hence the reservoir storage, required at Grand Falls to support the normal flood at Garissa.

The required storage at Grand Falls was estimated by a previous study (Nippon Koei, 1995a) as 423 MCM. The results presented here are at variance with this figure and suggest that either more or less storage is required depending on the volume of additional runoff to the Tana downstream of Grand Falls. The earlier study did not identify the different patterns of rainfall and inflow from Grand Falls which we now believe to be very important in flood production at Garissa and the Lower Tana.

In the case of a type A flood, with relatively low tributary inflow, the estimated release required from Grand Falls is 16% greater than that previously estimated. A release of this size should be able to guarantee normal flooding at Garissa regardless of inflows below Grand Falls. With relatively more runoff from tributaries of the lower Tana the release from Grand Falls could be reduced with the additional runoff supplementing flow in the main river to produce the normal flood at Garissa. In these circumstances, an estimated release of between 74-83% of that required in the type A situation should be sufficient to support the normal flood depending on the extent and intensity of rainfall.

These findings suggest two alternative strategies for the release of flood flows from Grand Falls. The first, and more straightforward, strategy is to release the flood flow which will guarantee the normal flood at Garissa regardless of other inflows (type A release). A possible concern with this strategy is that it could result in more extreme, and potentially hazardous, flooding than required at Garissa if coinciding with large inflows from the catchment downstream of Grand Falls.

The alternative strategy is to deliberately release floods flows to coincide with tributary inflows. This strategy would require a smaller release from Grand Falls, but is reliant on an ability to forecast runoff generation from the top end of the lower Tana catchment, particularly from the Nyambene Hills. Although not analysed here in detail, the lag time between rainfall in these areas and flow at Garissa appears to be around 3-4 days. The lag time between flows at Grand Falls and Garissa was estimated as 1-2 days. This difference in lag times suggests that a strategy of flood flow release which takes into account rainfall on the Nyambene Hills and lower slopes and in the area downstream of Grand Falls over the previous 1-2 days would indeed be feasible. This strategy would require a system of instrumentation to monitor rainfall in the critical areas of the catchment and a set of release control rules governing the volume of flows released in relation to threshold rainfall values. The release of flows in accordance with these control rules could ensure that extreme flooding would not occur at Garissa because inflows downstream of Grand Falls were always taken into account. This approach would also have the advantage of minimising the volumes which would have to be released from Grand Falls in order to ensure maintenance of downstream flooding.

One further comment relates to the frequency of the normal flood at Garissa. Floods of greater than 500 m^3s^{-1} currently occur in at least one of the two wet seasons in 8 out of every 10 years (see section 4.2). However, the chance that a flood of greater than 500 m^3s^{-1} will occur in only one wet season of any year is estimated to be 0.5. The release of flood flows, by whatever strategy, to allow out of bank flooding at Garissa in every wet season would therefore represent a marked improvement on the current pattern of seasonal flooding.

7 Conclusions

The pattern of flooding on the lower Tana river has been examined through an analysis of discharge and rainfall records during flood events. Flood events with at least one day of flow greater than 500 m^3s^{-1} at Garissa were analysed, with this figure taken to be the best estimate above which out of bank flow occurs. The 'normal' flood was found to be best represented by the event with median characteristics in terms of its duration, peak flow and total volume. The median flood has an estimated duration of 6.5 days, a peak flow of 785 m^3s^{-1} and a total volume of 394 MCM. It is assumed that a flood of this magnitude will inundate the floodplain both upstream and downstream of Garissa for a period sufficient to maintain the environment and level of economic activity currently supported by the current river regime.

Flooding on the lower Tana occurs on a bi-annual basis, usually during April/May and November/ December. However, out of bank flooding does not occur in all wet seasons and some years, particularly during the 1970s, have suffered from a lack of such flooding in both seasons. The release of flood discharges to guarantee out of bank flooding at Garissa and the inundation of the floodplain both upstream and downstream would represent a significant improvement on the current situation. Regulation of flood discharges could have the added advantage of reducing the magnitude of the more extreme, and potentially hazardous, flood events.

Further flood event analysis revealed that the relationship between floods at Grand Falls and those at Garissa is not constant but varies in one of four ways. During type A events the flood attenuates as it moves downstream with a reduction in both peak flow and total volume. In contrast, the flood hydrograph appears to undergo little attenuation as it moves downstream during type C floods whilst peak flow and total volume increase between Grand Falls and Garissa during a type D event. Type B events, during which massive attenuation occurs between Grand Falls and Garissa, were excluded from detailed analysis as they do not appear to be a current feature of the flood regime of the river

The analysis of rainfall identified variations in the pattern of rainfall corresponding with each of event types A, C and D. These differences in rainfall appear to play an important role in determining the additional runoff to the Tana between Grand Falls and Garissa and hence the relationship between floods at the two sites. Rainfall during a type A event is concentrated on the Nyambene Hills and results in relatively large losses as runoff is carried to the main river via various tributaries. The impact of these tributary inflows on the flood flows of the Tana are relatively insignificant and the flood attenuates as it travels downstream. During type C and D events rainfall is more widespread over the top end of the lower Tana catchment. The mean travel time of runoff between source areas and the main river is less than during a type A event with a consequent reduction in losses. Inflows from tributaries between Grand Falls and Garissa during these events can help to sustain a flood or even boost it to as it moves downstream. As floods move downstream beyond Garissa they appear to attenuate in a consistent fashion with flood peaks and total volumes falling significantly as they reach first Nanigi and then Garsen. There appears to be no real difference in flood behaviour downstream of Garissa resulting from floods of type A, C or D. This confirms that runoff generation at the top end of the lower Tana catchment is the critical influence on the characteristics of floods as they move downstream.

The estimated release, and hence the reservoir storage, required at Grand Falls to support the normal flood at Garissa varies according to the different types of flood. In the case of a type A flood, with relatively low tributary inflow, the estimated release required from Grand Falls is 490 MCM, 16% greater than that estimated in previous studies. A release of this size should be able to guarantee normal flooding at Garissa regardless of inflows below Grand Falls, although there would be a risk of generating large downstream floods in certain circumstances with this type of release pattern. With relatively more runoff from the tributaries of the lower Tana (type C and D floods), the release from Grand Falls could be reduced by 17-26% depending on the extent and intensity of rainfall.

These findings suggest two alternative strategies for the release of flood flows from Grand Falls.

- The first, and more straightforward, strategy is to release the flood flow which will guarantee the normal flood at Garissa regardless of other inflows (full type A release).
- The alternative strategy is to deliberately release floods flows to coincide with tributary inflows. This strategy would require a smaller release, and hence have less impact upon storage at Grand Falls, but is reliant on an ability to make short-term forecasts of runoff generation from the top end of the lower Tana catchment. Such an approach would require a system of instrumentation to monitor rainfall in the critical areas of the catchment combined with a set of release control rules governing the volume of flows released in relation to threshold rainfall values. We would recommend adoption of this second approach, as it makes better used of the stored water, and as it should prevent excessive downstream flooding which might occur from unexpected heavy rainfall and runoff over the lower catchment coinciding with a flood release.

8 Recommendations for further work

1 More detailed quantification of inflows from tributaries to allow:

Strategy 1 - Assessment of the range of floods resulting from fixed releases as inflows from tributaries downstream of Grand Falls vary, both during minimum normal flood periods, and during major floods (of say greater than once in 10 or 20 years).

Strategy 2 - Identification of rainfall thresholds necessary for effective flood release.

2 Investigation into the use of remote sensing for rainfall/runoff forecasting.

3 Design of a suitable network of instrumentation and telemetry to guide effective flood releases.

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Nippon Koei Co. Ltd. 1995a. Feasibility Study on Mutonga/Grand Falls Hydropower Project. Progress Report (1) Volume 1: Main report. Report to Japan International Cooperation Agency and Tana and Athi Rivers Development Authority. February 1995.

Nippon Koei Co. Ltd. 1995b. Feasibility Study on Mutonga/Grand Falls Hydropower Project. Progress Report (1) Volume 1: Main report. Report to Japan International Cooperation Agency and Tana and Athi Rivers Development Authority. February 1995.

Location of gauging stations on the Lower Tana

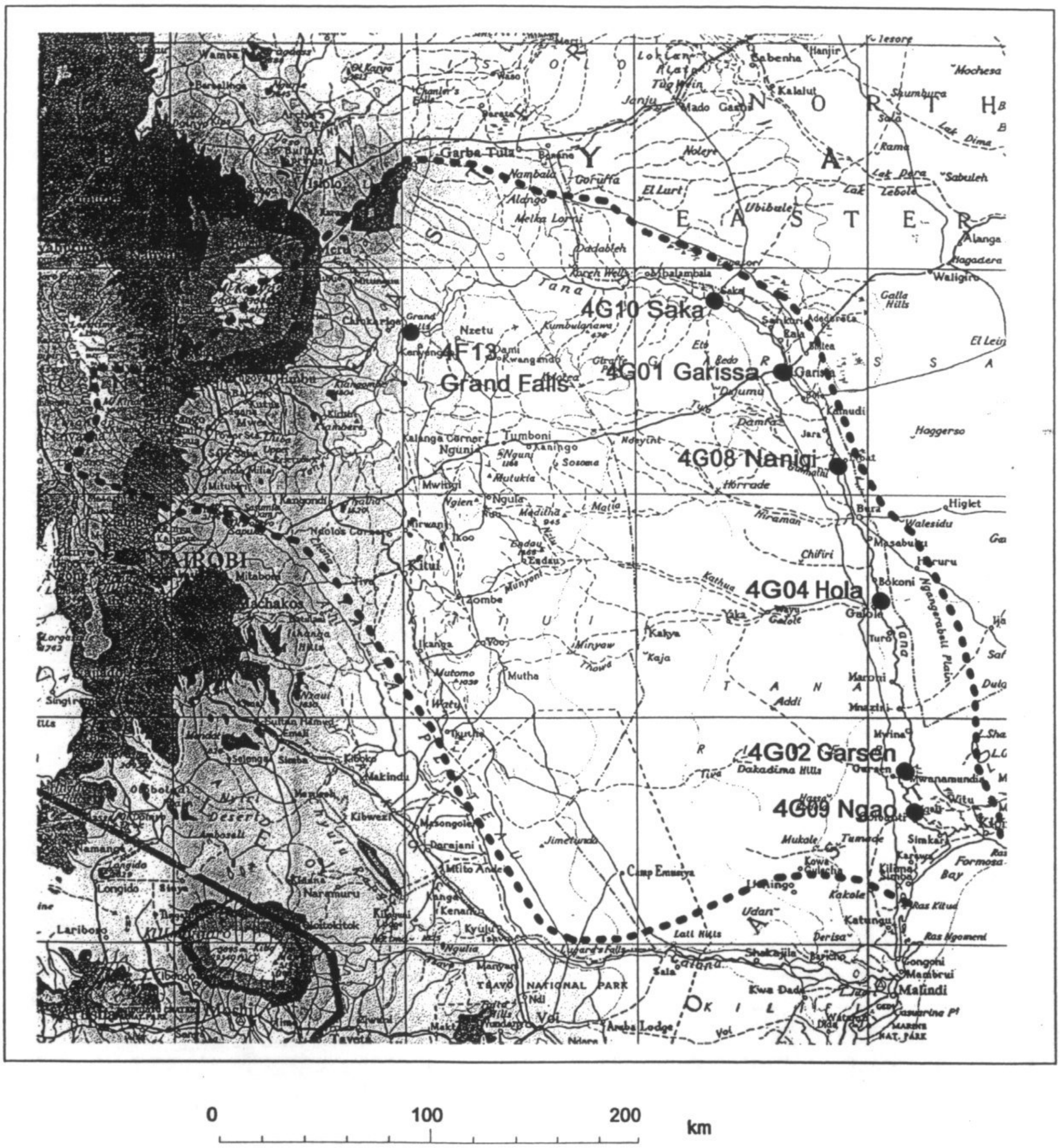
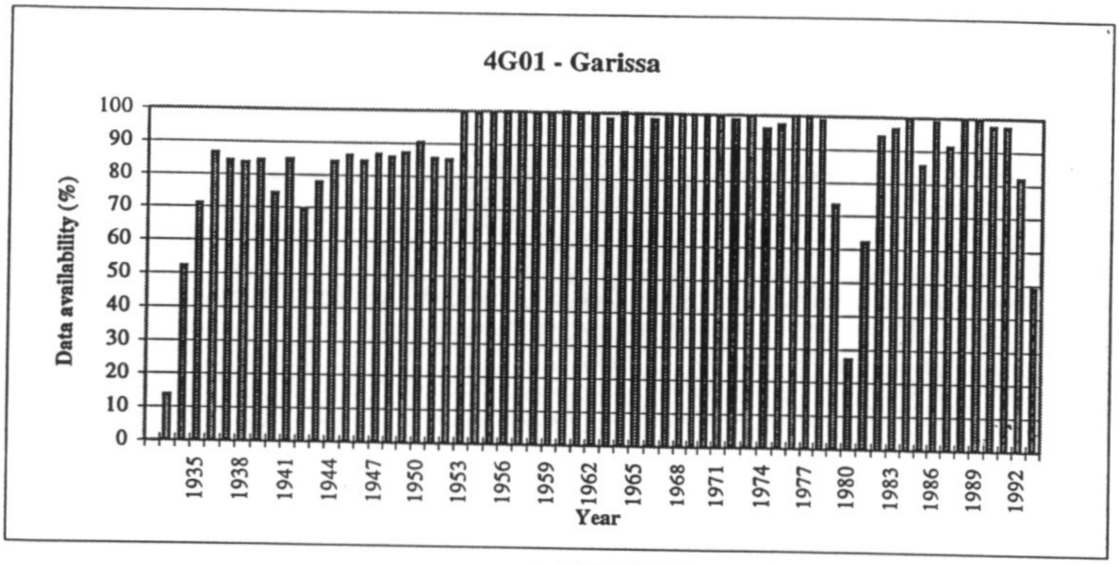
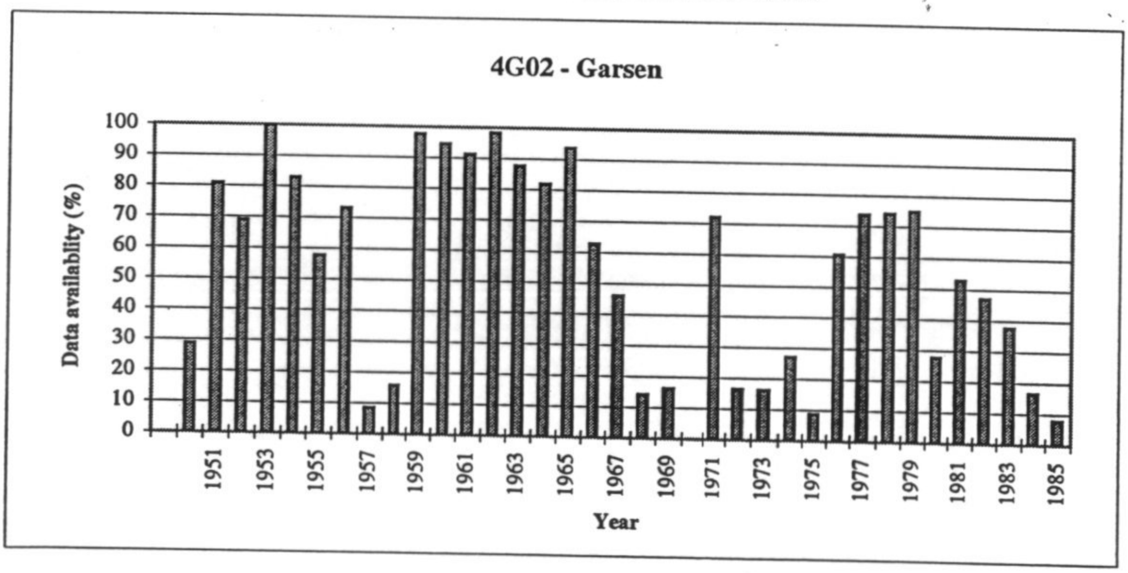


Figure 2.1

Figure 2

Availability of daily mean flow data for each gauging station





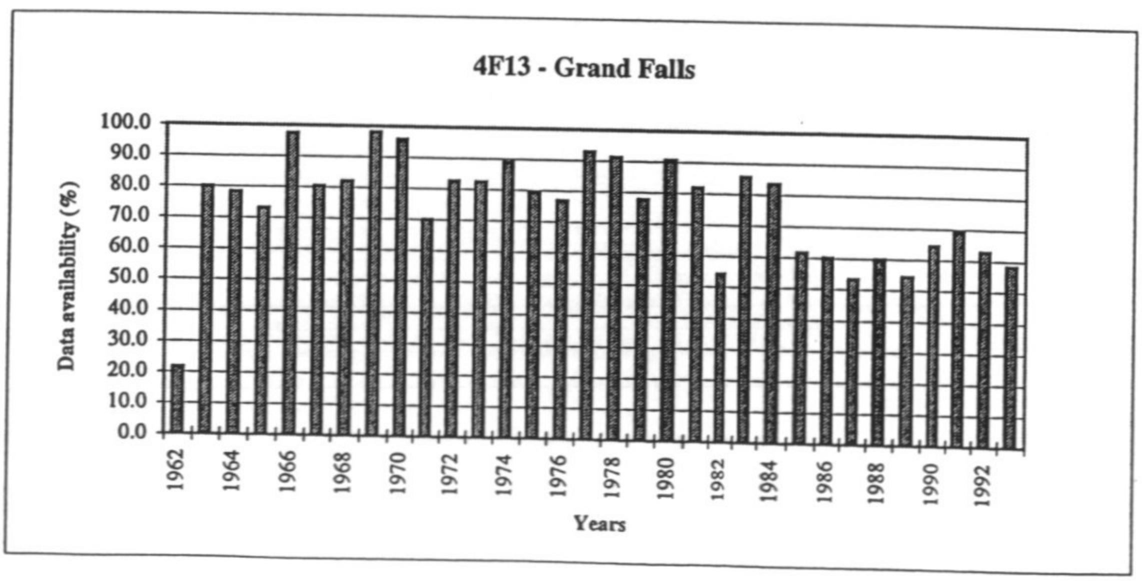
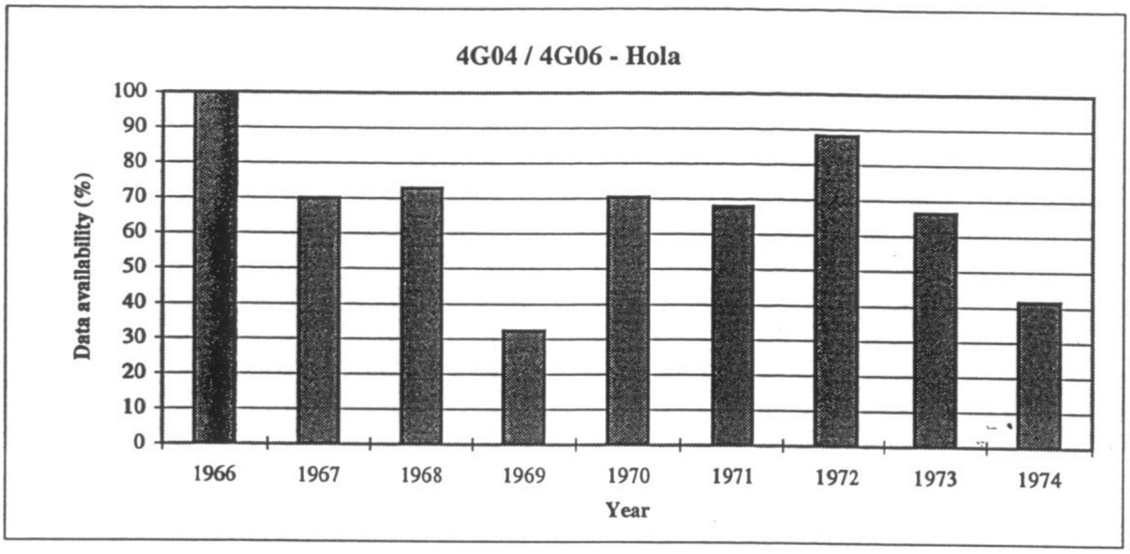
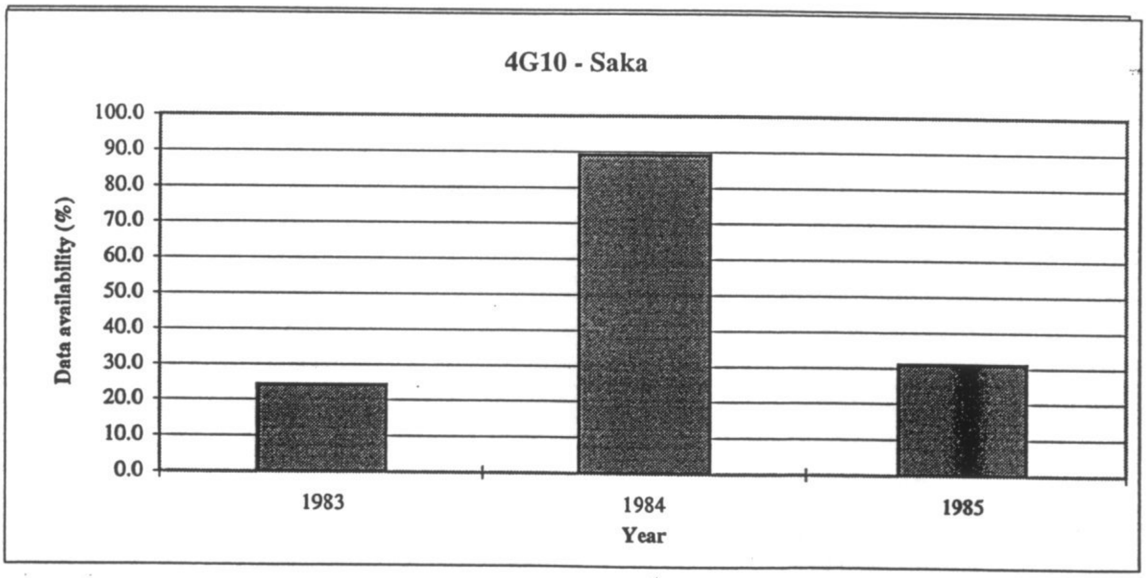
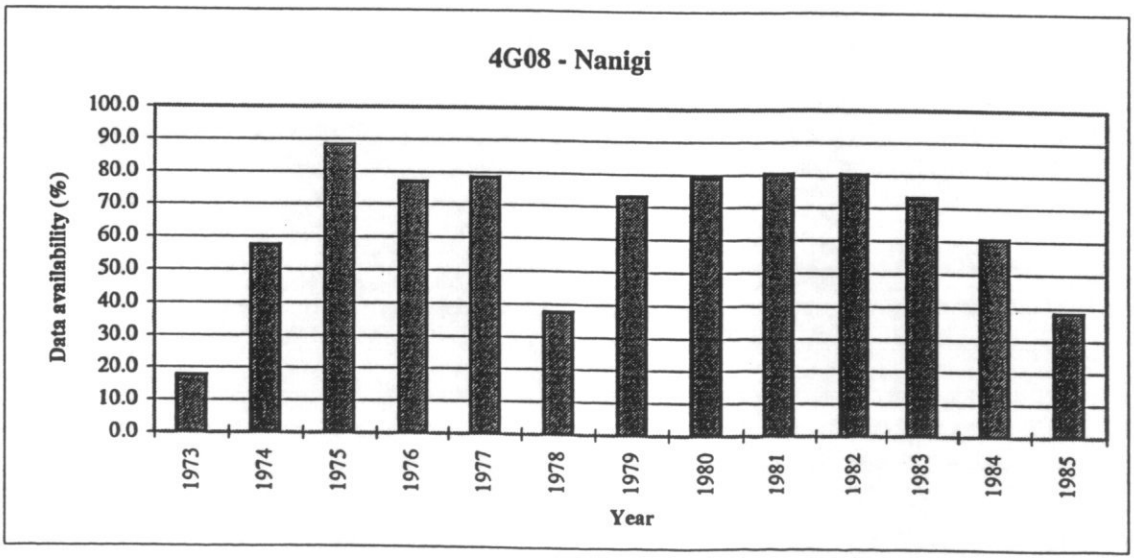


Figure 2.2 (continued)

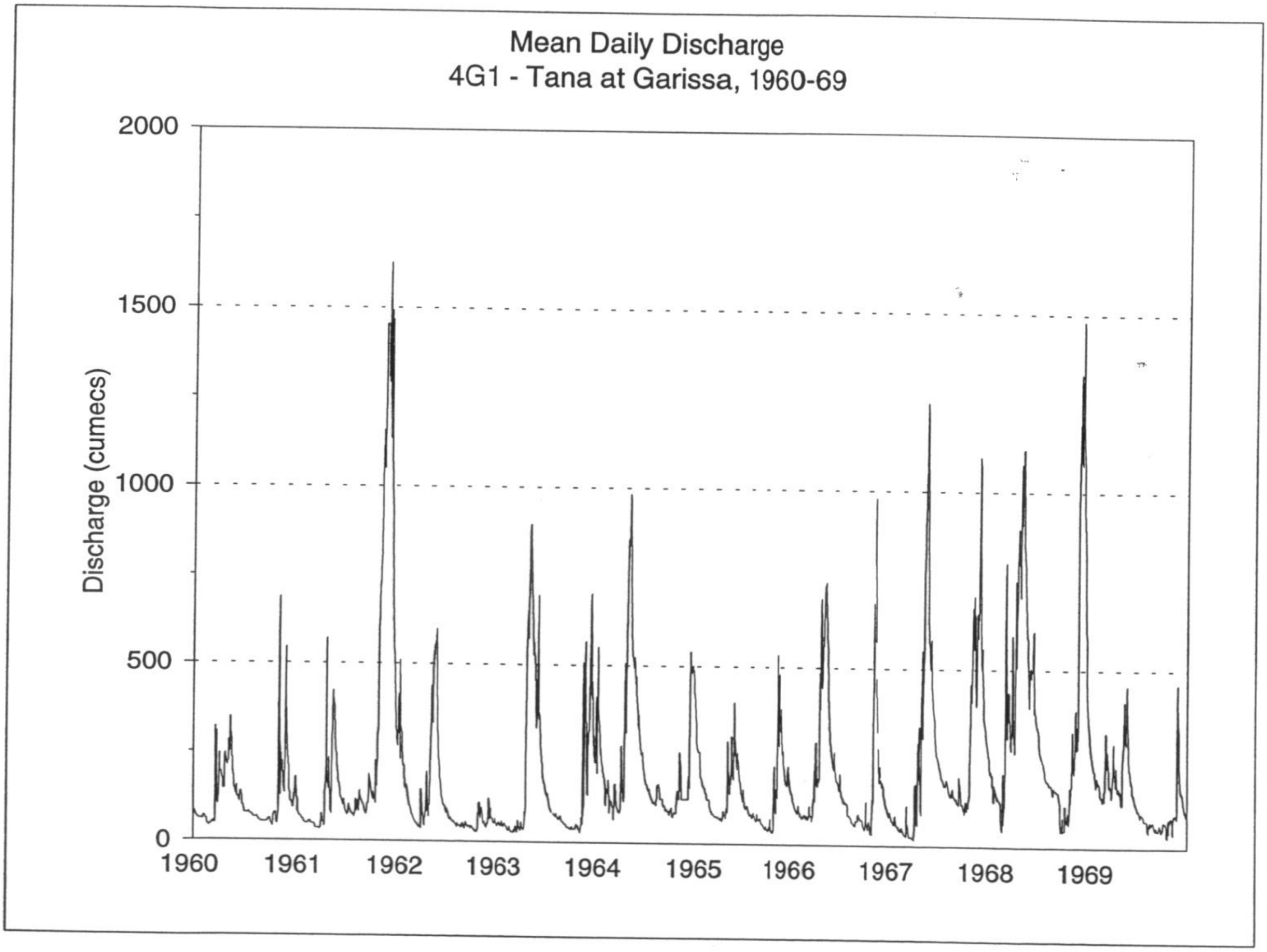
Availability of daily mean flow data for each gauging station





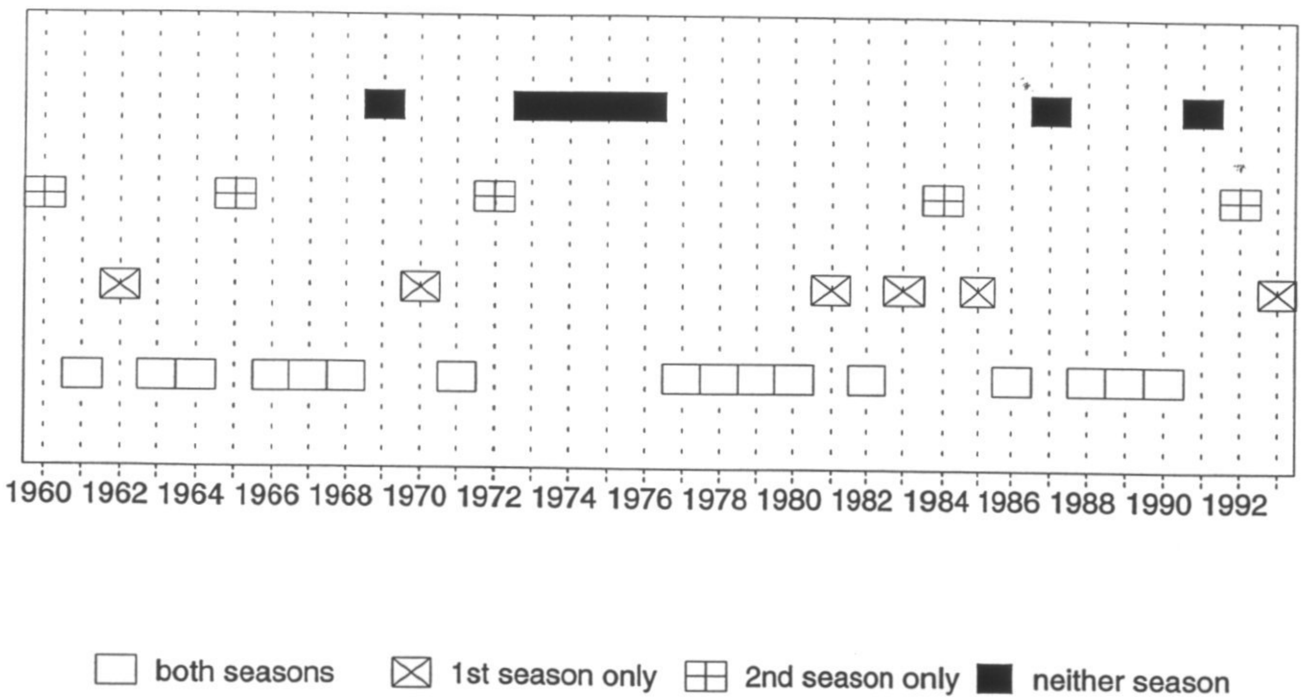


~~4-2~~ 4-1

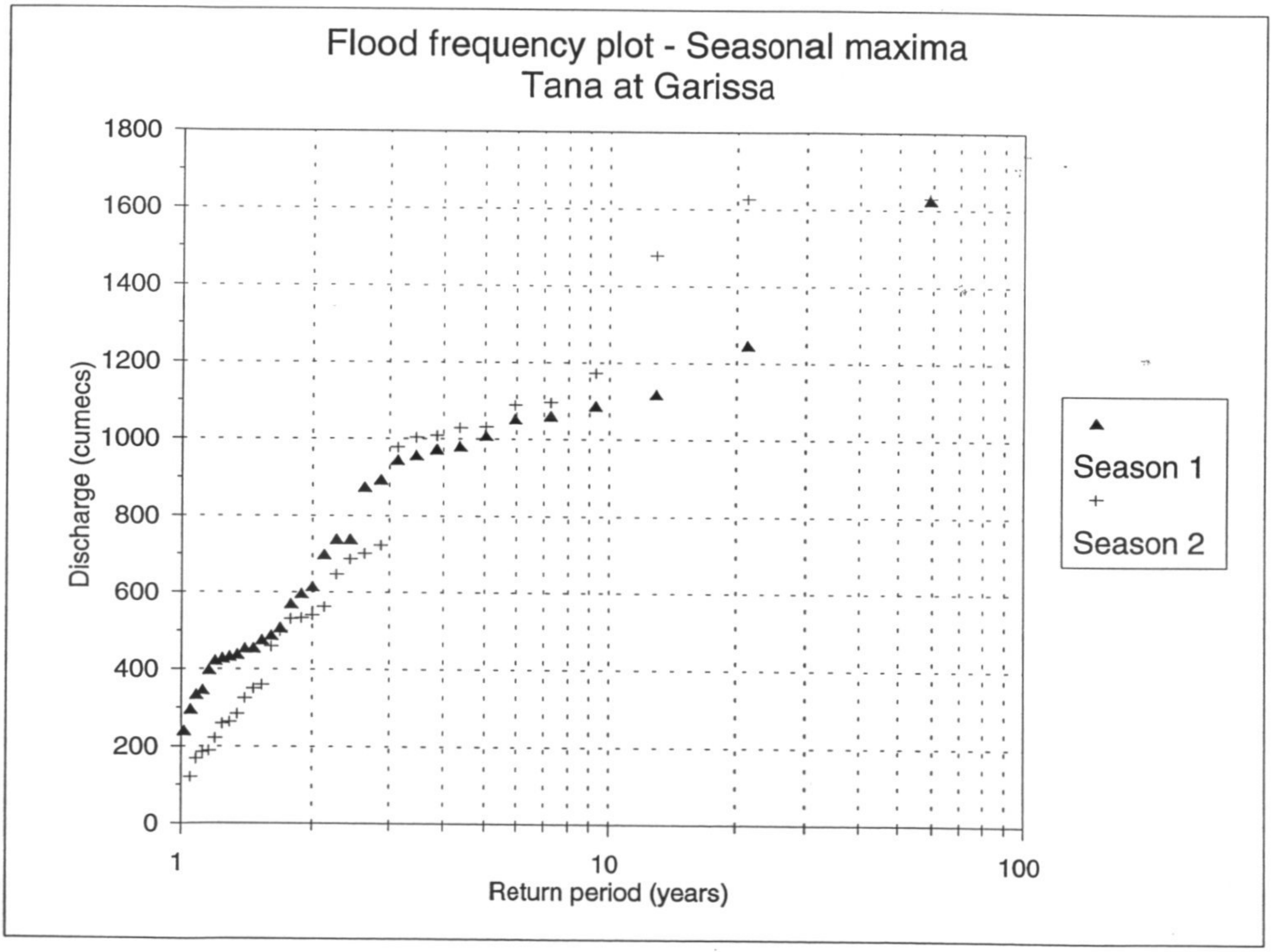


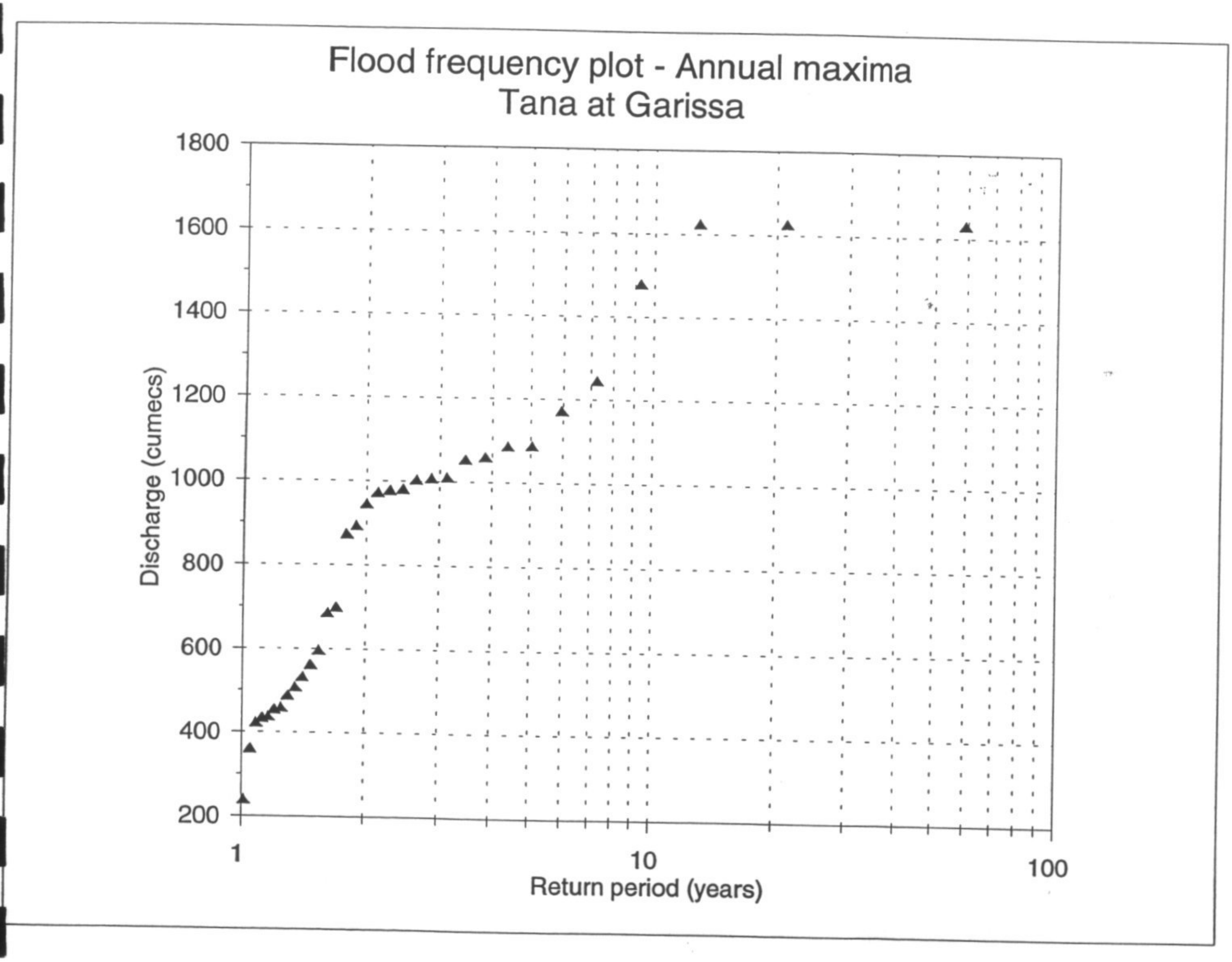
Mean Daily Discharge
4G1 - Tana at Garissa, 1960-69
Discharge (cumecs)
2000
1500
1000
500
0
1960
1961
1962
1963
1964
1965
1966
1967
1968
1969

3 4.2



Pattern of Floods > 500 cumecs
Garissa 1960-93


Flood frequency plot - Seasonal maxima
Tana at Garissa
Discharge (cumecs)
Return period (years)
0
200
400
600
800
1000
1200
1400
1600
1800
1
10
100
Season 1
Season 2



Flood frequency plot - Annual maxima
Tana at Garissa
Discharge (cumecs)
1800
1600
1400
1200
1000
800
600
400
200
1
10
100
Return period (years)

Types of flood identified from flood event analysis

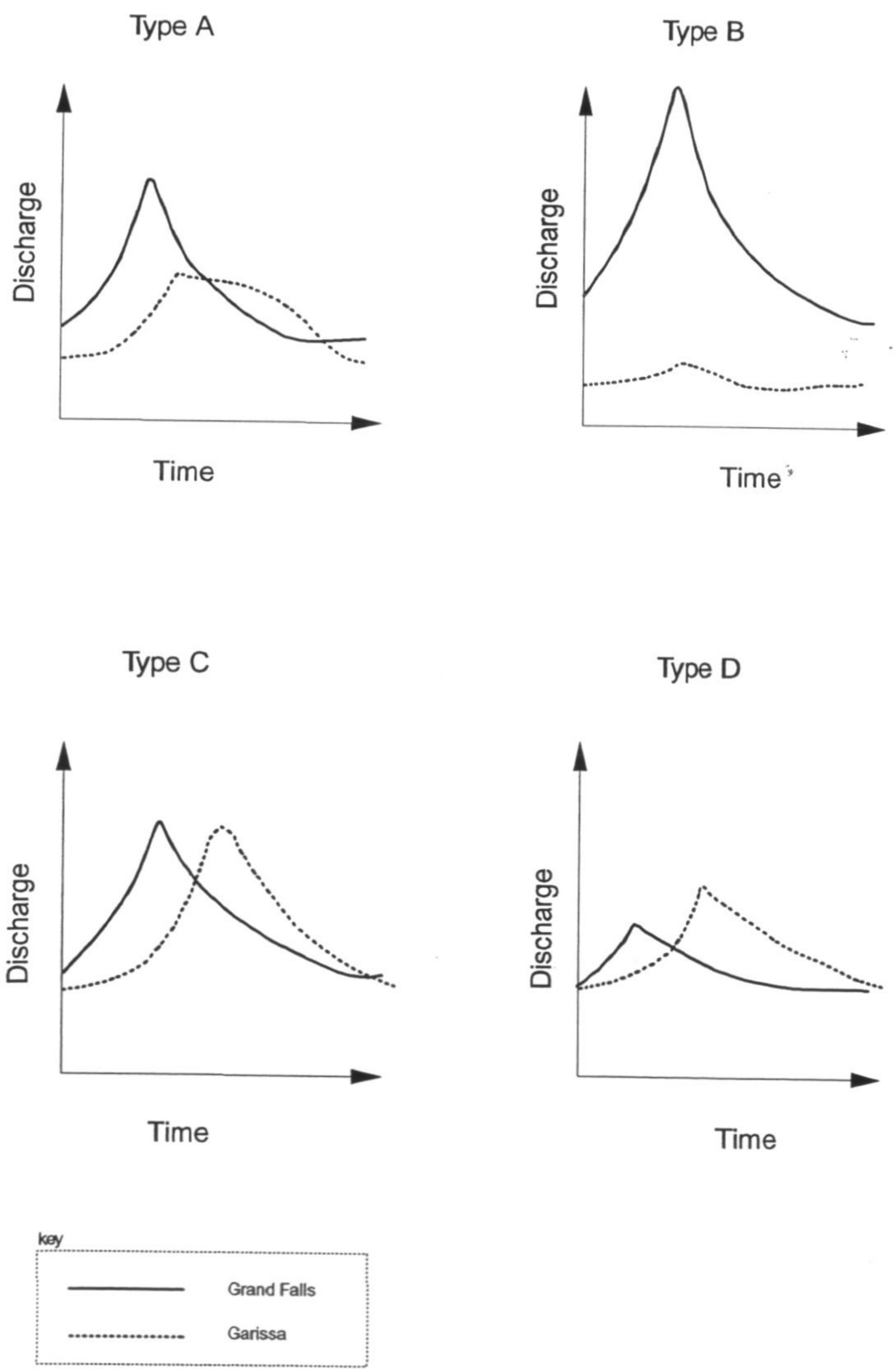
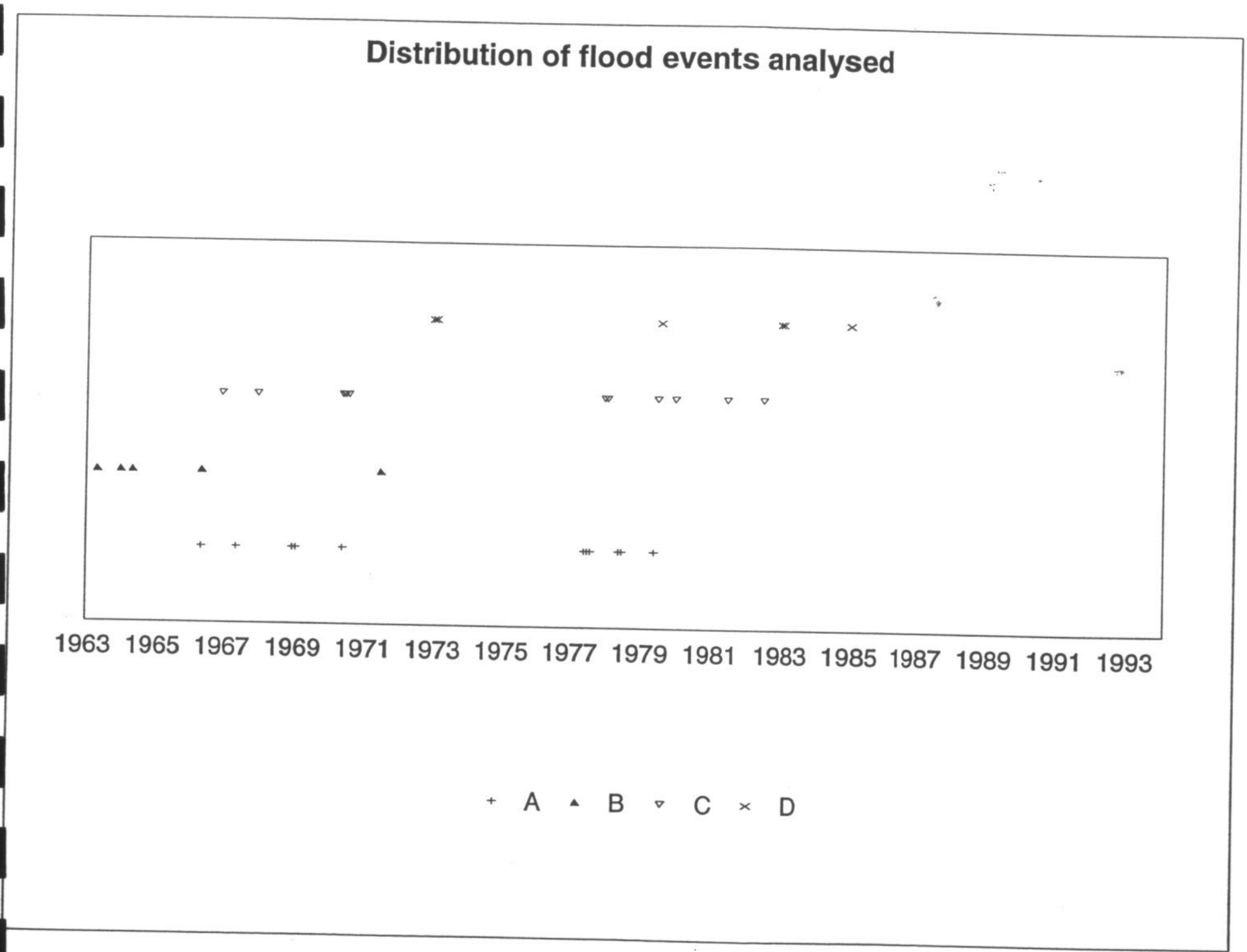
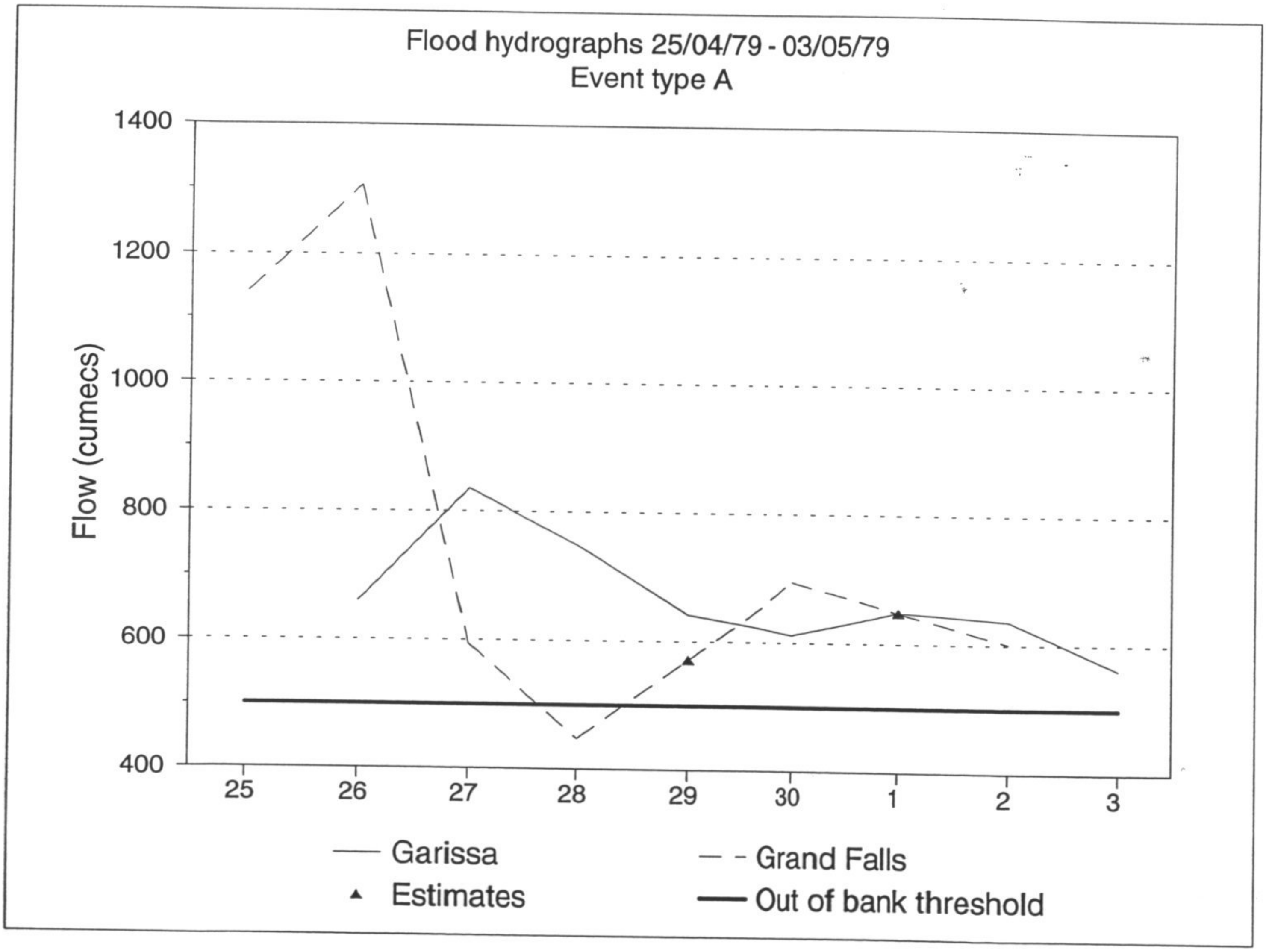


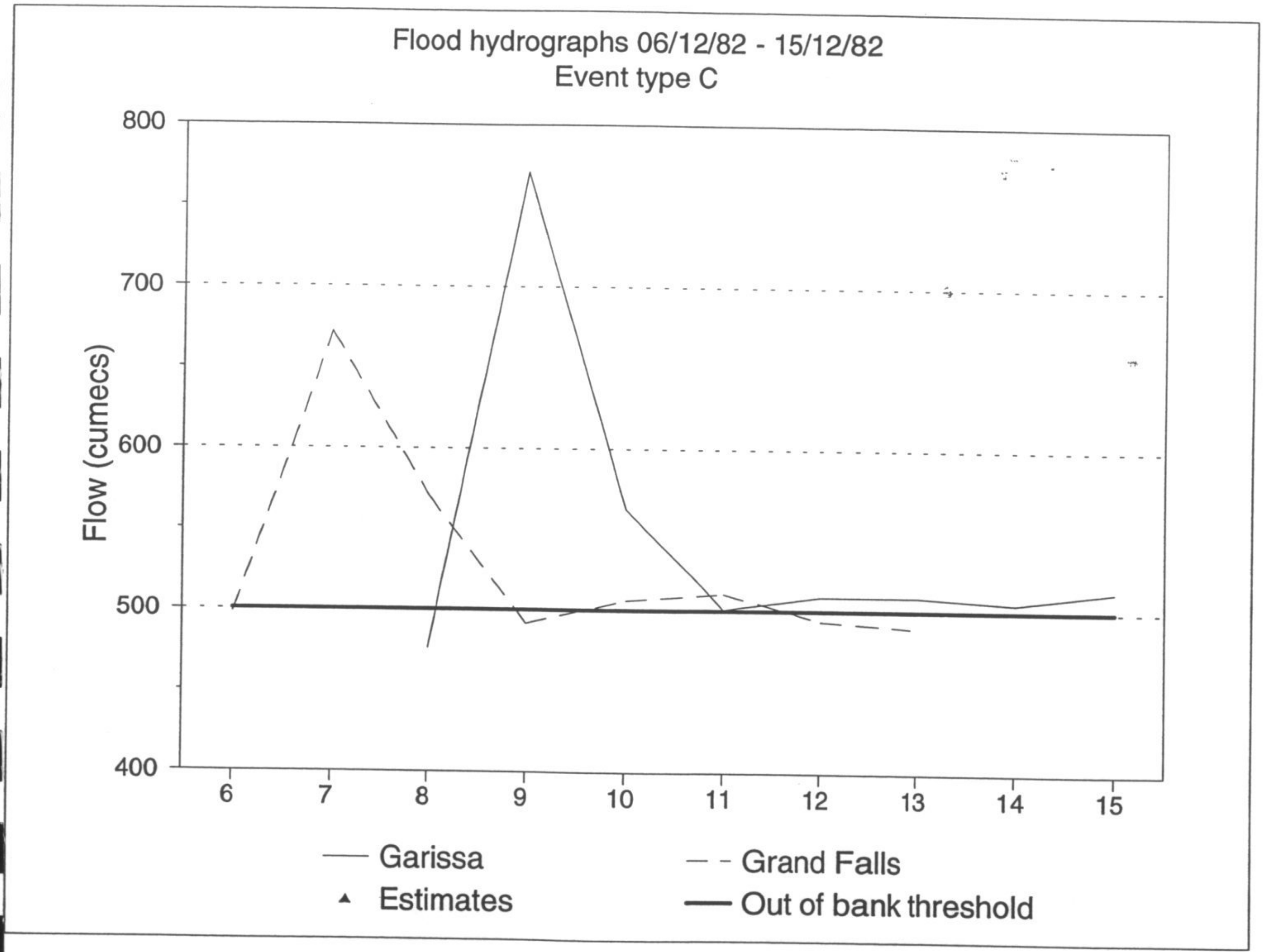
Figure 4.5

4.6


Distribution of flood events analysed
1963 1965 1967 1969 1971 1973 1975 1977 1979 1981 1983 1985 1987 1989 1991 1993
A
B
C
D

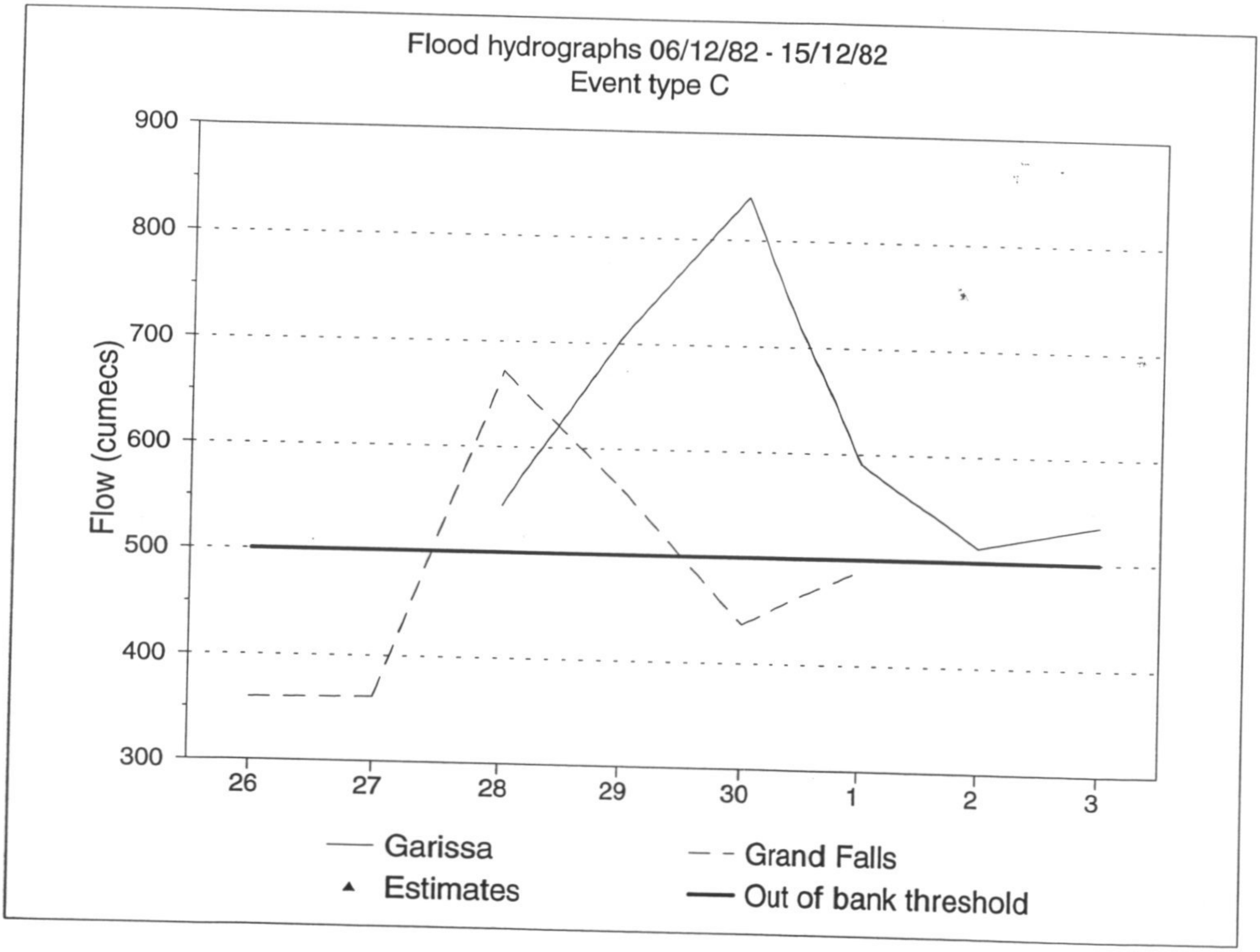
4.7a


Flood hydrographs 25/04/79 - 03/05/79
Event type A
1400
1200
1000
800
600
400
Flow (cumecs)
25
26
27
28
29
30
1
2
3
Garissa
Grand Falls
Estimates
Out of bank threshold



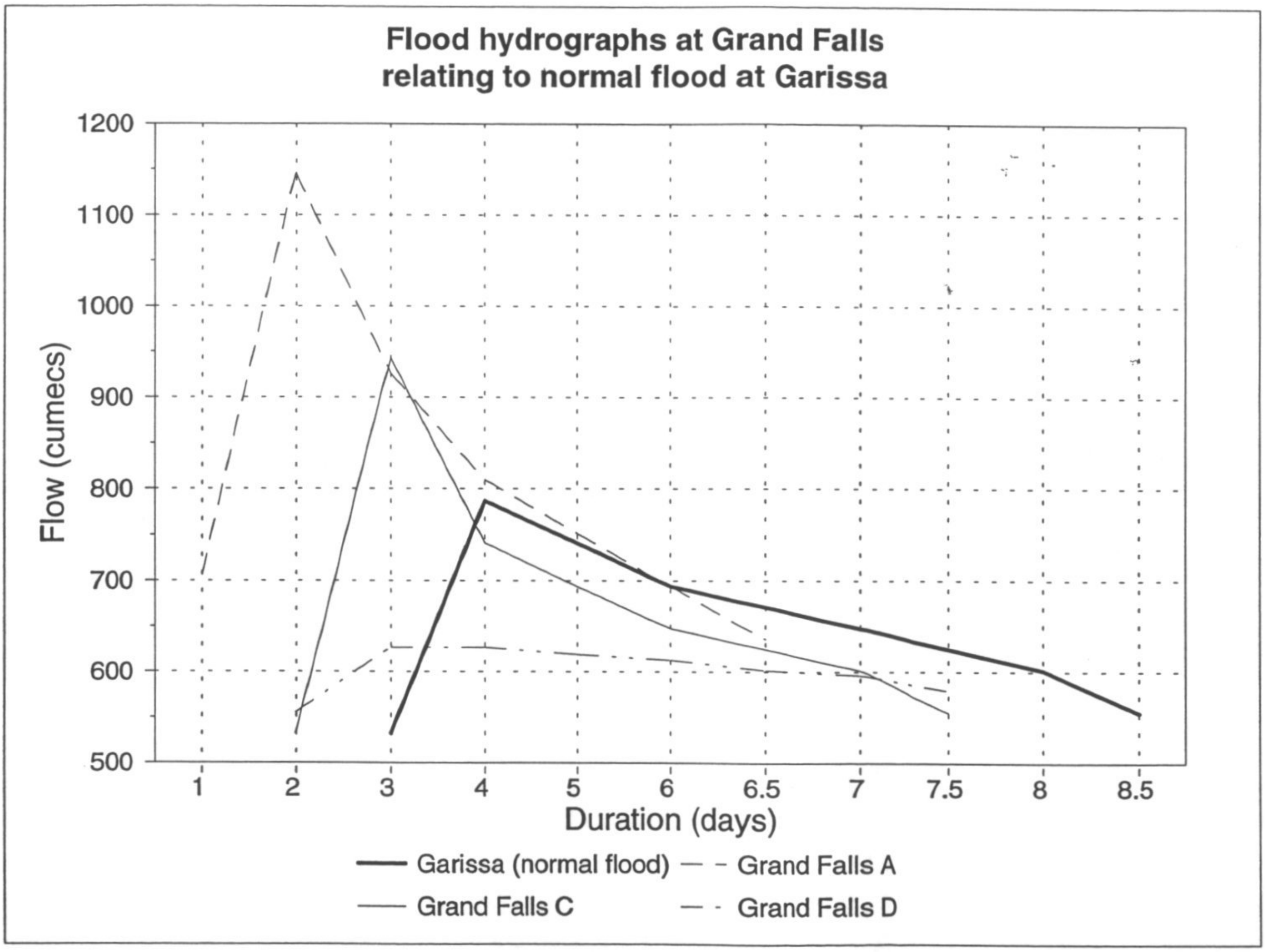
Flood hydrographs 06/12/82 - 15/12/82
Event type C
800
700
600
500
400
Flow (cumecs)
6
7
8
9
10
11
12
13
14
15
Garissa
Grand Falls
Estimates
Out of bank threshold

4.7c

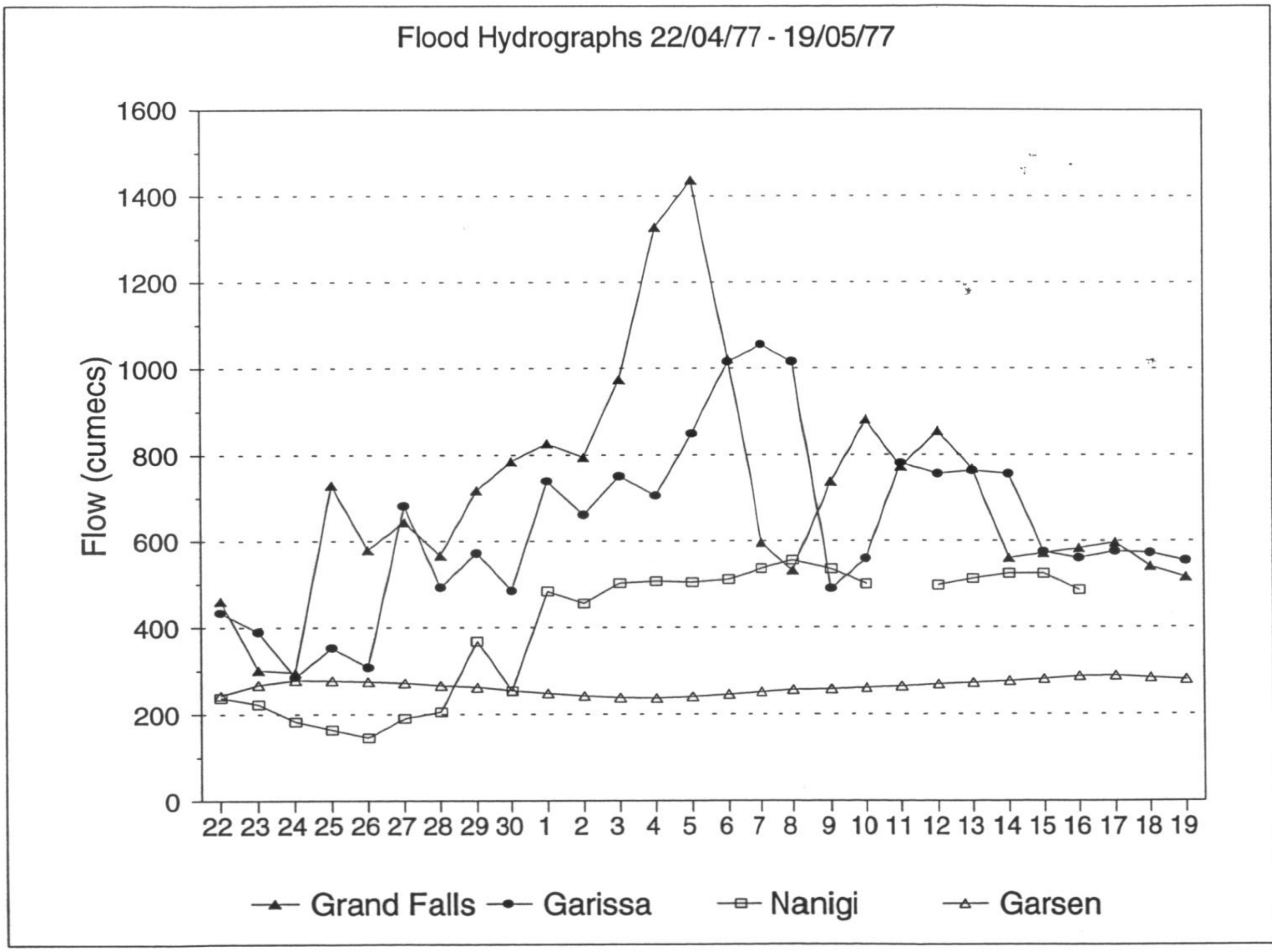


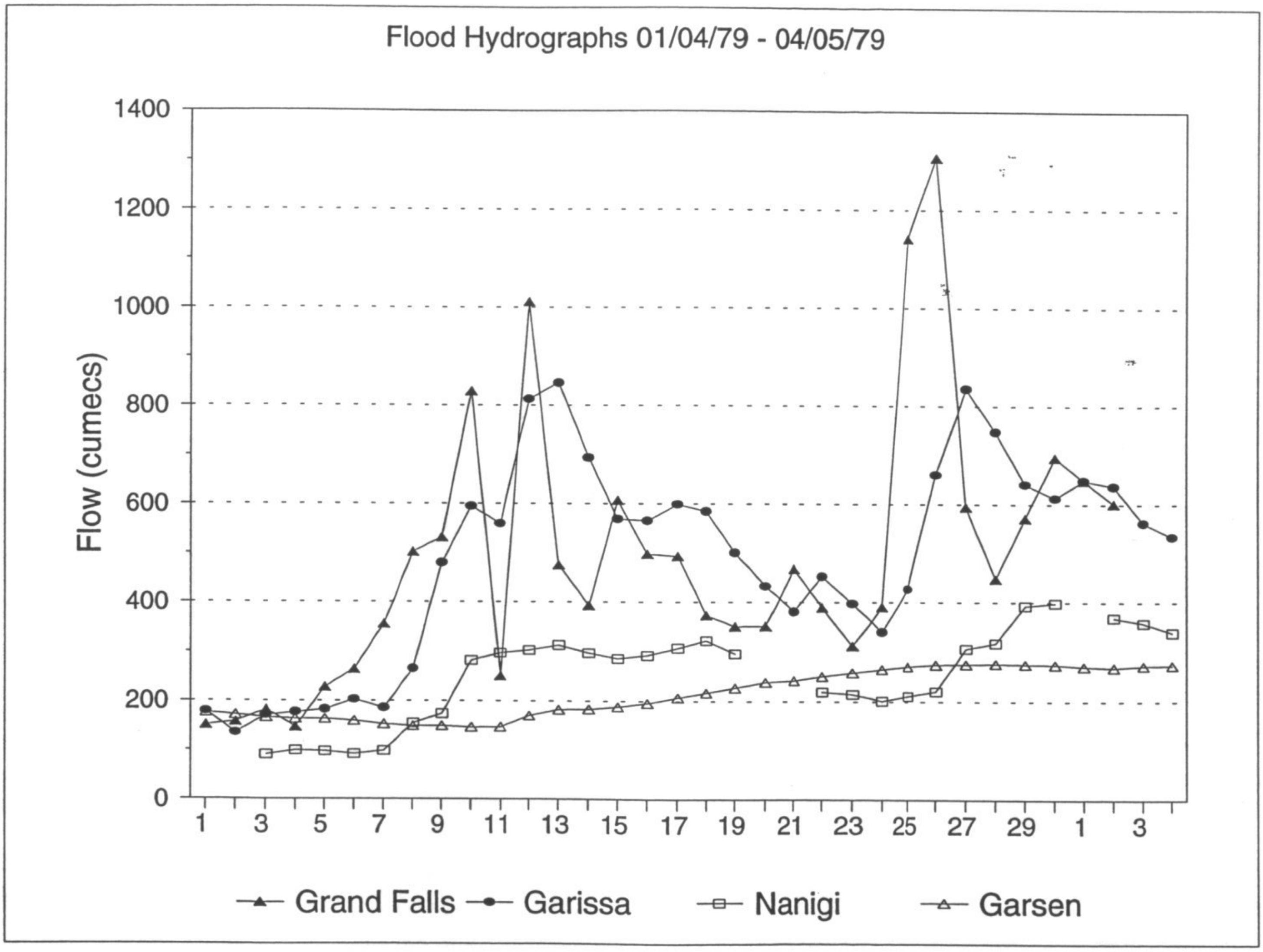
Flood hydrographs 06/12/82 - 15/12/82
Event type C
900
800
700
600
500
400
300
Flow (cumecs)
26
27
28
29
30
1
2
3
Garissa
Grand Falls
Estimates
Out of bank threshold

4.8


Flood hydrographs at Grand Falls
relating to normal flood at Garissa
Flow (cumecs)
1200
1100
1000
900
800
700
600
500
1
2
3
4
5
6
6.5
7
7.5
8
8.5
Duration (days)
Garissa (normal flood)
Grand Falls A
Grand Falls C
Grand Falls D

4.9a


Flood Hydrographs 22/04/77 - 19/05/77
Flow (cumecs)
1600
1400
1200
1000
800
600
400
200
0
22 23 24 25 26 27 28 29 30 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19
Grand Falls
Garissa
Nanigi
Garsen



Flood Hydrographs 01/04/79 - 04/05/79
Flow (cumecs)
1400
1200
1000
800
600
400
200
0
1 3 5 7 9 11 13 15 17 19 21 23 25 27 29 1 3
Grand Falls
Garissa
Nanigi
Garsen

Location of rainfall stations used in the analysis

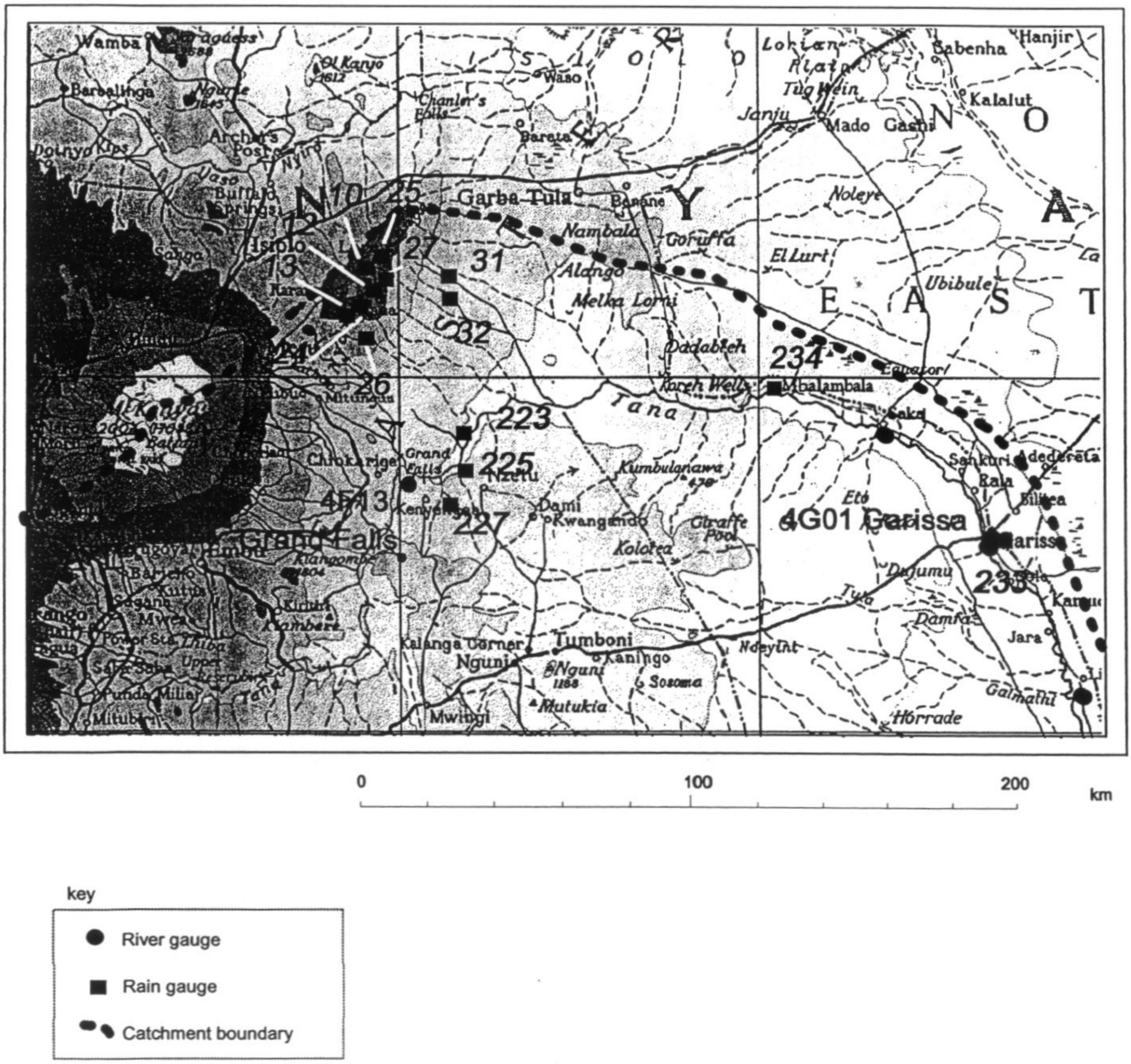
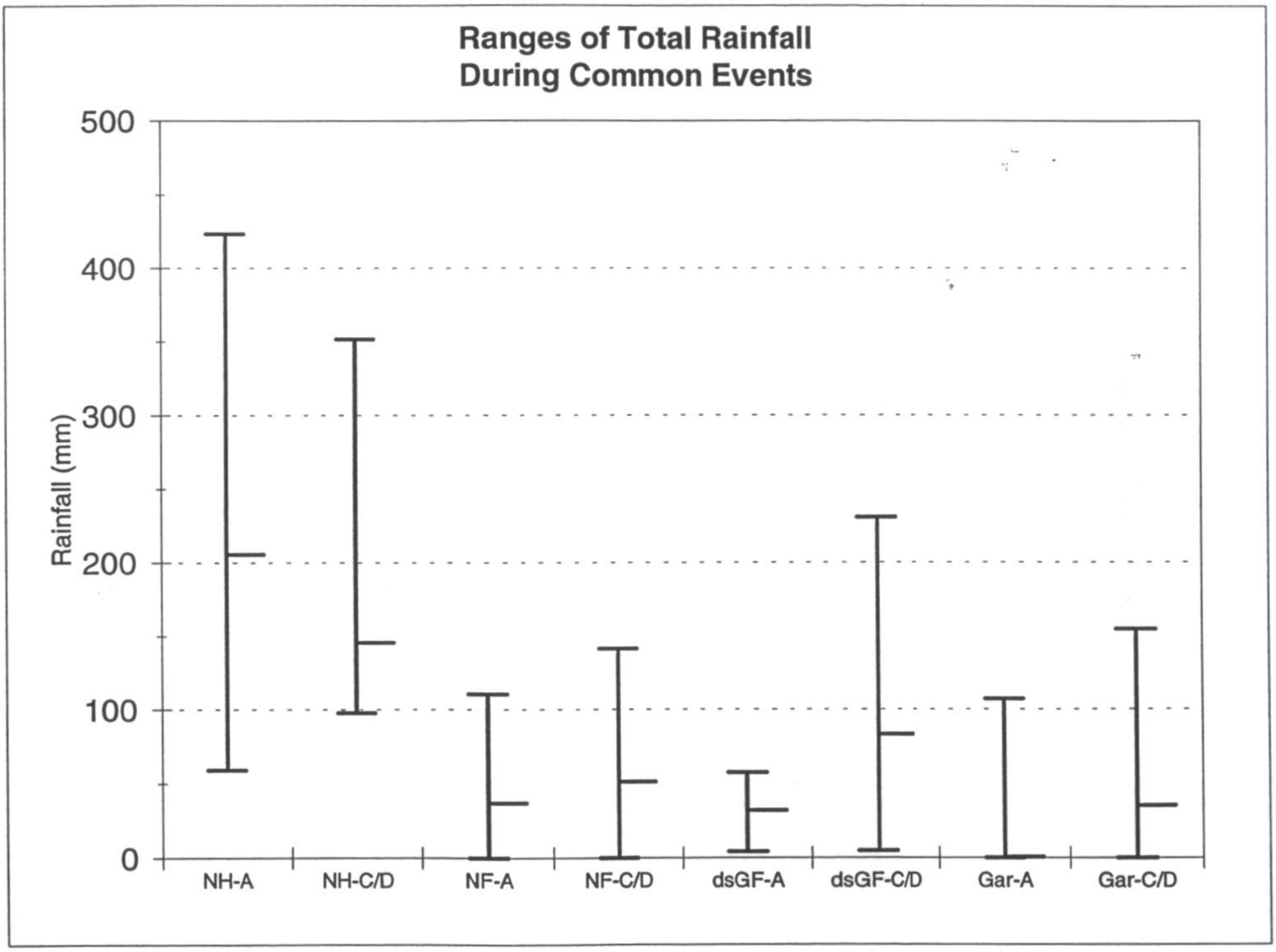


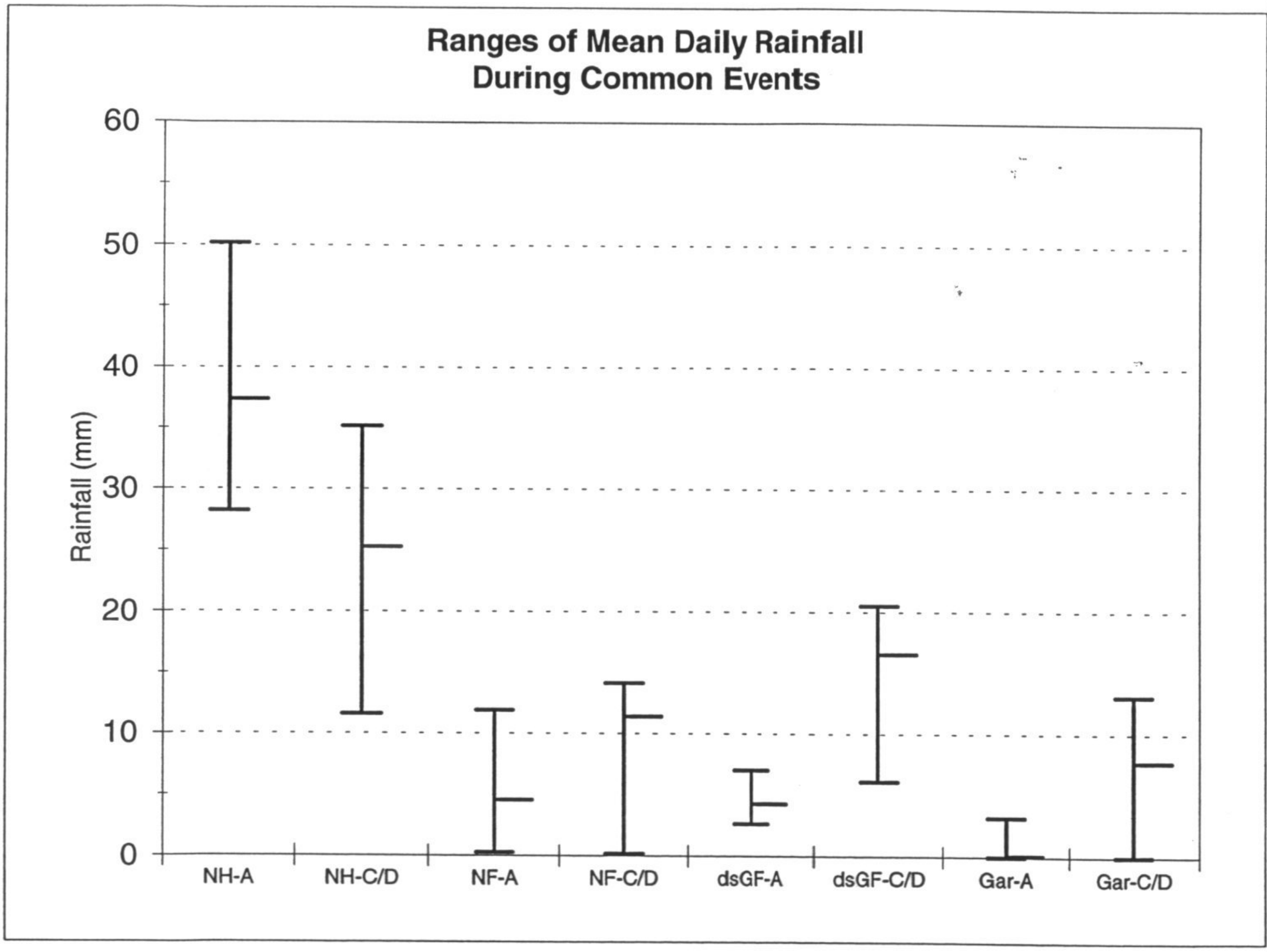
Figure 5.1

2a



Ranges of Total Rainfall
During Common Events
500
400
300
200
100
0
Rainfall (mm)
NH-A
NH-C/D
NF-A
NF-C/D
dsGF-A
dsGF-C/D
Gar-A
Gar-C/D

5.26


Ranges of Mean Daily Rainfall
During Common Events
Rainfall (mm)
60
50
40
30
20
10
0
NH-A
NH-C/D
NF-A
NF-C/D
dsGF-A
dsGF-C/D
Gar-A
Gar-C/D

Typical rainfall pattern for Event Type A

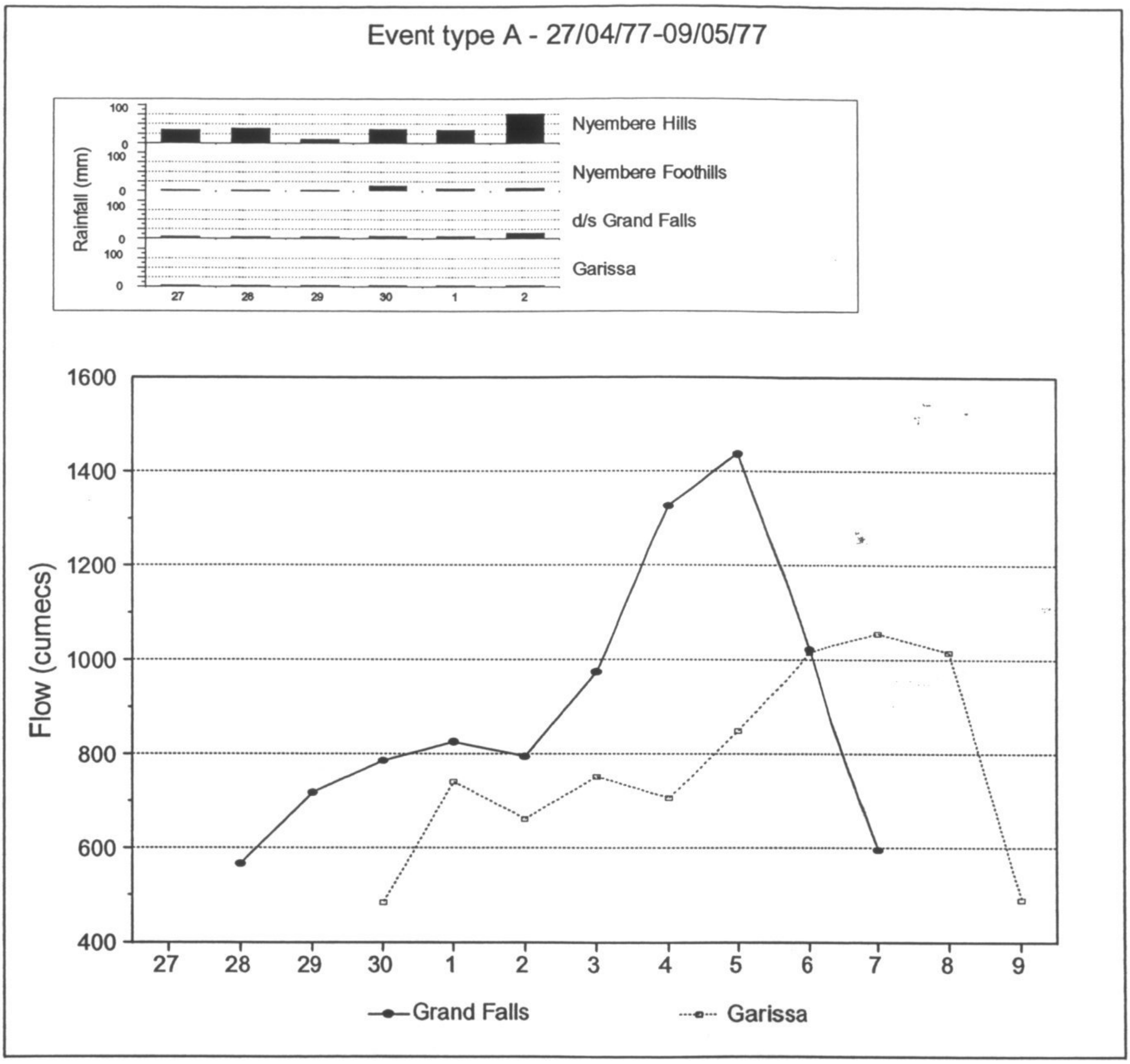


Figure 5.3a

Typical rainfall pattern for Event Type C

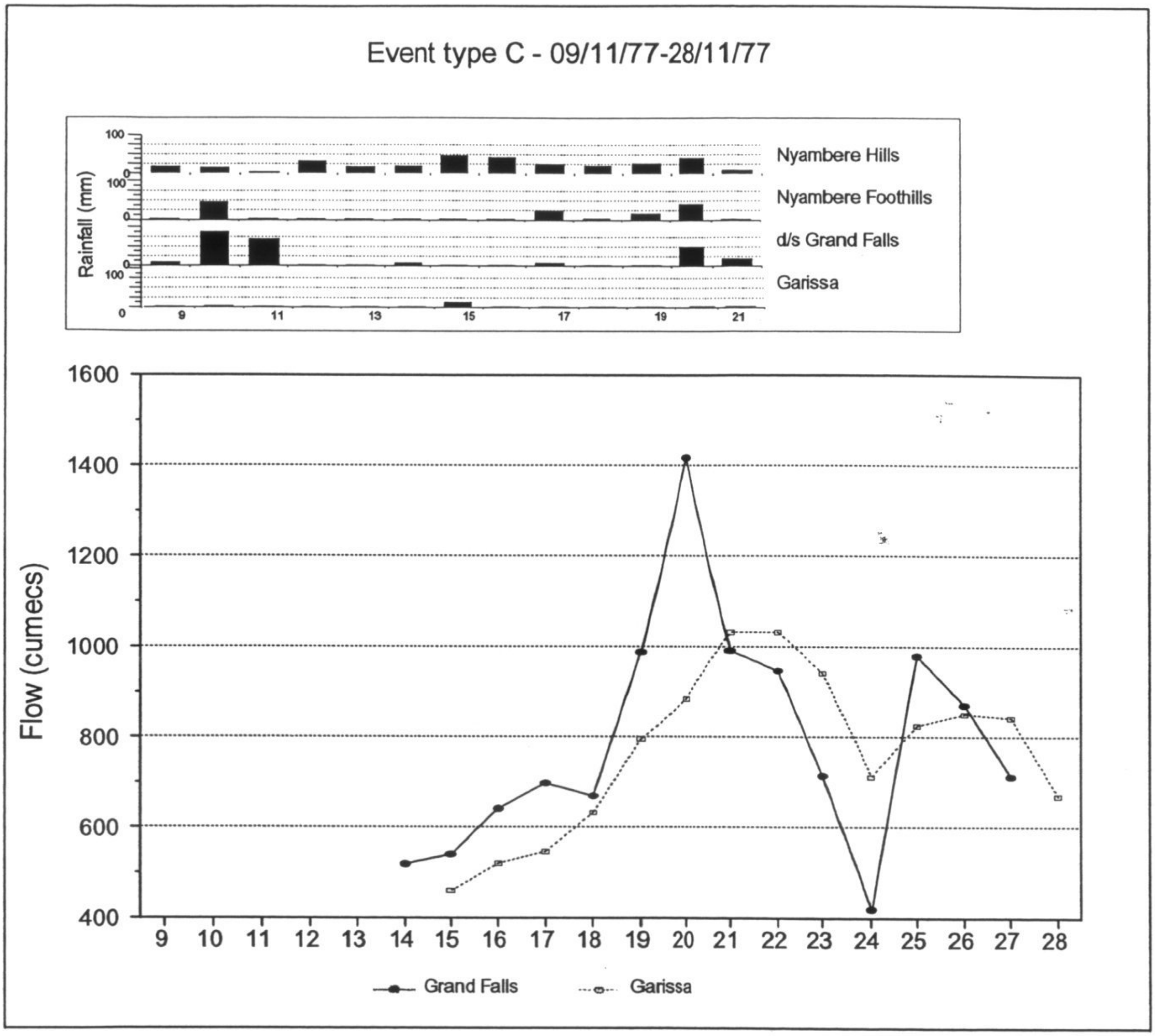


Figure 5.3b

Typical rainfall pattern for Event Type D

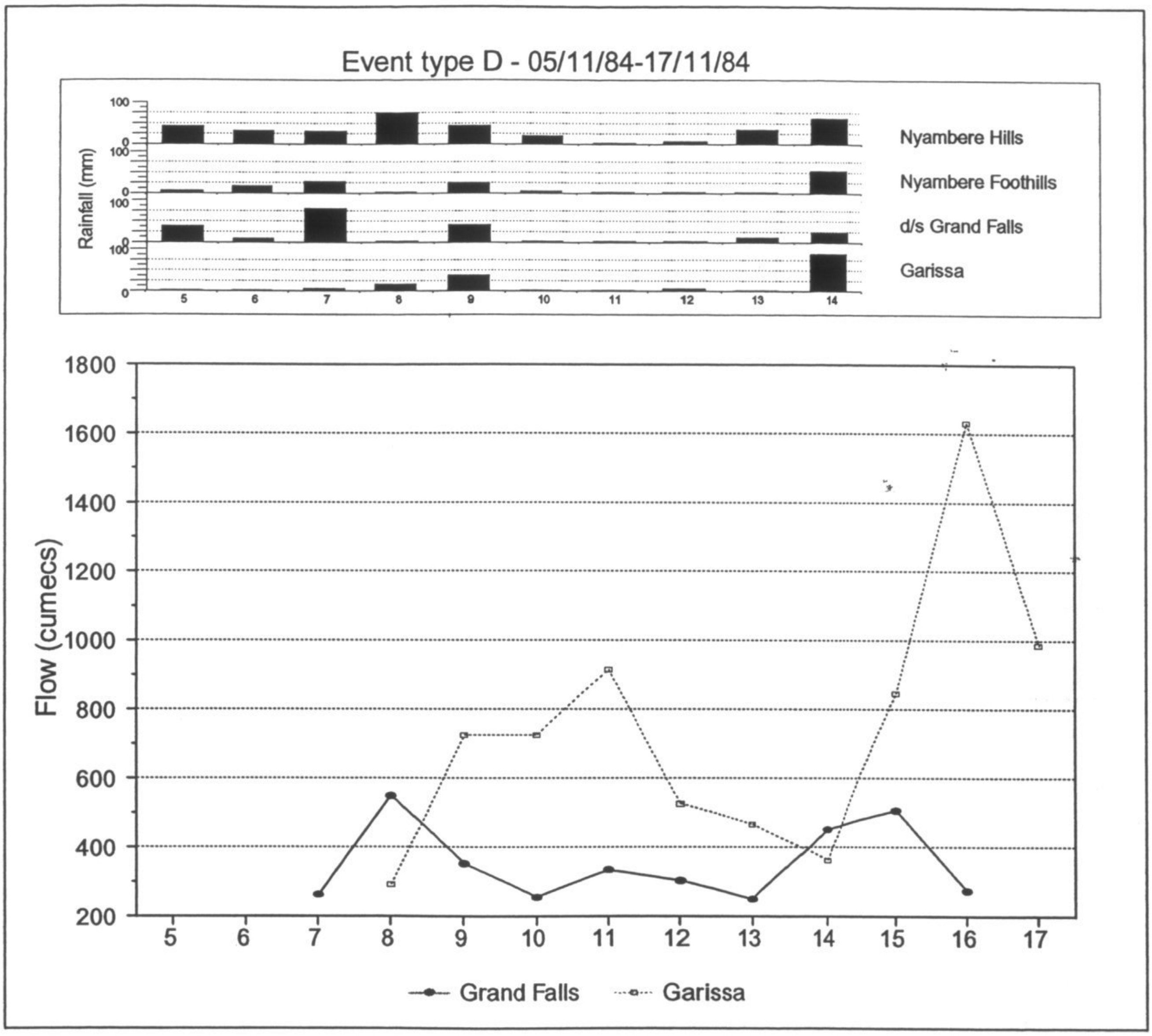


Figure 5.3c

Effects of variation in rainfall distribution on pattern of flooding

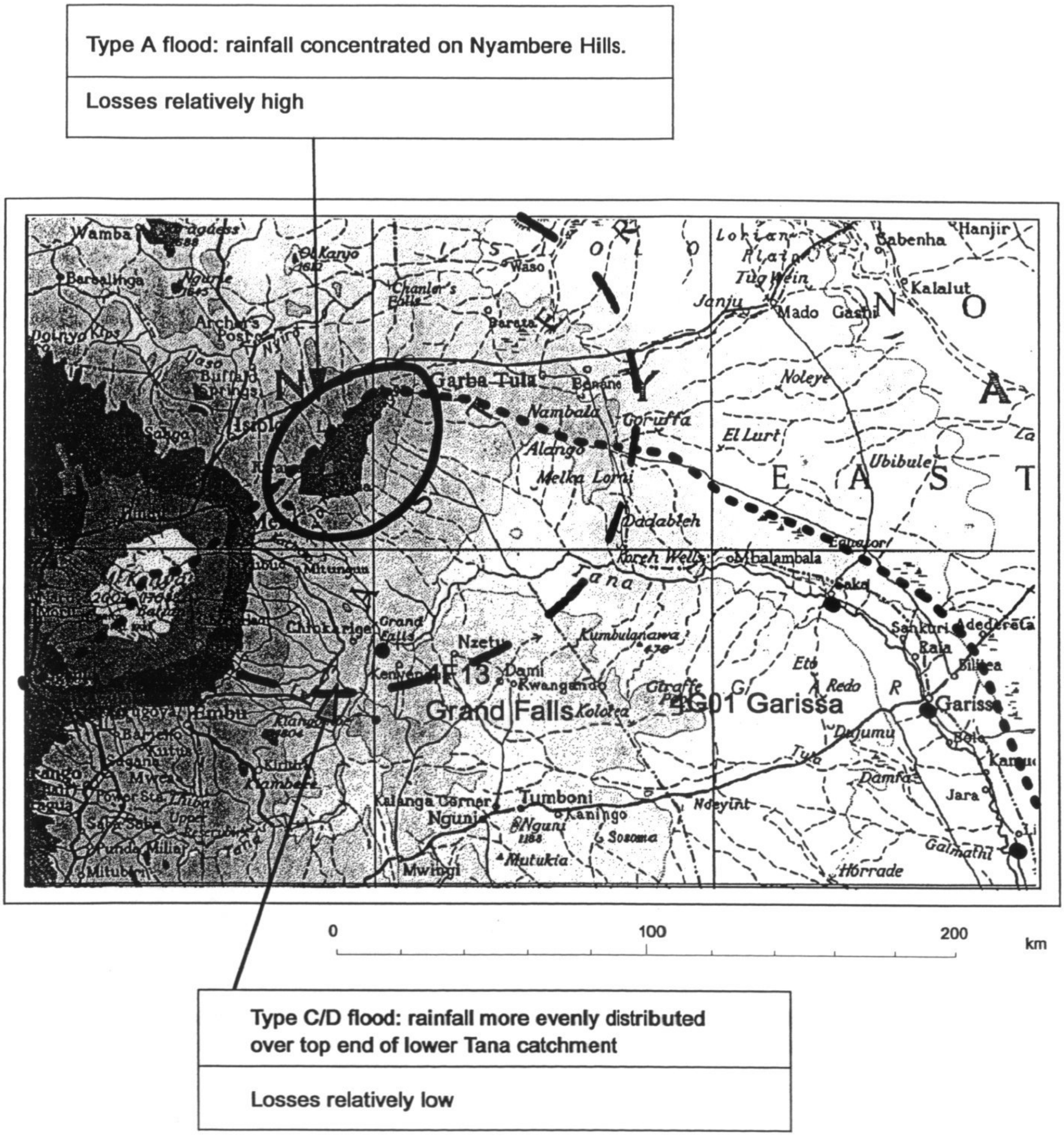
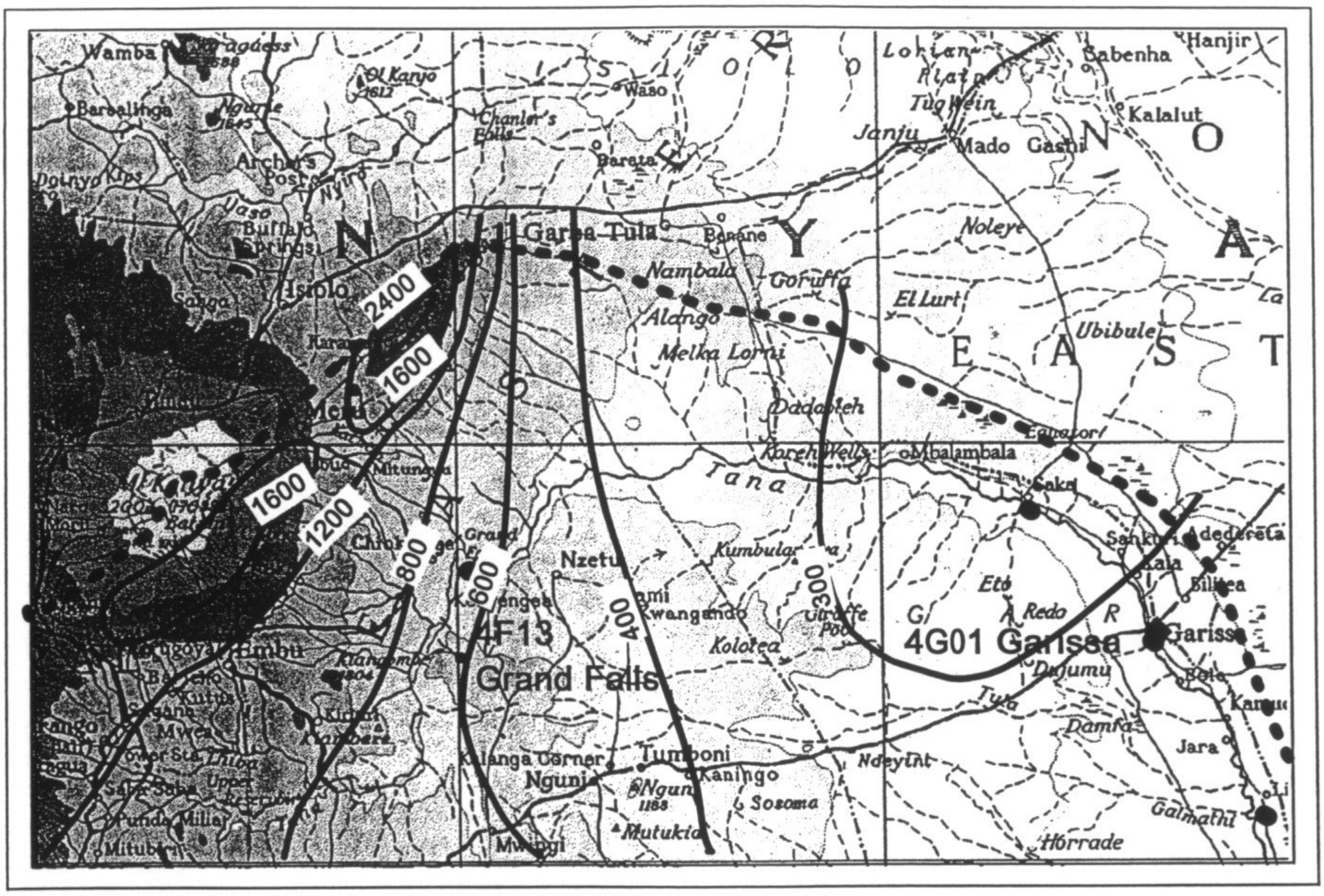


Figure 6.1

Map of mean annual rainfall in lower Tana catchment



Source: Nippon Koei (1995a)

0 100 200 km

Figure 6.2

Appendix A - Rating Curves

Appendix A - Rating Curves

A.1 Review of existing curves

Rating curves for the Tana at Grand Falls, Garissa, Garsen, Saka and Nanigi are given in DHV (1986). These curves were fitted by MOWD except for the curves for Saka which were fitted by consultants. The equations of the curves are given in imperial units except for those at Saka and Nanigi which are in metric. The following errors were detected:

- In table 3-2a the rating for Garissa 01/08/79-30/06/85 is in metric units not imperial as stated.
- In table 3-2b the range is in metres not feet as stated.
- In table 3-2b part 1 of the rating for Saka 01/12/84-30/06/85 is actually part 3 of the rating for 05/10/83-30/11/84. The dates of the second rating have been typed one line above the correct position in the table.

The rating equations and curves for the Tana at Grand Falls and Garissa are reproduced in Nippon Koei (1995a) although converted into metric units. As part of the present study a check was performed by converting the original imperial unit equations given in DHV (1986) to metric units. The results agreed with the Nippon Koei (1995) equations in all but one instance (part 3 of the rating for Garissa 28/11/45-16/04/50). The only other difference between the two sets of ratings is that those given in Nippon Koei (1995) cover the period of time since the DHV(1986) study was published.

The existing MOWD rating equations are given in table A.1 and are reviewed below for each station in turn. The curves are plotted in figures A.1 to A.14 which compare the existing curves with the new ratings fitted on HYDATA.

4F13 Tana at Grand Falls

R (01/08/62-15/11/63) The gaugings provided for this period are in two clusters. The curve fits both clusters but there are no gaugings to check the fit at other levels, particularly high stages.

S (16/11/63-04/12/68) The curve fits the gaugings well apart from a small number which lie some way below the curve.

T (05/12/68-31/12/93) The gaugings provided suggest a good fit at low stages. However, the curve may be overestimating at higher stages due to the influence of two suspected erroneous gaugings.

4G01 Tana at Garissa

J (01/04/41-27/11/45) In the data provided there are only four gaugings during this period. These suggest a good fit for part 1 of the curve but do not provide a check on part 2.

K (28/1145-16/04/50) The curve fits the scatter of gaugings although there is one outlier.

L (17/04/50-30/04/58) The gaugings suggest a good fit for part 1 of the curve but do not provide a check on part 2.

M (01/05/58-21/12/61) Parts 1 and 2 fit the gaugings well but part 3 is poor, overestimating flows.

N (01/01/62-20/04/63) No gaugings were provided for this period to check the curve.

O (21/04/63-09/04/70) The gaugings suggest a good fit for part 1 of the curve but only allow a check on the lower end of the range of part 2.

P (10/04/70-18/04/73) The gaugings suggest a good fit for parts 1 and 2 of the curve but do not provide a check on part 3 .

Q (19/04/73-31/07/91) Part 1 fits the gaugings well but part 2 may be underestimating flows. One suspected erroneous gauging was amended (see table A.2).

R (01/08/79-30/06/85) and S (01/08/79-29/03/85) These curves are identical except that the period covered by S is slightly shorter due to the inclusion of data after 29/03/85 with more recent gaugings for curve T. Both parts of the curve appear to fit the gaugings well.

T (30/03/85-31/12/94) The gaugings suggest a good fit for both parts 1 and 2 although most of the scatter lies above the rating curve.

4G02 Tana at Garsen

S (16/09/50-11/12/62) The rating curve fits the gauging data well.

T (12/12/62-31/12/80) Part 1 of the curve fits the gaugings well at low values of stage but may be overestimating flows above this. The gaugings provided do not allow a check on part 2 of the rating. Four suspected erroneous gaugings were amended (see table A.2).

4G08 Tana at Nanigi

T (15/10/73-05/12/78) Both parts 1 and 2 of the curve fit the gaugings well except for four outliers. These four gaugings were amended (see table A.2).

4G10 Tana at Saka

S (05/10/83-30/11/84) The curve appears to fit the gaugings well although perhaps overestimating flow at low stages.

T (01/12/84-30/06/85) The curve fits the three gaugings provided for this period well but does not allow estimation of flows at stages below 2.0 metres.

A.2 Fitting of curves on HYDATA

New rating curves were fitted to the gauging data of each station. The gaugings were first assessed for any possible shifts in the relationship between stage and discharge and split into what appeared to be periods during which this relationship remained consistent. These periods are broadly the same as those used in the existing MOWD ratings although in the case of Grand Falls and Garissa several of the new rating periods span two or more of those used in the development of the existing ratings (eg rating A is concurrent with ratings J,K and L). The rating periods for curves at Garsen are also slightly different to the existing ones, starting earlier and finishing more recently, reflecting the provision of both earlier and later gaugings than were covered by the existing rating periods.

Table A.1 Existing MOWD rating equations

Station	Rating	Period	Range		Constants		
			Low (metres)	High (metres)	a	b	c
Grand Falls	R	01/08/62-15/11/63	0.000	99.990	28.082	1.882	
	S	16/11/63-04/12/68	0.762	2.118	49.880	1.007	
			2.118	5.059	28.617	1.747	
			5.059	13.715	15.368	2.130	
	T	5/12/68-31/12/93	0.003	2.865	58.655	1.060	
			2.865	12.191	19.893	2.087	
Garissa	J	01/04/41-27/11/45	0.244	3.075	75.008	1.519	
			3.075	5.486	22.121	2.606	
	K	28/11/45-16/04/50	0.305	2.012	52.798	1.408	
			2.012	3.414	32.992	2.081	
			3.414	5.181	12.151	2.895	
	L	17/04/50-30/04/58	0.549	2.194	61.177	1.459	
			2.194	4.191	43.810	1.884	
			4.191	7.010	4.257	3.511	
	M	01/05/58-31/12/61	0.792	1.524	45.657	1.310	
			1.524	3.962	33.692	2.031	
			3.962	7.010	4.739	3.455	
	N	01/01/62-20/04/63	0.640	4.191	101.896	1.294	
			4.191	7.010	4.257	3.511	
	O	21/04/63-09/04/70	0.610	3.261	55.710	1.849	
			3.261	6.096	32.478	2.305	
	P	10/04/70-18/04/73	0.152	1.451	86.566	1.322	
			1.451	3.109	75.336	1.695	
			3.109	4.572	39.730	2.259	
	Q	19/04/73-31/07/79	0.305	1.829	59.681	1.677	
			1.829	5.791	56.471	1.768	
	R	01/08/79-30/06/85	0.100	3.000	26.580	2.359	
			3.000	6.000	41.260	1.959	
	S	01/08/79-29/03/85	0.000	3.000	26.580	2.359	
			3.000	99.000	41.260	1.959	
	T	30/03/85-31/12/94	0.000	1.800	38.910	1.931	
			1.800	99.000	30.531	2.343	
Garsen	S	16/09/50-11/12/62	0.914	6.096	26.319	1.401	
	T	12/12/62-31/12/80	0.914	4.572	13.976	1.816	
			4.572	6.096	26.319	1.401	
Saka	S	05/10/83-30/11/84	0.000	1.000	75.000	1.710	0.500
			1.000	1.250	150.000	1.561	0.000
	T	01/12/84-30/06/85	1.250	2.000	144.640	1.724	0.000
			2.000	2.400	26.150	2.579	0.000
			2.400	3.000	18.290	2.987	0.000
Nanigi	T	15/10/73-05/12/78	0.020	1.070	16.840	2.020	1.000
			1.070	5.500	66.990	1.270	0.000

Sources: DHV (1986) and Nippon Koei (1995)

Table A.2 - *Suspected errors and amendments to gauging data*

Station	Date of gauging	Suspected error	Suggested amendment
4F13 Grand Falls*	17/08/63	h = 2.21m	h = 1.21 m
	04/05/66	h = 4.15 m	h = 5.98 m
	03/06/66	h = 1.17 m	h = 3.00 m
	15/04/71	h = 2.44 m	h = 1.44 m
	18/10/71	Q = 4.01 m^3s^{-1}	h = 40.01 m^3s^{-1}
	19/02/74	h = 3.42 m	h = 1.03 m
	03/08/77	h = 2.33 m	h = 3.33 m
	01/08/79	h = 2.78 m	h = 1.78 m
4G01 Garissa	11/05/73	Q = 523.78 m^3s^{-1}	Q = 123.78 m^3s^{-1}
4G02 Garsen	06/03/74	h = 2.009 m	h = 1.009 m
	07/03/74	h = 1.999 m	h = 0.999 m
	08/03/74	h = 1.999 m	h = 0.999 m
	20/08/82	h = 0.79 m	h = 2.79 m
4G08 Nanigi	10/06/78	h = 3.94 m	h = 2.94 m
	17/07/78	h = 3.34 m	h = 2.34 m
	25/08/78	h = 0.9 m, V = 2.68 ms^{-1}	h = 1.68 m, V = 0.9 ms^{-1}
	28/09/79	h = 0.41 m, V = 2.05 ms^{-1}	h = 1.05 m, V = 0.41 ms^{-1}

* Suggested amendments to gaugings at Grand Falls were made on the basis of evidence supplied by staff at MOWD whilst the consultant was in Nairobi.

Rating curves were fitted to each of the periods of gauging data using the automatic fitting procedure on the Institute of Hydrology's HYDATA hydrological database and analysis software. Curves were fitted with between one and three parts with the goodness of fit judged by an automatically computed error function but with an experienced hydrologist also exercising some degree of judgement. The rating equations are of the form

$$Q = a\,(h - c)^{b}$$

where Q is flow (or discharge) in m^3s^{-1}, h is stage (or level) in m, and a, b and c are constants.

The new HYDATA rating equations are given in table A.3. In most cases it was clear which curve (1,2 or 3 parts) gave the best fit with the gauging data and only one curve is given for these rating periods. In two instances, however, more than one curve is given for a single rating period. These are curves B and C for Garsen and curves A, C, D, and E for Nanigi. In the former case a 1 part and a 2 part curve are compared. In the latter case the comparison is also between 1 part and 2 part curves

Table A.3 New HYDATA rating equations

Station	Rating	Period	Range		Constants		
			Low (metres)	High (metres)	a	b	c
Grand Falls	A	27/07/62-28/01/81	0.000	2.100	13.842	1.706	1.310
			2.100	4.000	69.384	1.300	-0.690
			4.000	10.000	39.494	1.763	-0.690
Garissa	A	27/03/45-04/04/59	0.000	1.900	55.225	1.344	0.009
			1.900	3.750	64.200	1.718	-0.368
			3.750	7.000	17.624	2.800	-0.368
	B	05/04/59-03/03/64	0.000	3.500	6.528	2.800	0.965
			3.500	7.000	104.562	1.567	-1.035
	C	04/03/64-22/04/70	0.000	2.150	106.199	1.300	-0.385
			2.150	7.000	57.847	1.835	-0.089
	D	23/04/70-10/05/73	0.000	7.000	10.040	2.800	1.062
	E	11/05/73-11/02/80	0.000	1.700	78.740	1.300	-0.189
			1.700	7.000	107.184	1.508	-0.500
	F	12/02/80-02/03/95	0.000	3.100	9.262	2.800	0.569
			3.100	7.000	14.472	2.800	0.046
Garsen	A	31/03/46-15/01/63	0.000	6.000	22.860	1.483	0.056
	B	16/01/63-30/11/91	0.000	6.000	3.230	2.503	1.011
	C	16/01/63-30/11/91	0.000	2.750	3.190	2.512	1.011
			2.750	6.000	43.340	1.300	-0.989
Saka	A	09/02/84-13/11/84	0.000	1.150	165.860	1.300	-0.019
			1.150	2.340	98.520	2.037	0.232
	B	14/11/84-29/05/85	2.340	3.000	49.600	2.300	-0.330
Nanigi	A	30/10/74-09/06/78	0.000	1.750	5.150	2.800	1.552
			1.750	5.500	14.731	1.855	1.770
	B	10/06/78-29/09/79	0.000	5.500	44.633	1.300	-0.642
	C	30/10/74-09/06/78	0.000	5.500	28.660	1.711	0.715
	D	30/10/74-09/06/78	0.000	5.500	34.070	1.576	0.611
	E	30/10/74-09/06/78	0.000	1.750	4.740	2.800	1.614
			1.750	5.500	12.840	1.899	1.770

with two of each fitted, one with the amendments to gauging data suggested in table A.2 and one with this data excluded.

The new HYDATA rating curves are plotted figures A.1 to A.14 where they are compared with the existing MOWD curves.

A.3 Comparison and selection of curves

The new HYDATA rating curves are plotted against the existing MOWD curves in figures A.1 to A.14. The existing and new curves for each rating period at each station were compared in term of the goodness of fit with the gauging data provided. In the majority of cases the HYDATA curves appear to fit the gauging data more closely. Where both existing and new curves gave a good fit it was decided to adopt the new ratings for consistency. Details of the comparison are given below.

4F13 Tana at Grand Falls

Comparison of A with R, S and T
Although curves R, S and T all fit the gauging data provided reasonably well it was felt that there was enough cause for concern in the ratings R and T (due to lack of gaugings and presence of possible erroneous gaugings) to fit a single curve to the whole period. Curve A provides a satisfactory fit through the gaugings provided.

4G01 Tana at Garissa

Comparison of A with J,K and L
The gaugings over the existing rating periods for curves J, K and L appear to be consistent. The single curve A fits this combined set of gaugings better than any of the existing curves.

Comparison of B with M and N
There are no gaugings provided for the rating period of curve N and curve M does not give a good fit across the full range of gaugings. Curve B provides the best fit.

Comparison of C with O
Curve C provides the best fit.

Comparison of D with P
There are no gaugings to guide the upper part of the rating. D gives the best fit with the gaugings provided.

Comparison of E with Q
Curve E provides the best fit.

Comparison of F with R/S and T
Curves R/S and T both fit the individual rating periods reasonably well but curve F gives the best fit for the period as a whole.

4G02 Tana at Garsen

Comparison of A with S
Both curves give a good fit, use A for consistency.

Comparison of B and C with T
Curve C gives the better fit of the two HYDATA curves for this period. Curve T gives poor fit in region of part 2. Use curve C.

4G08 Tana at Nanigi

Comparison of A and C with T
With the suspected errors listed in table A.2 excluded the best fit is given by curve A.

Comparison of D and E with T
With the suspected errors listed in table A.2 amended the best fit is given by curve E but note that the amended gaugings do not lie on any of the fitted curves. The decision was therefore taken to exclude these gaugings and accept curve A as the best fit.

Curve B for Nanigi is not concurrent with any existing MOWD curve and is fitted against only two points. It is unlikely to be used in converting stages to discharges.

4G10 Tana at Saka

Comparison of A with S
Both curves give a good fit, use A for consistency.

Comparison of B with T
Both curves give a good fit, use B for consistency.

Figure A.1 Rating Curves - Grand Falls

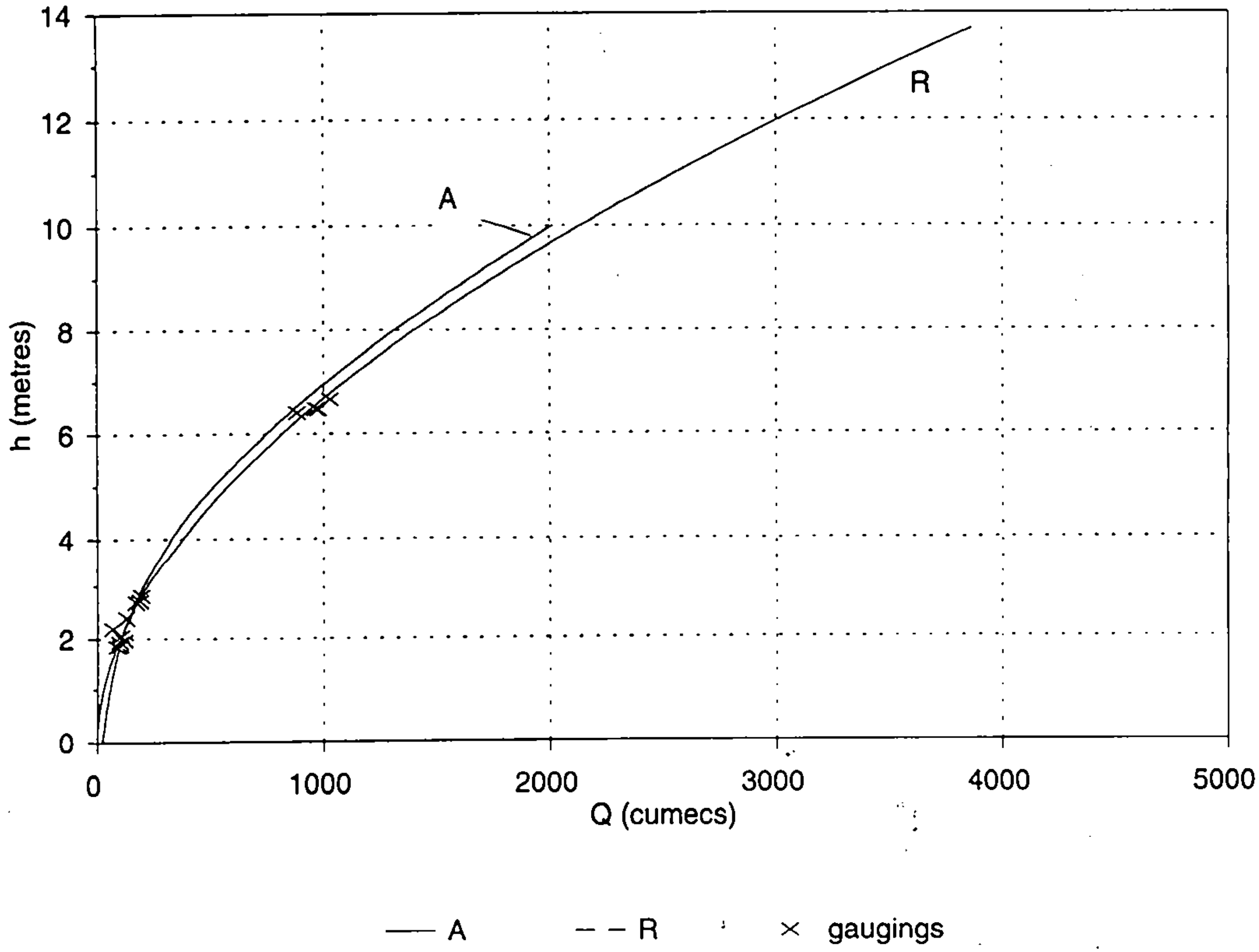


Figure A.2 Rating Curves - Grand Falls

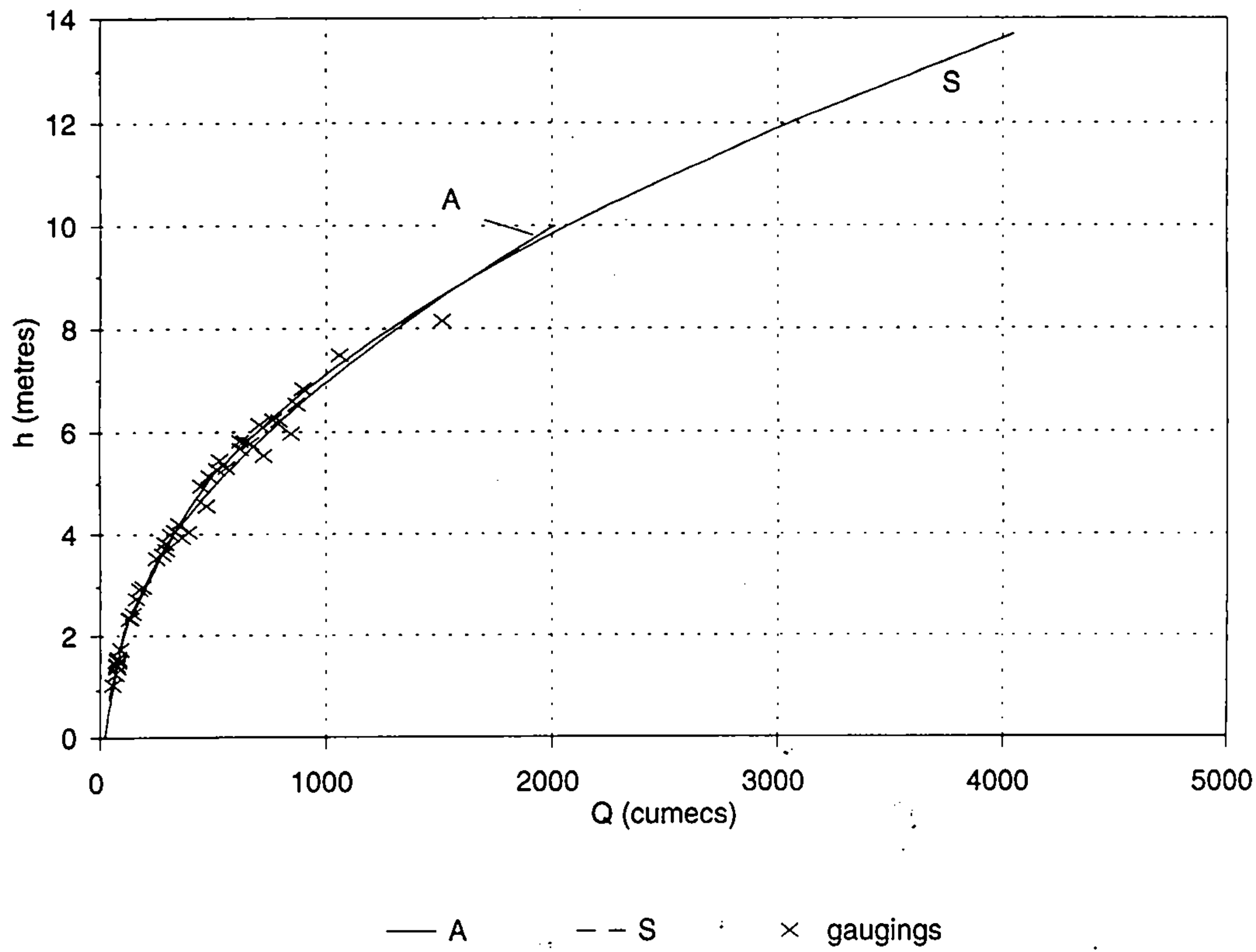


Figure A.3 Rating Curves - Grand Falls

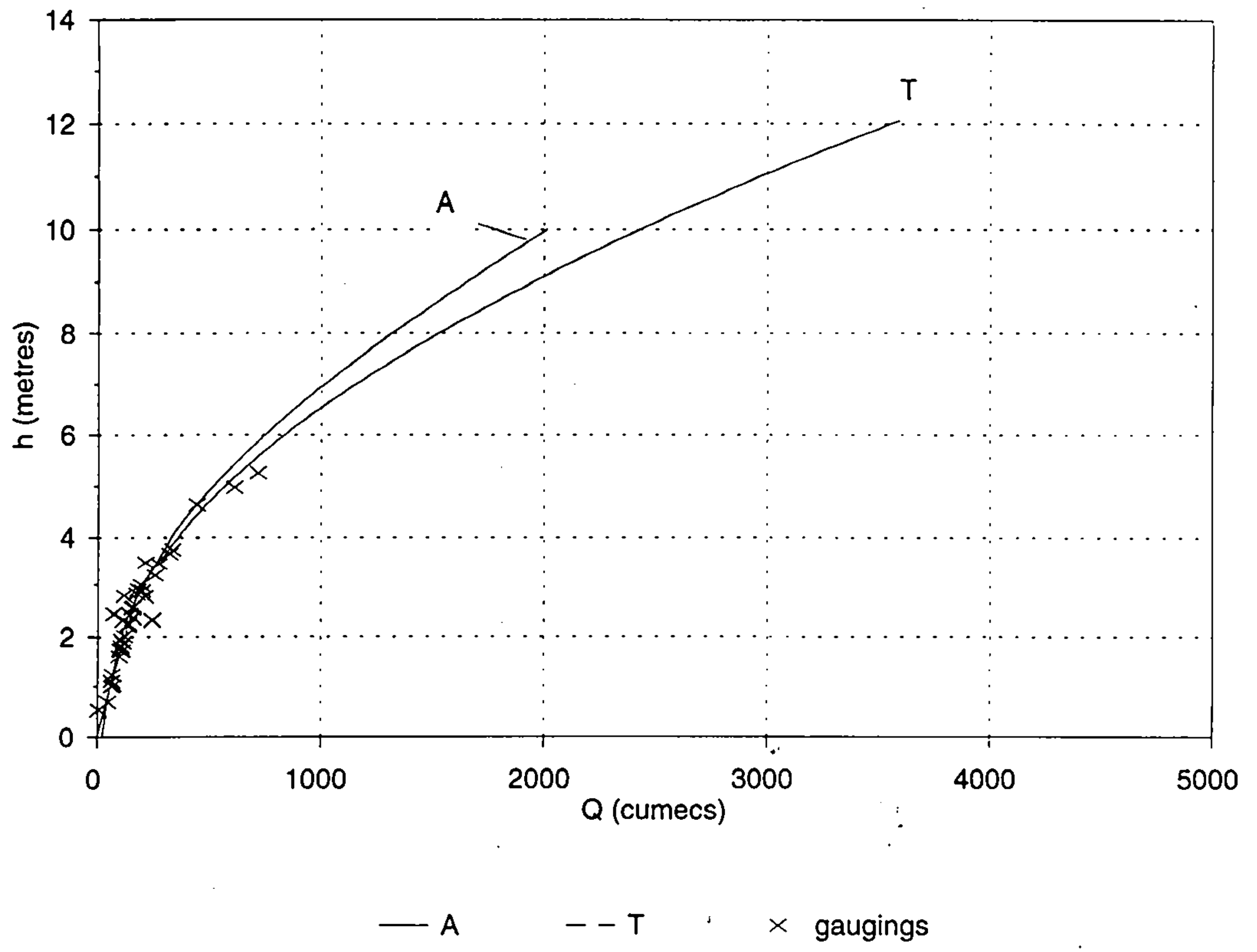


Figure A.4 Rating Curves - Garissa

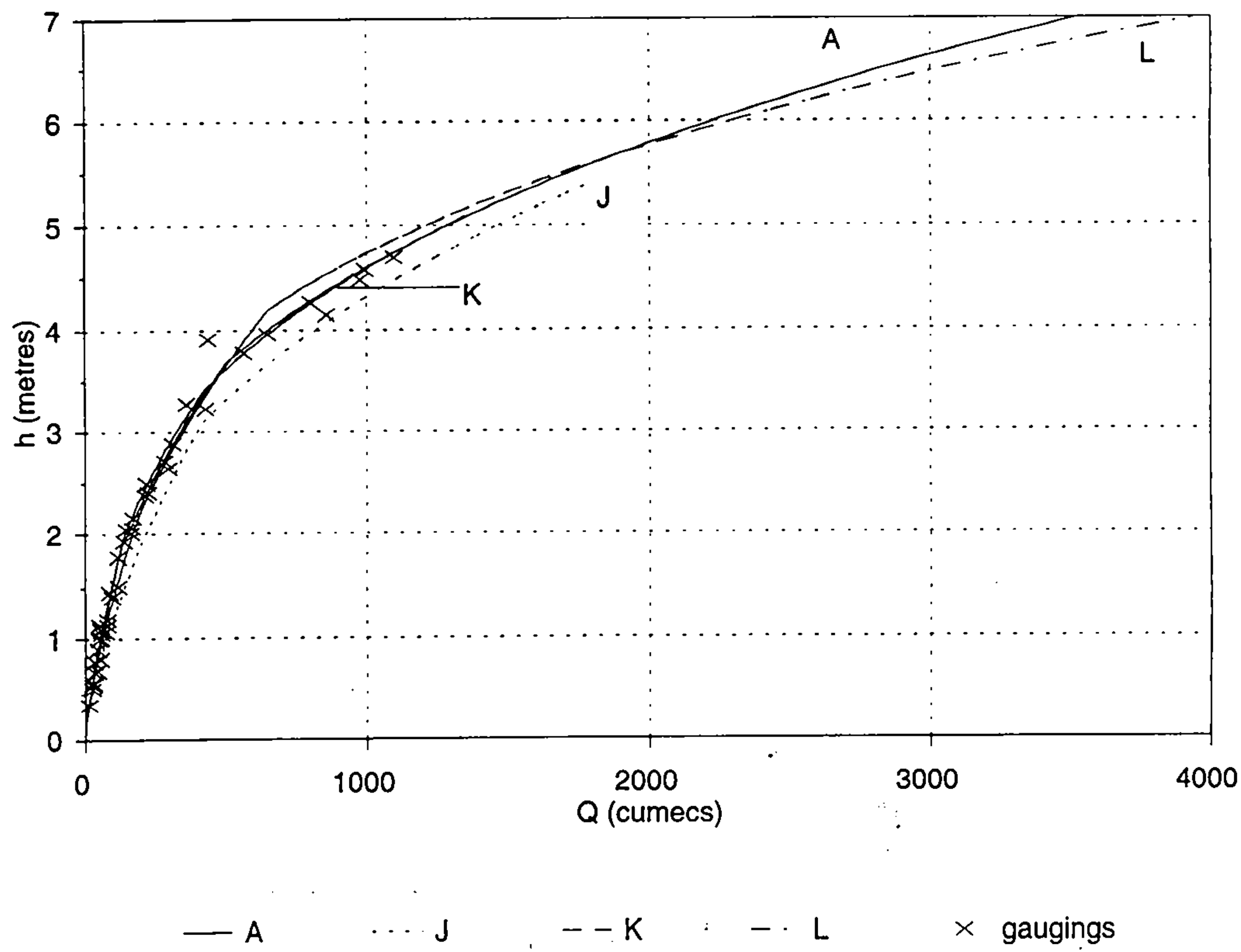


Figure A.5 Rating Curves - Garissa

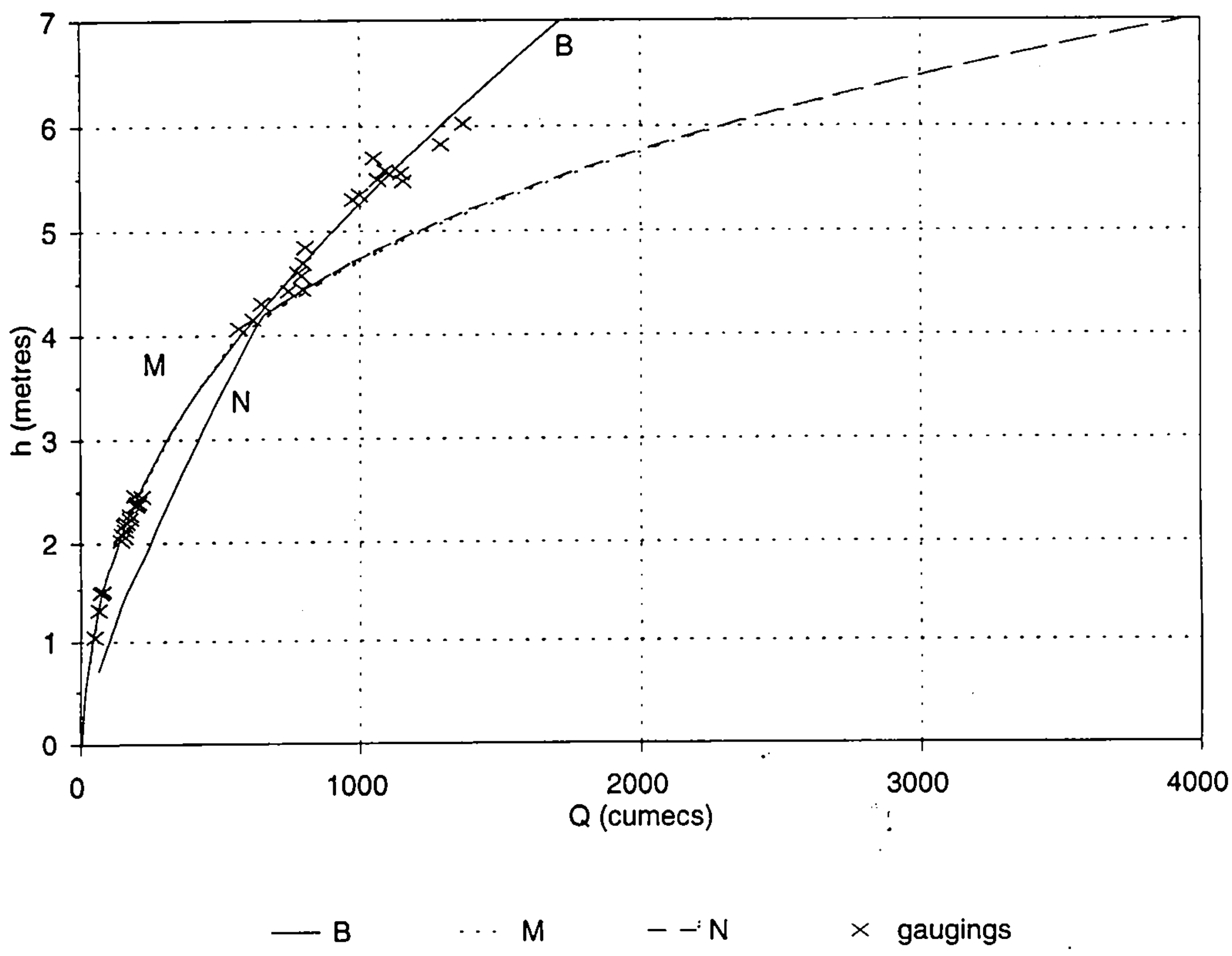


Figure A.6 Rating Curves - Garissa

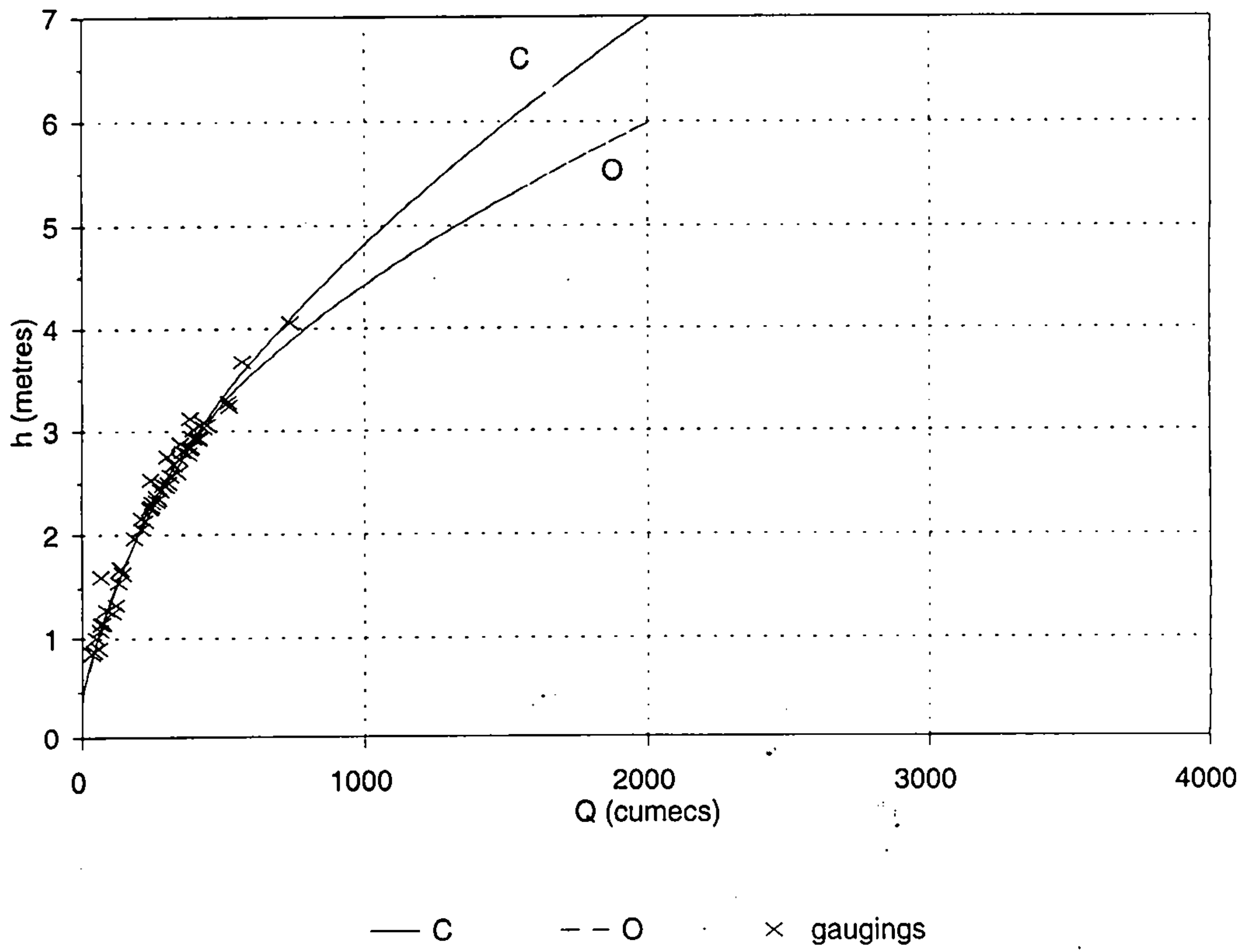


Figure A.7 Rating Curves - Garissa

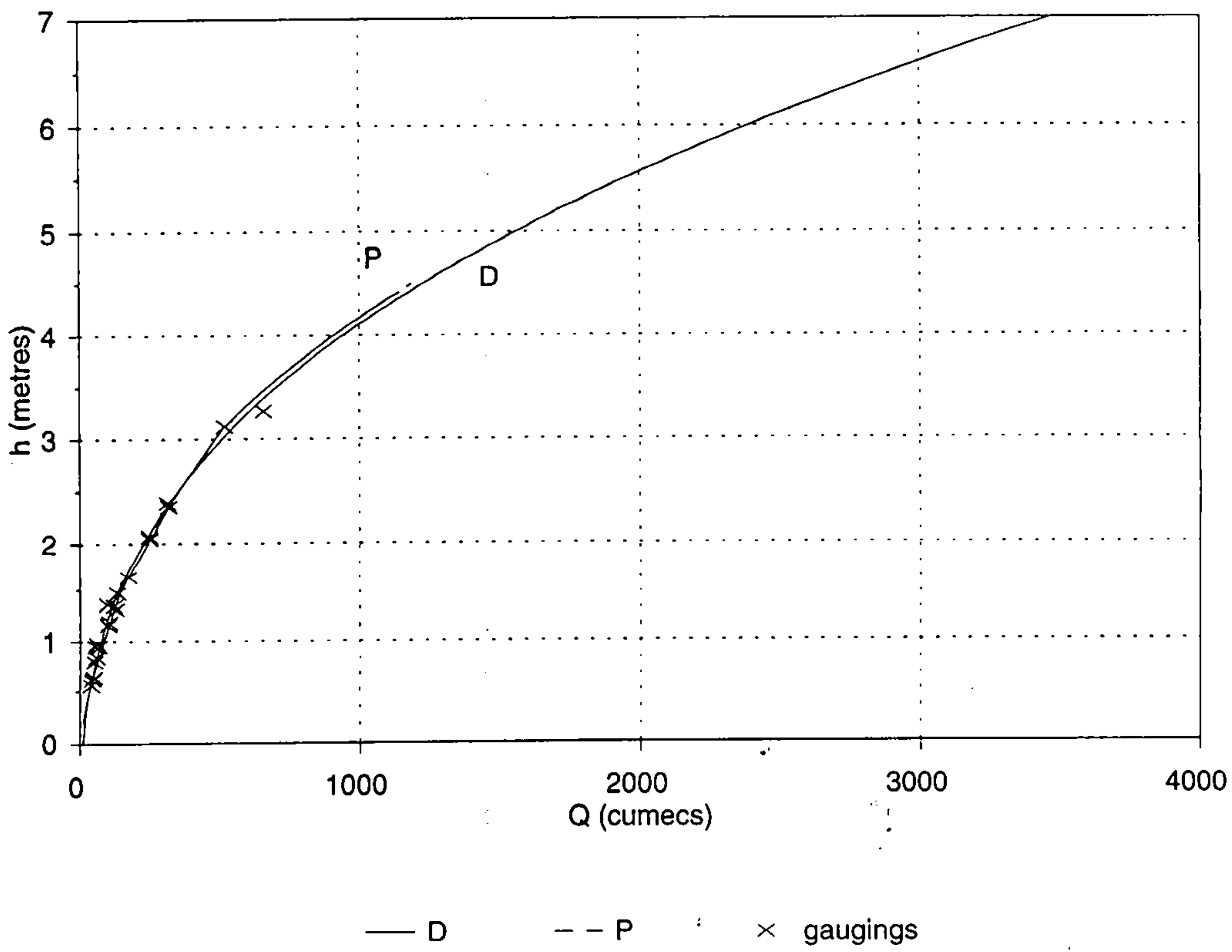


Figure A.8 Rating Curves - Garissa

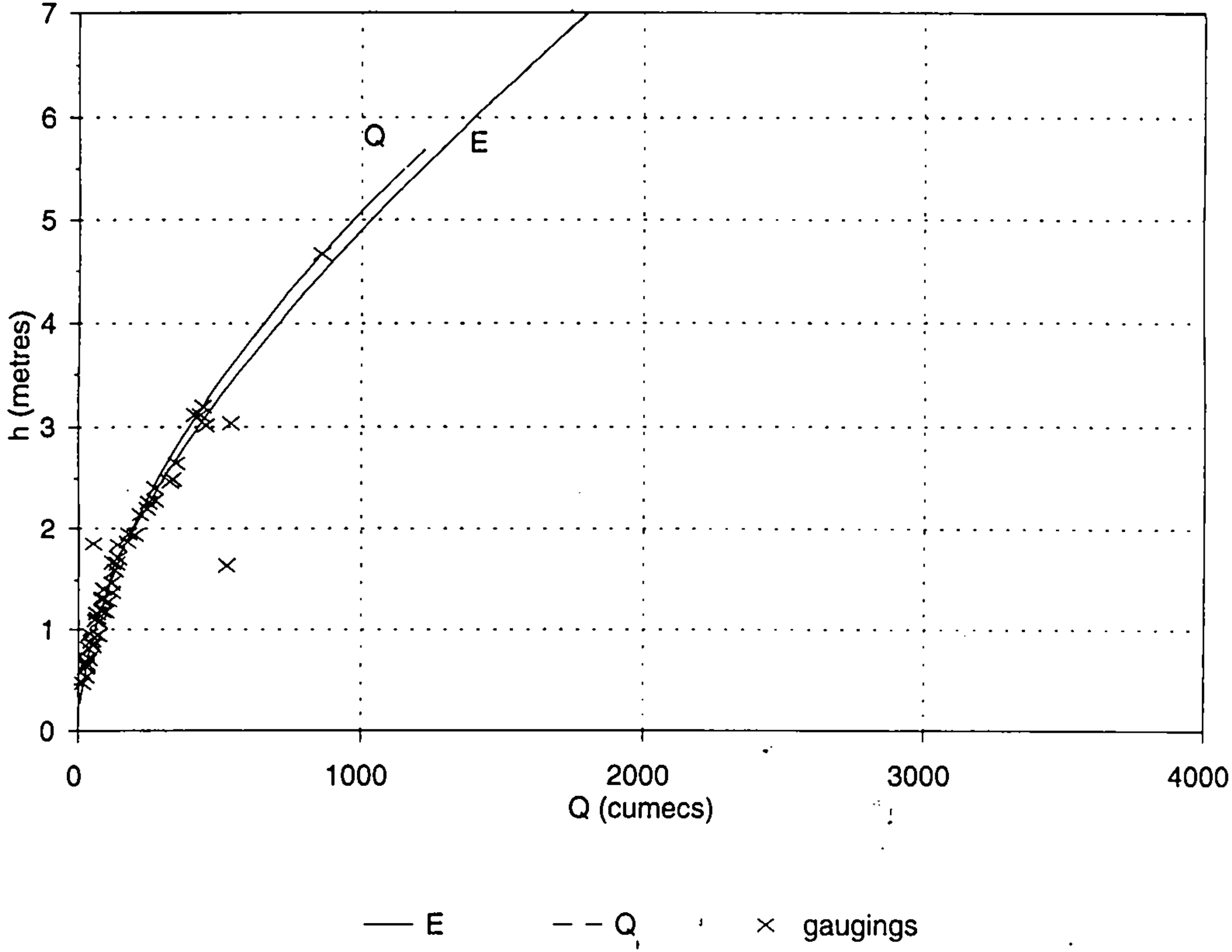


Figure A.9 Rating Curves - Garissa

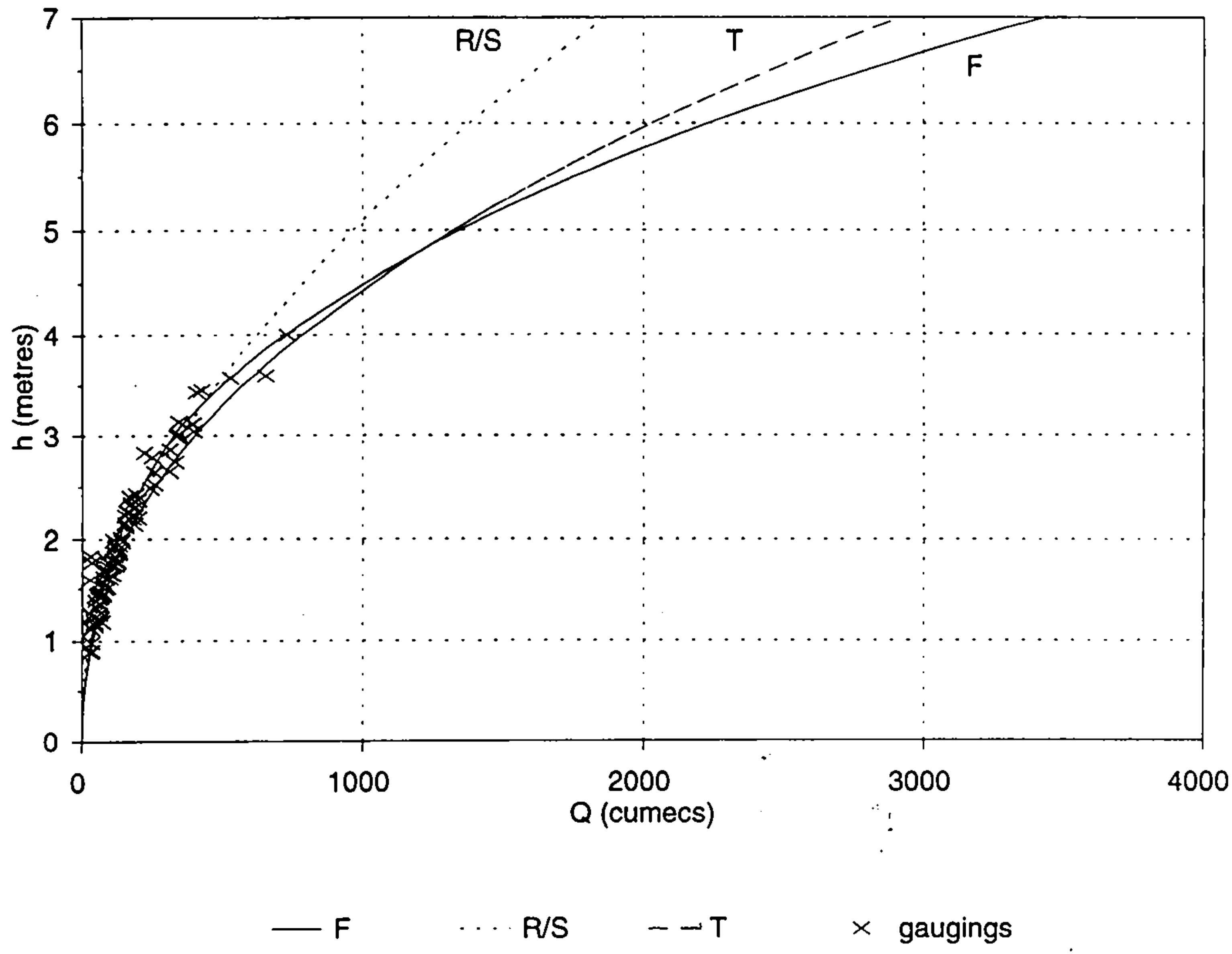


Figure A.10 Rating Curves - Garsen

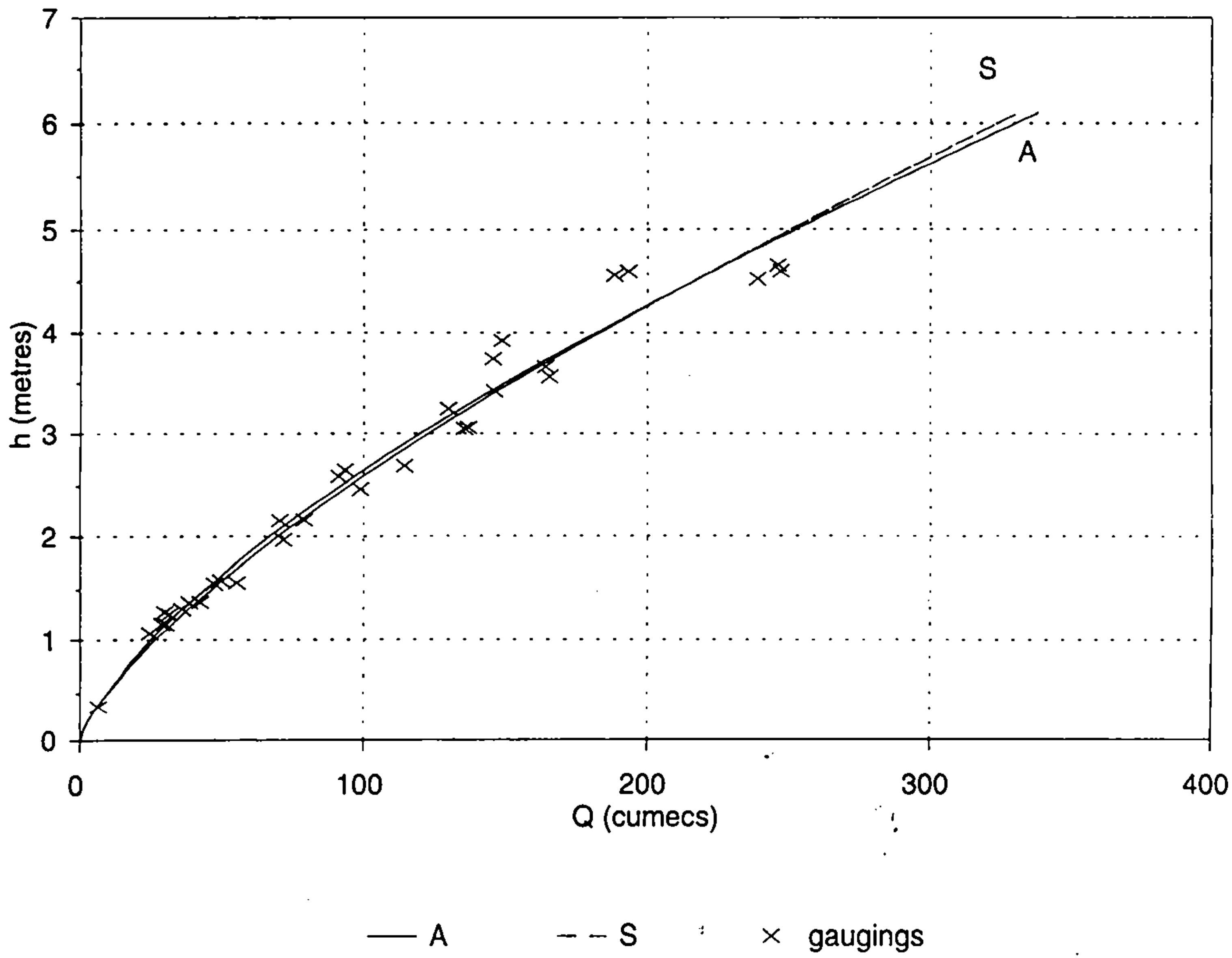


Figure A.11 Rating Curves - Garsen

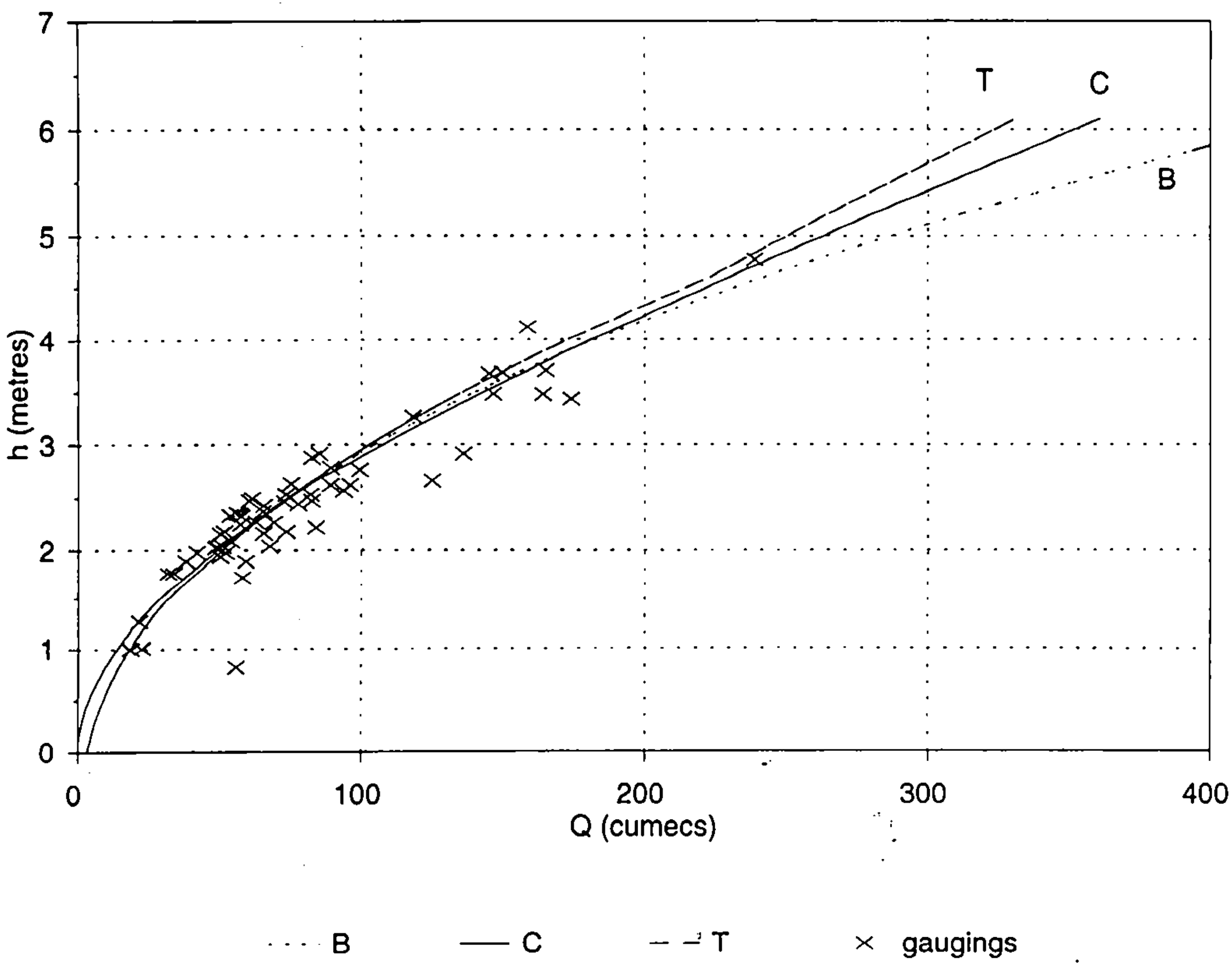


Figure A.12 Rating Curves - Nanigi

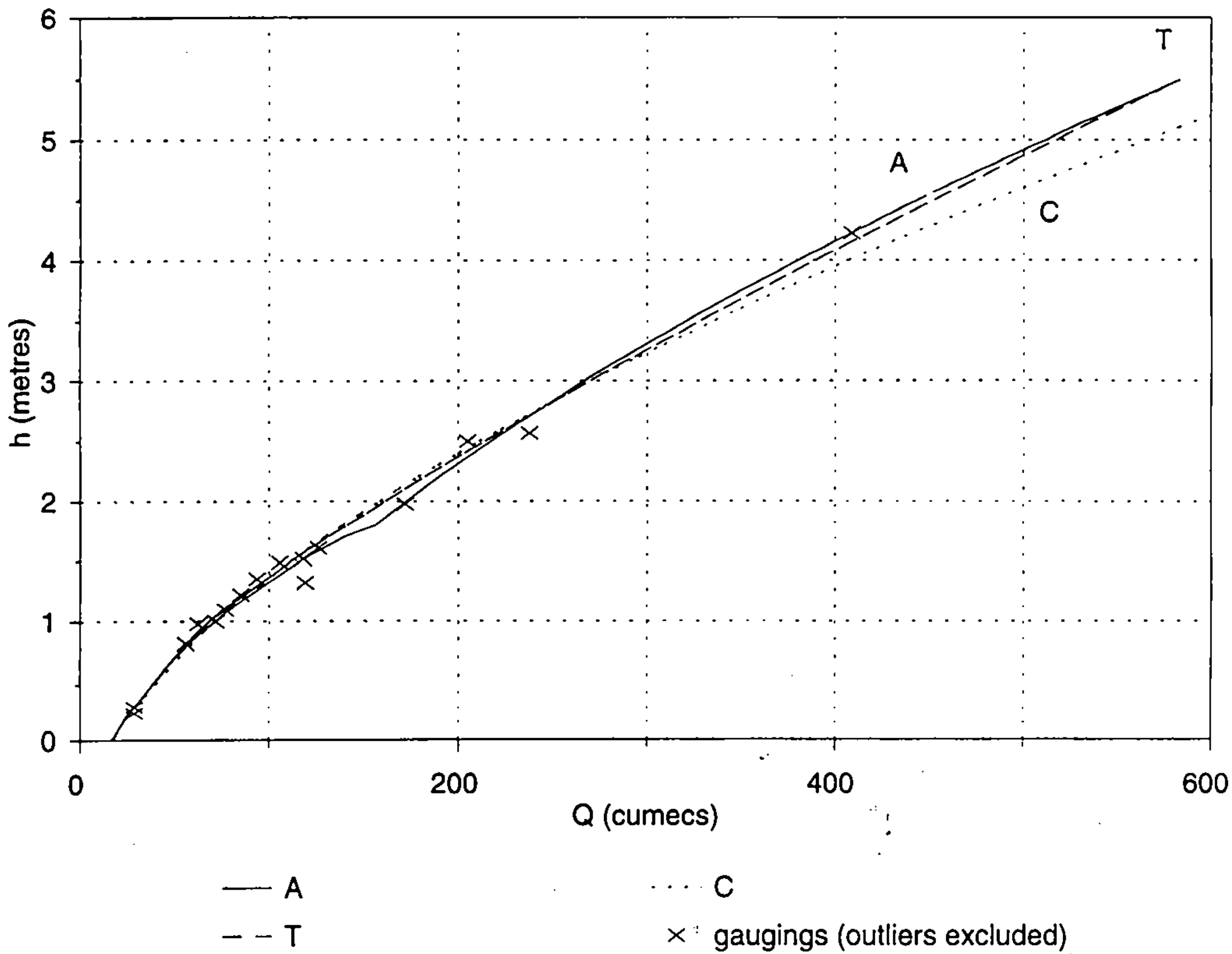


Figure A.13 Rating Curves - Nanigi

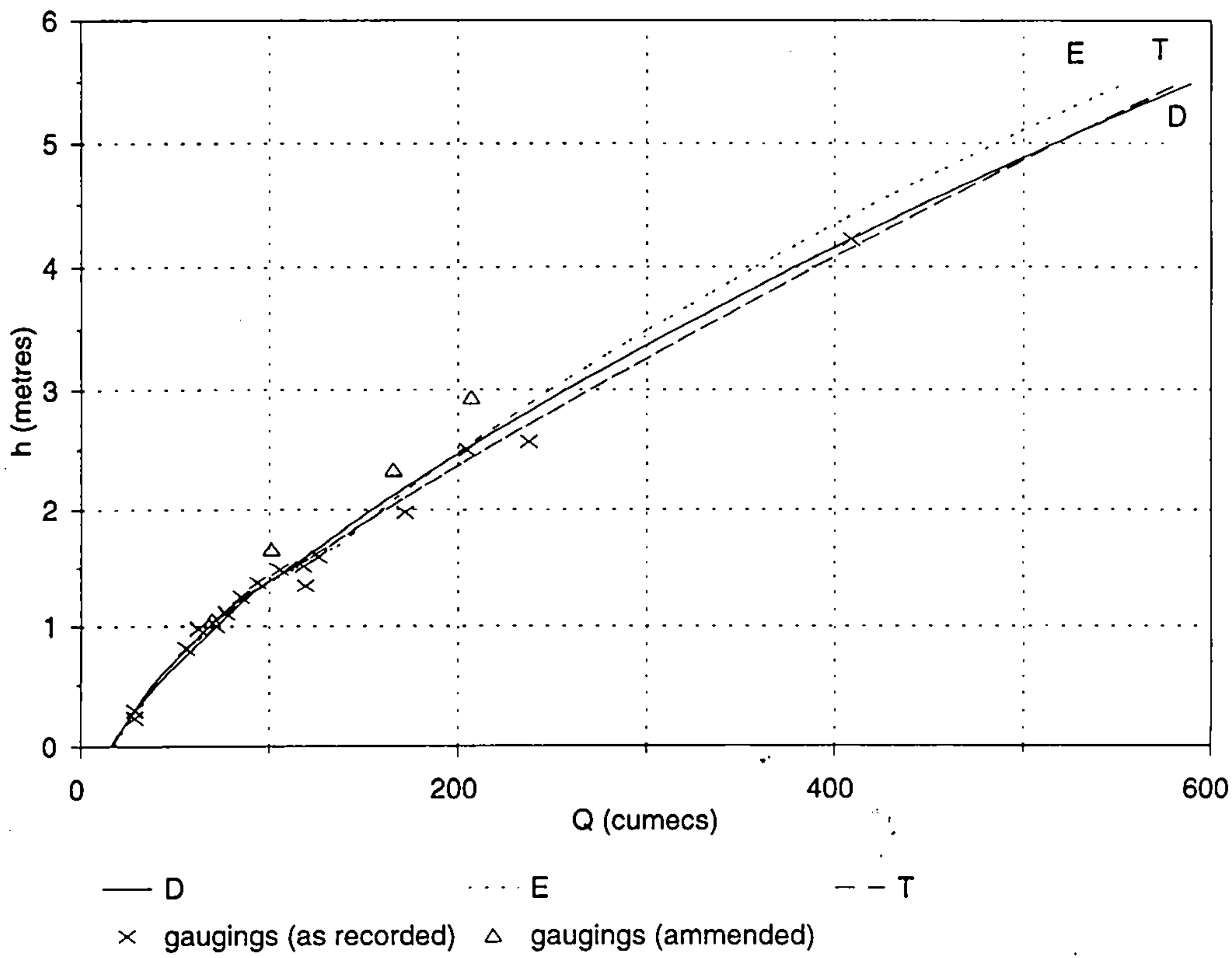
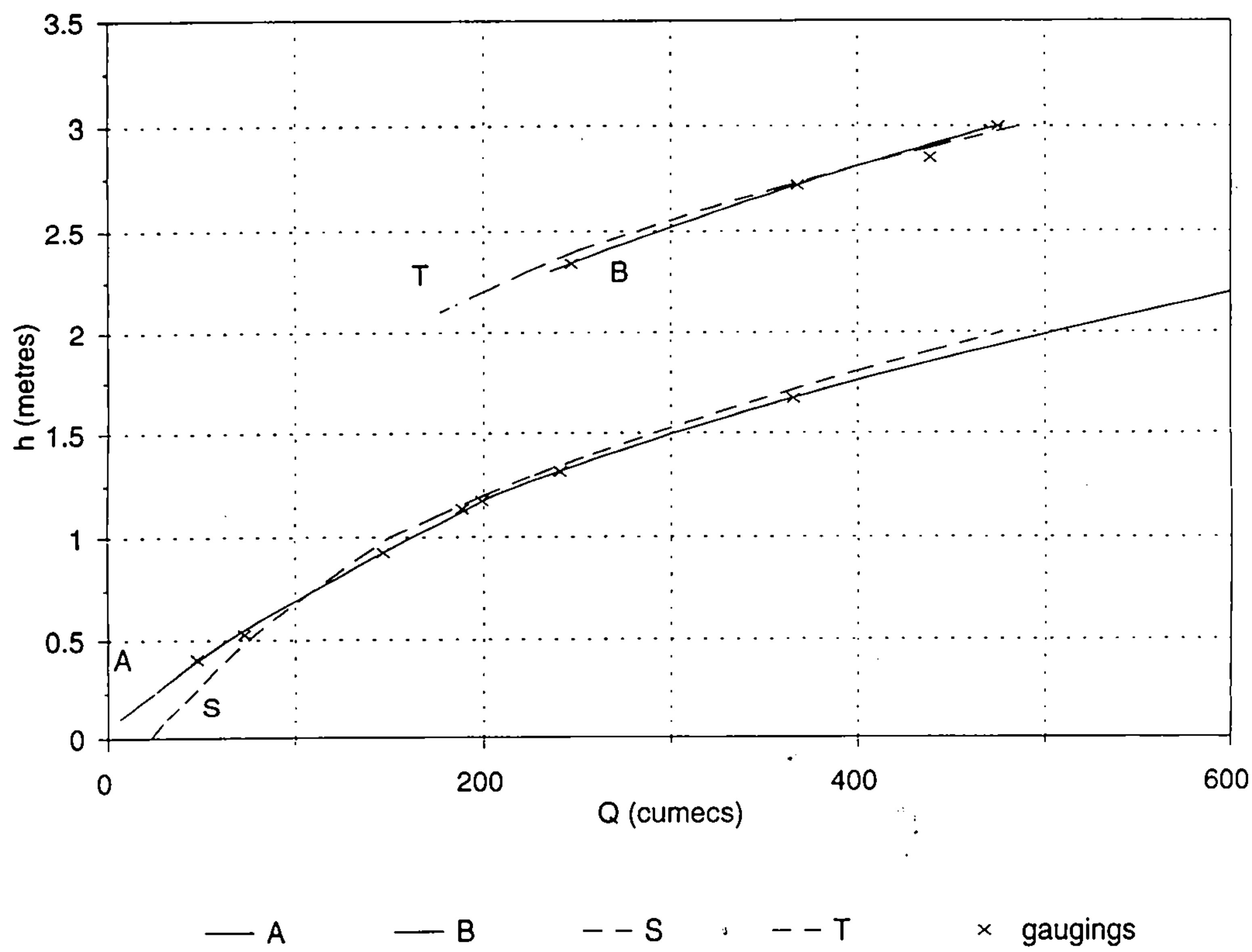


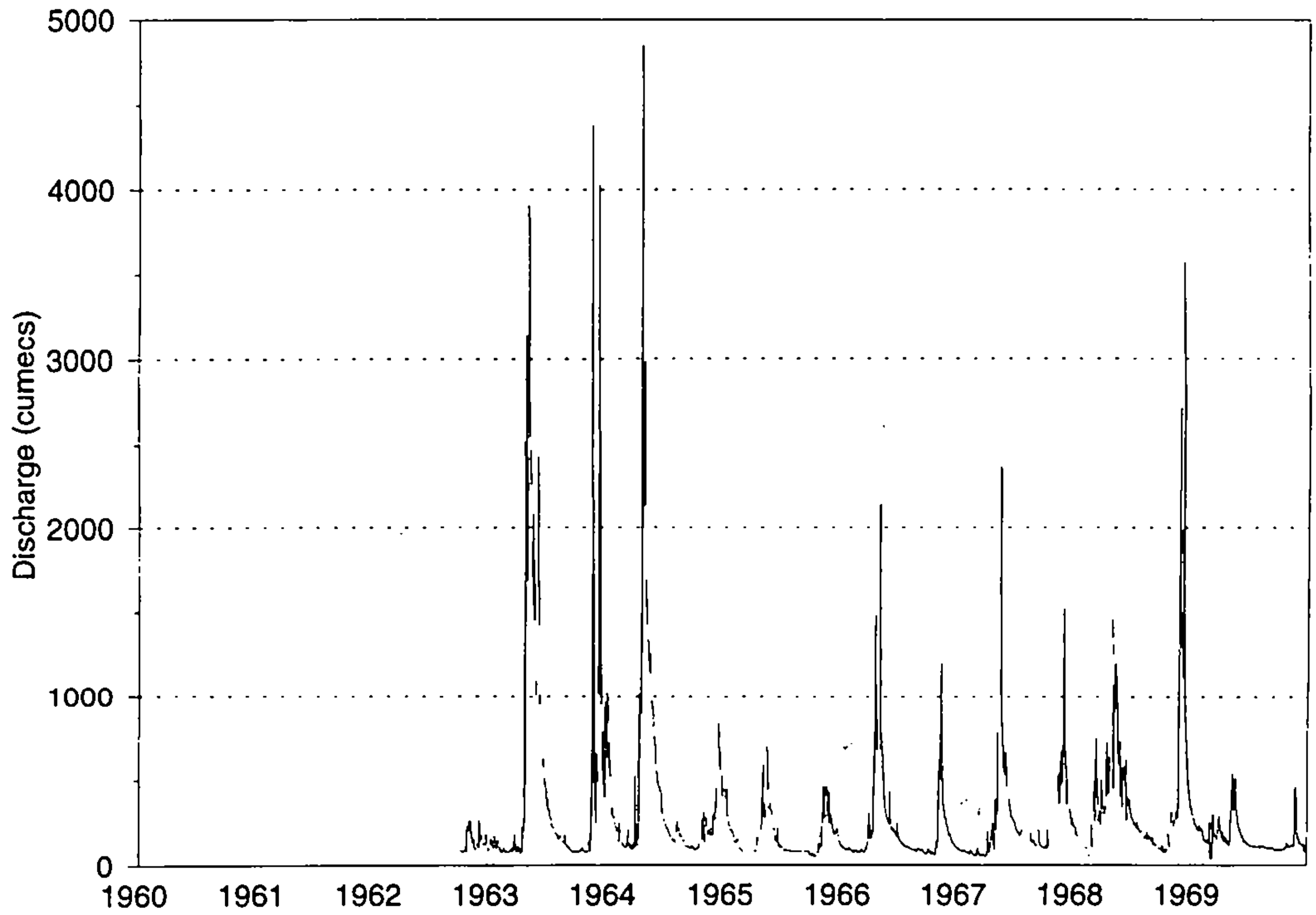
Figure A.14 Rating Curves - Saka



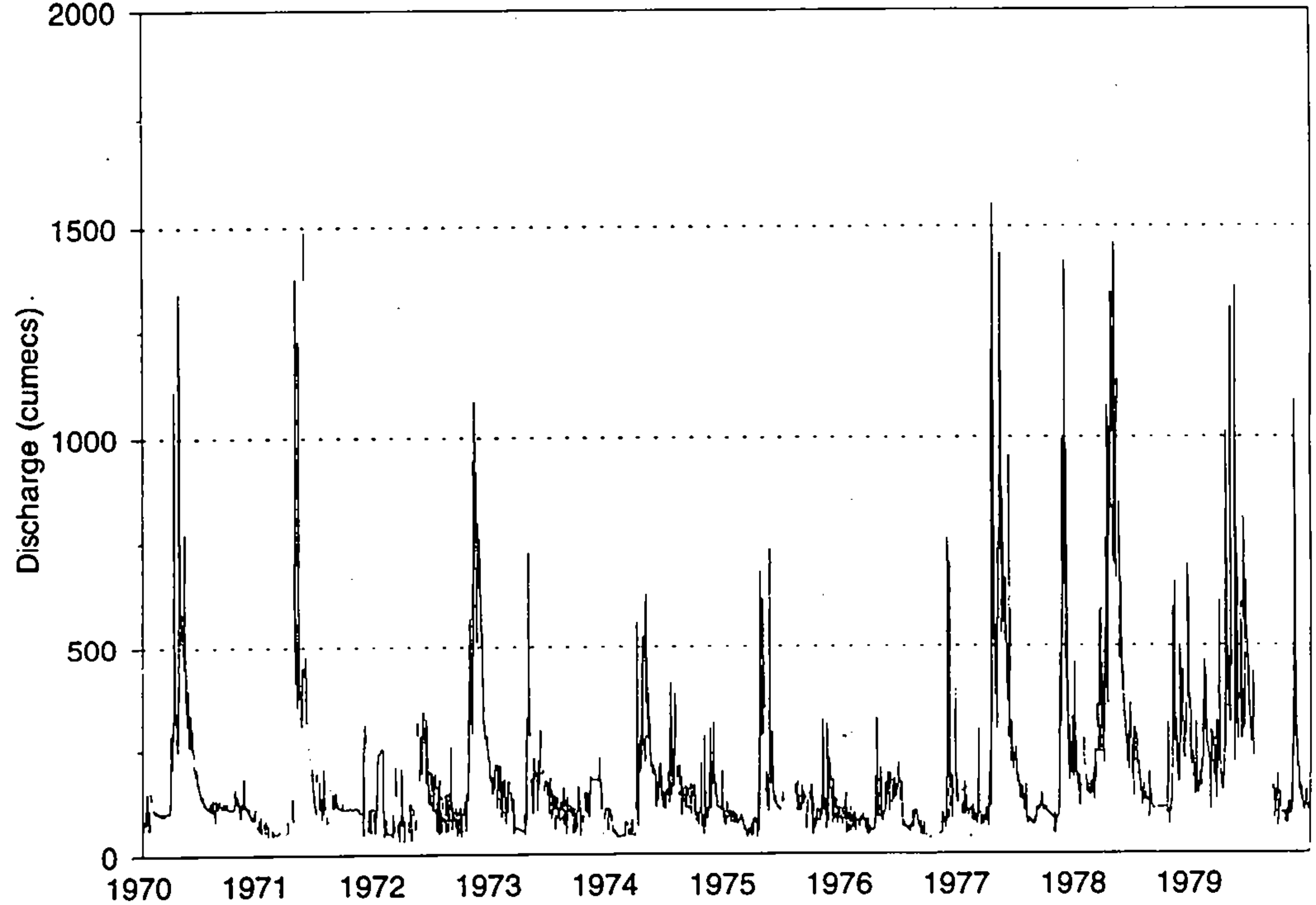
Appendix B - Daily Discharge Series

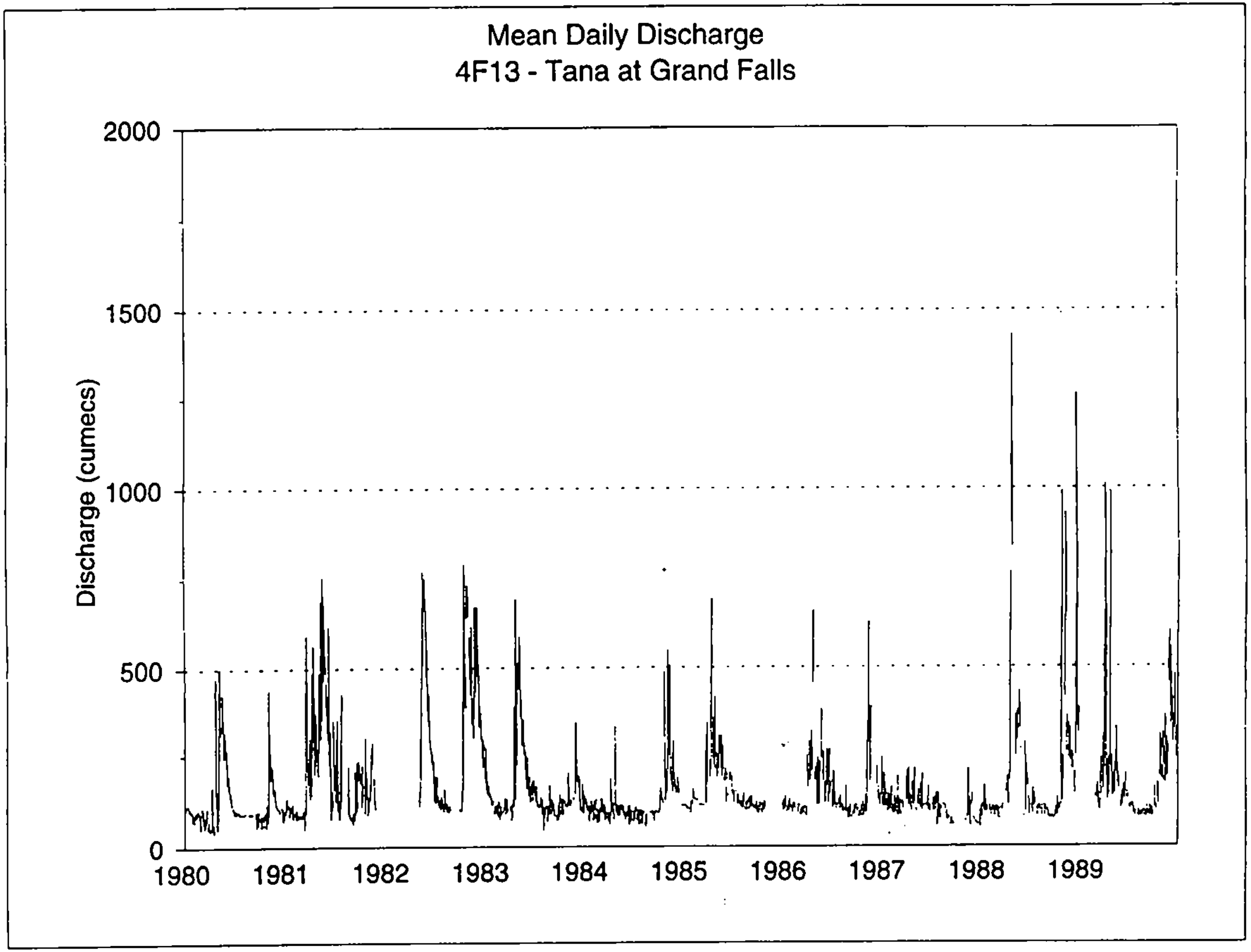
B.1 Plots of mean daily discharges

Mean Daily Discharge
4F13 - Tana at Grand Falls

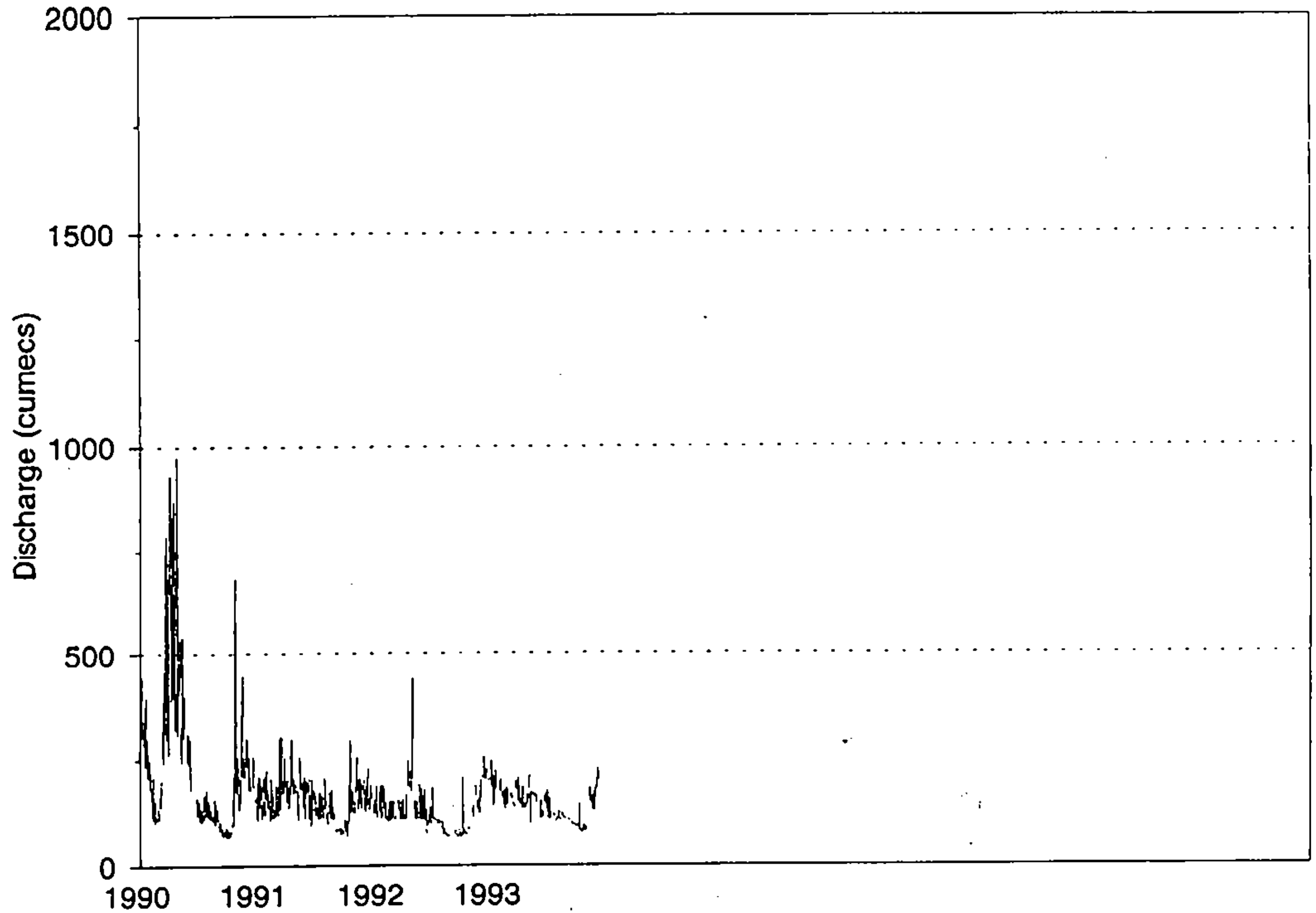


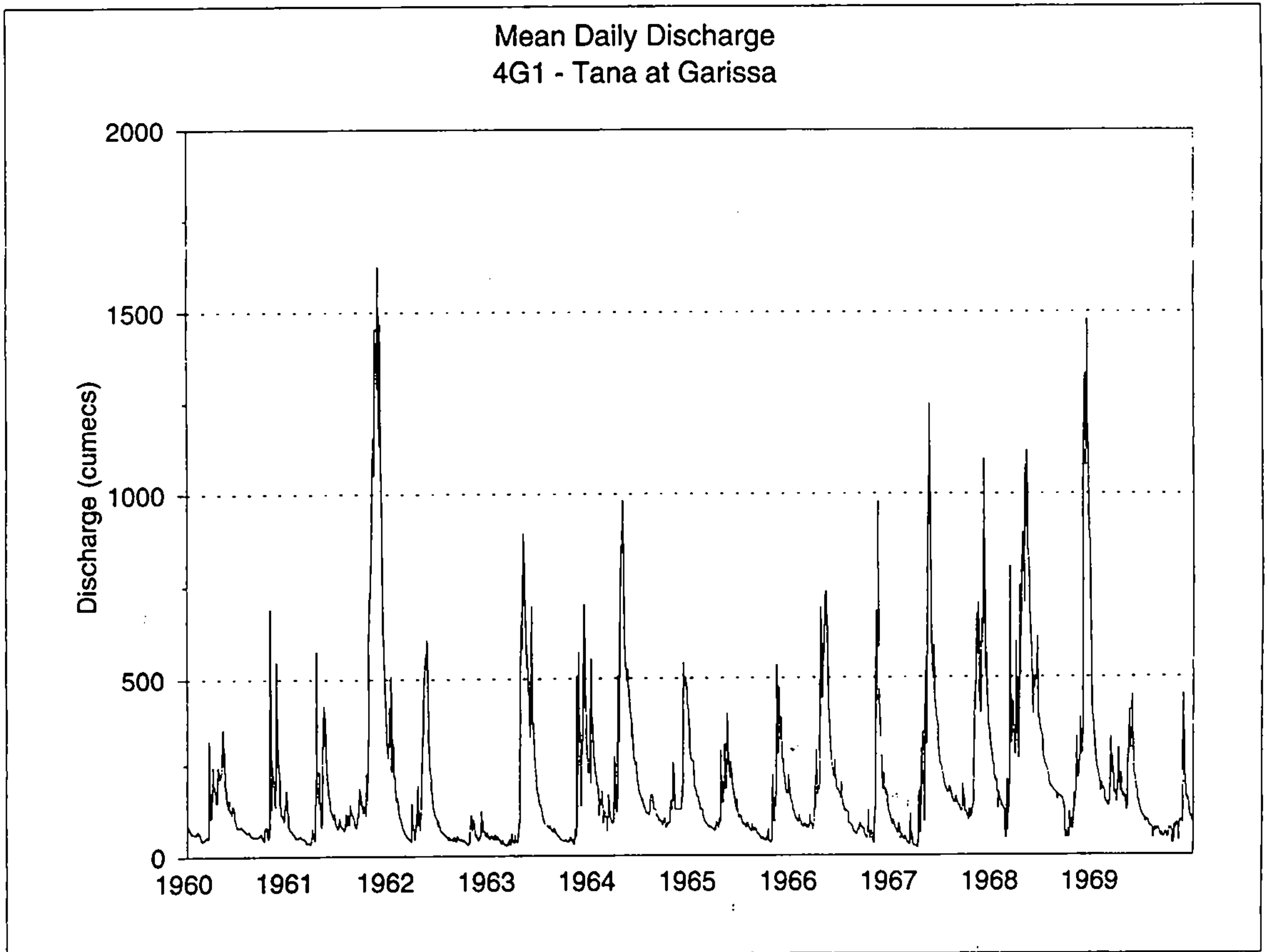
Mean Daily Discharge
4F13 - Tana at Grand Falls

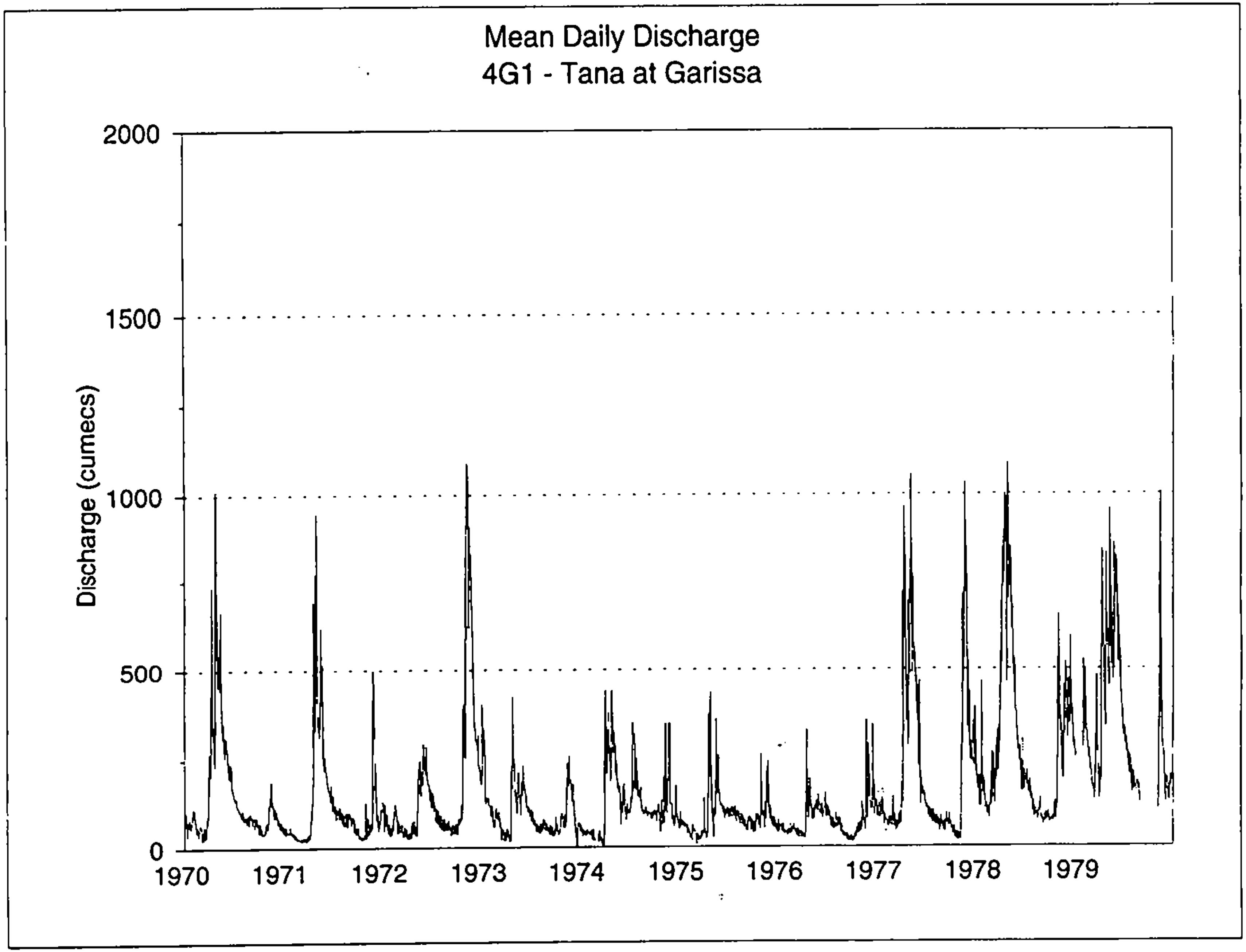



Mean Daily Discharge
4F13 - Tana at Grand Falls
Discharge (cumecs)
2000
1500
1000
500
0
1980
1981
1982
1983
1984
1985
1986
1987
1988
1989

Mean Daily Discharge
4F13 - Tana at Grand Falls

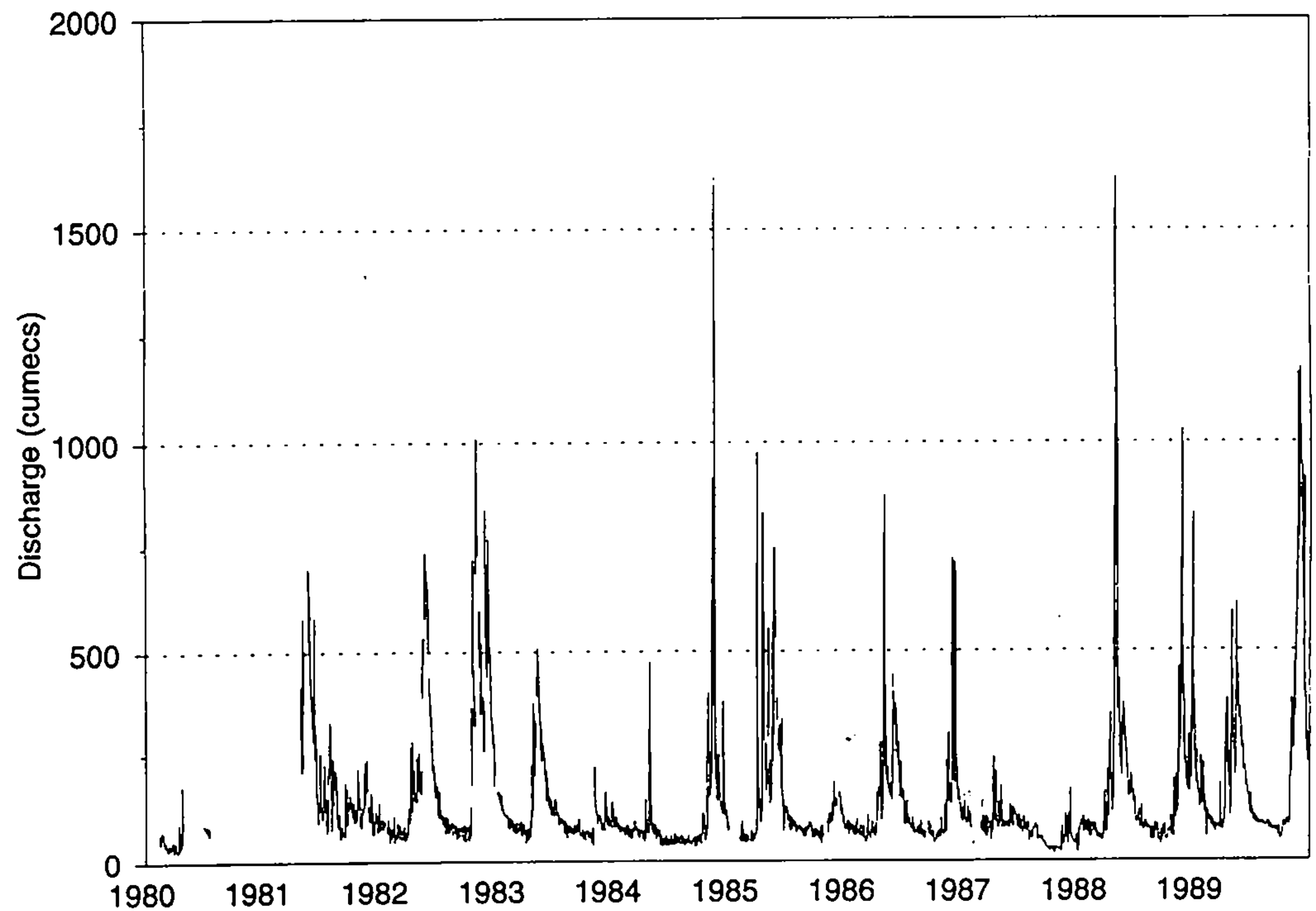


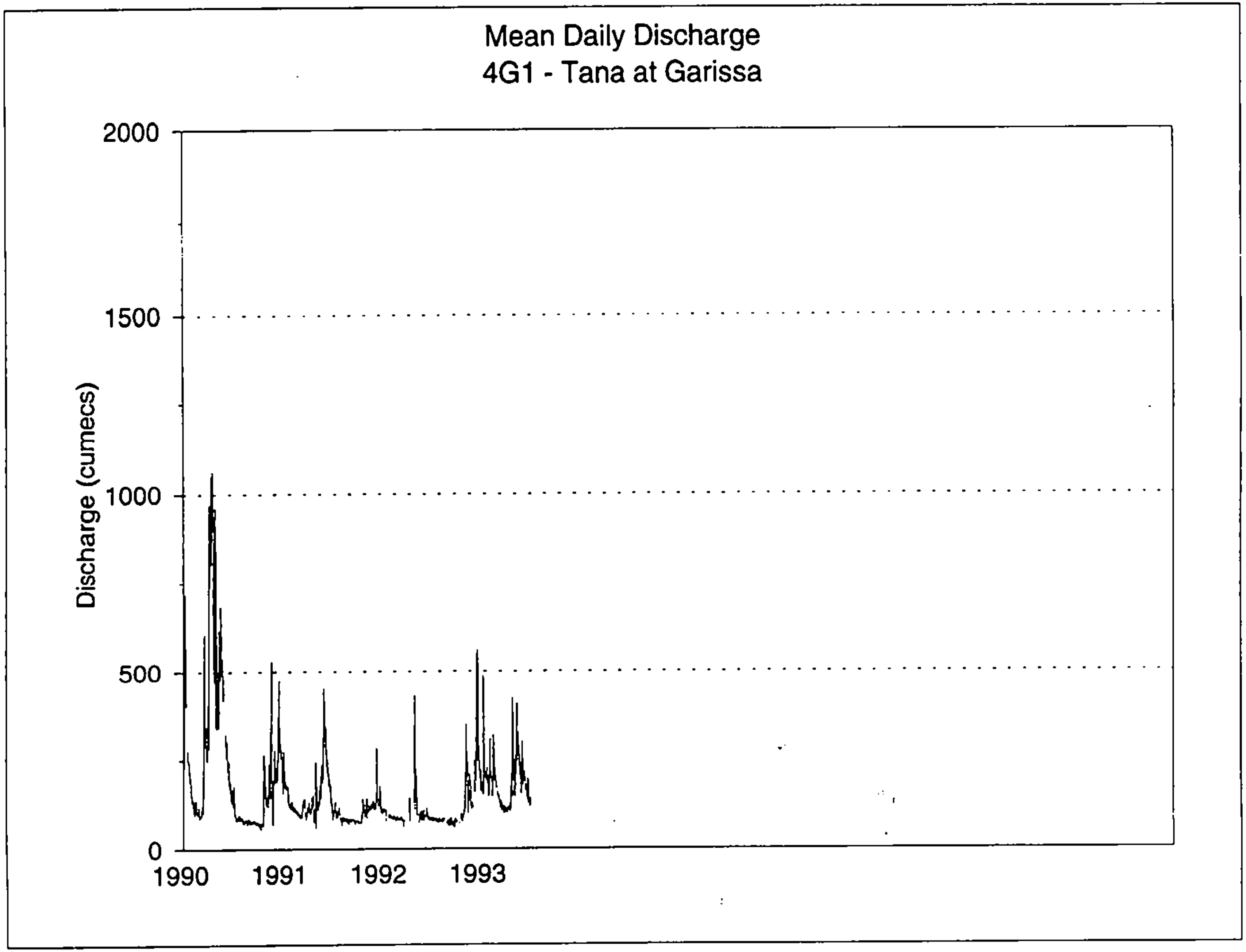

Mean Daily Discharge
4G1 - Tana at Garissa
Discharge (cumecs)
2000
1500
1000
500
0
1960
1961
1962
1963
1964
1965
1966
1967
1968
1969

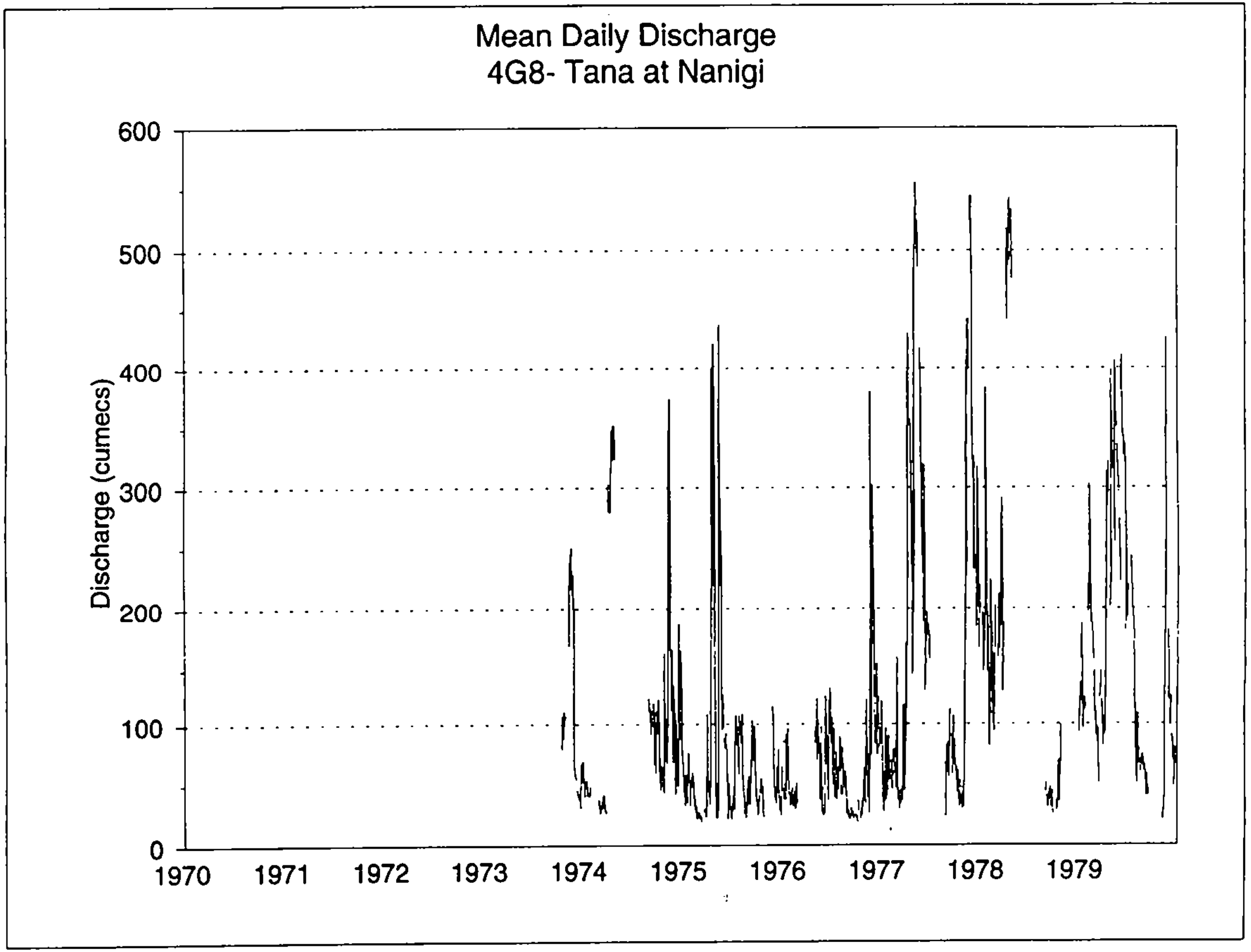


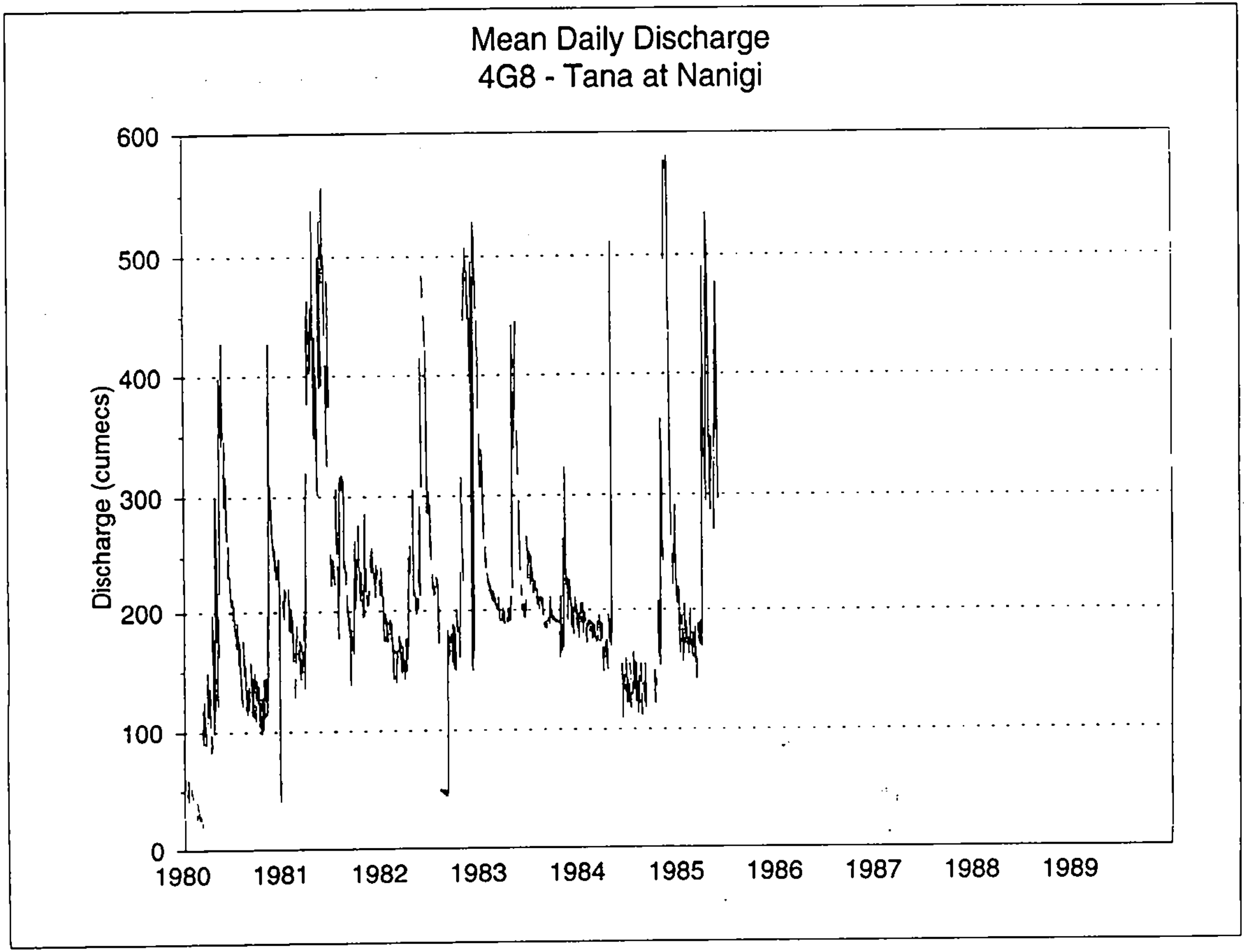
Mean Daily Discharge
4G1 - Tana at Garissa
Discharge (cumecs)
2000
1500
1000
500
0
1970
1971
1972
1973
1974
1975
1976
1977
1978
1979

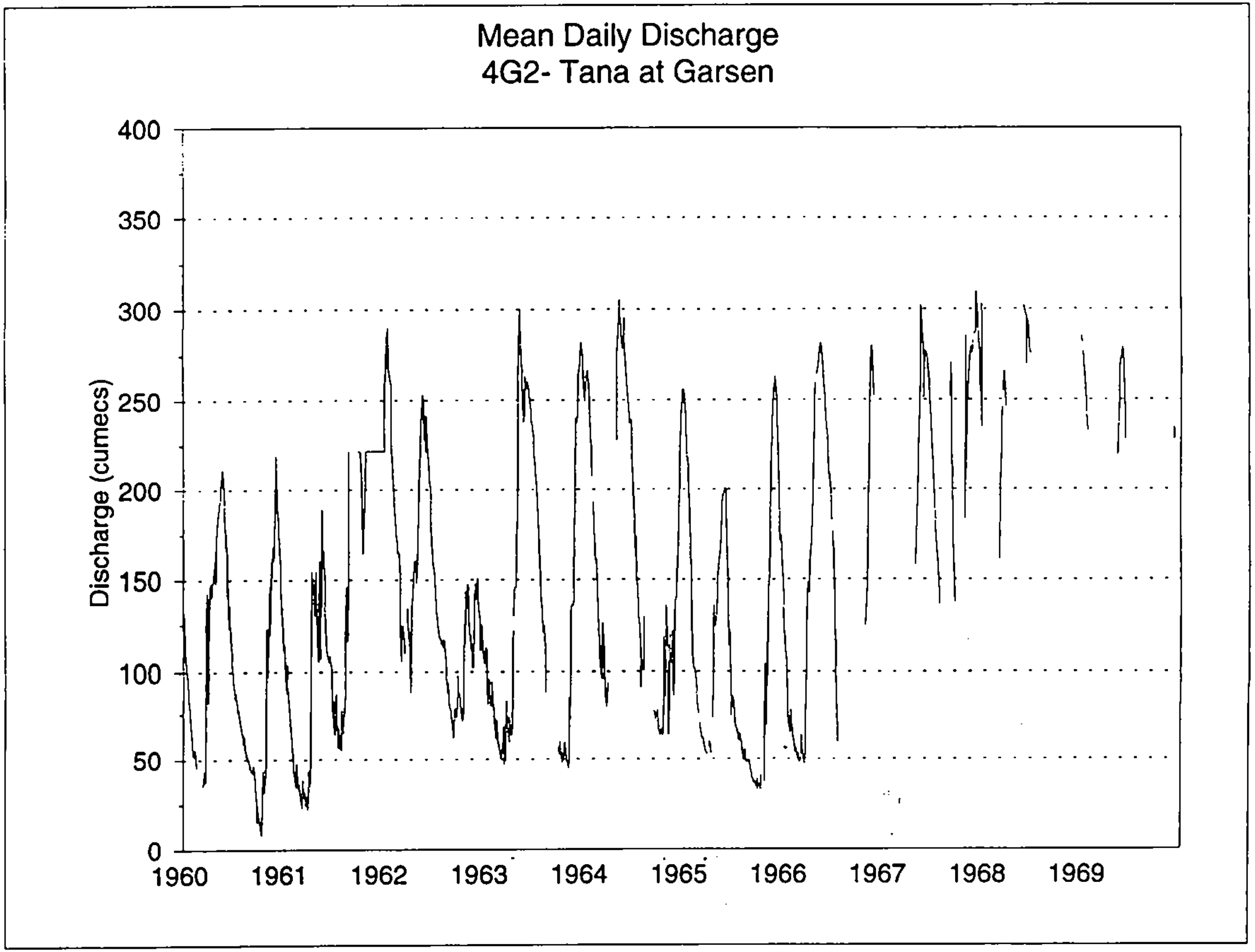
Mean Daily Discharge
4G1 - Tana at Garissa



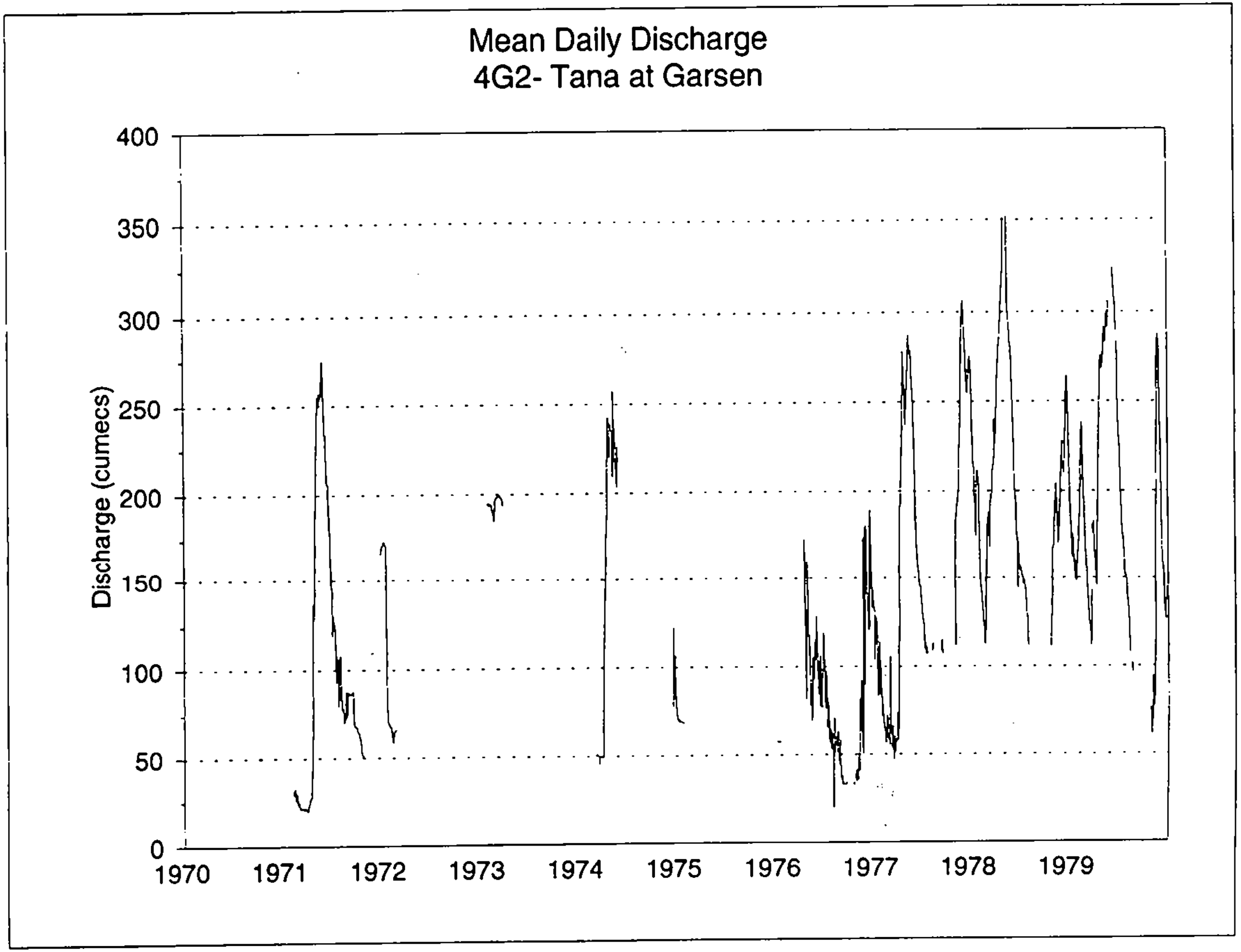

Mean Daily Discharge
4G1 - Tana at Garissa
Discharge (cumecs)
2000
1500
1000
500
0
1990
1991
1992
1993


Mean Daily Discharge
4G8- Tana at Nanigi
Discharge (cumecs)
600
500
400
300
200
100
0
1970
1971
1972
1973
1974
1975
1976
1977
1978
1979


Mean Daily Discharge
4G8 - Tana at Nanigi
Discharge (cumecs)
0
100
200
300
400
500
600
1980
1981
1982
1983
1984
1985
1986
1987
1988
1989

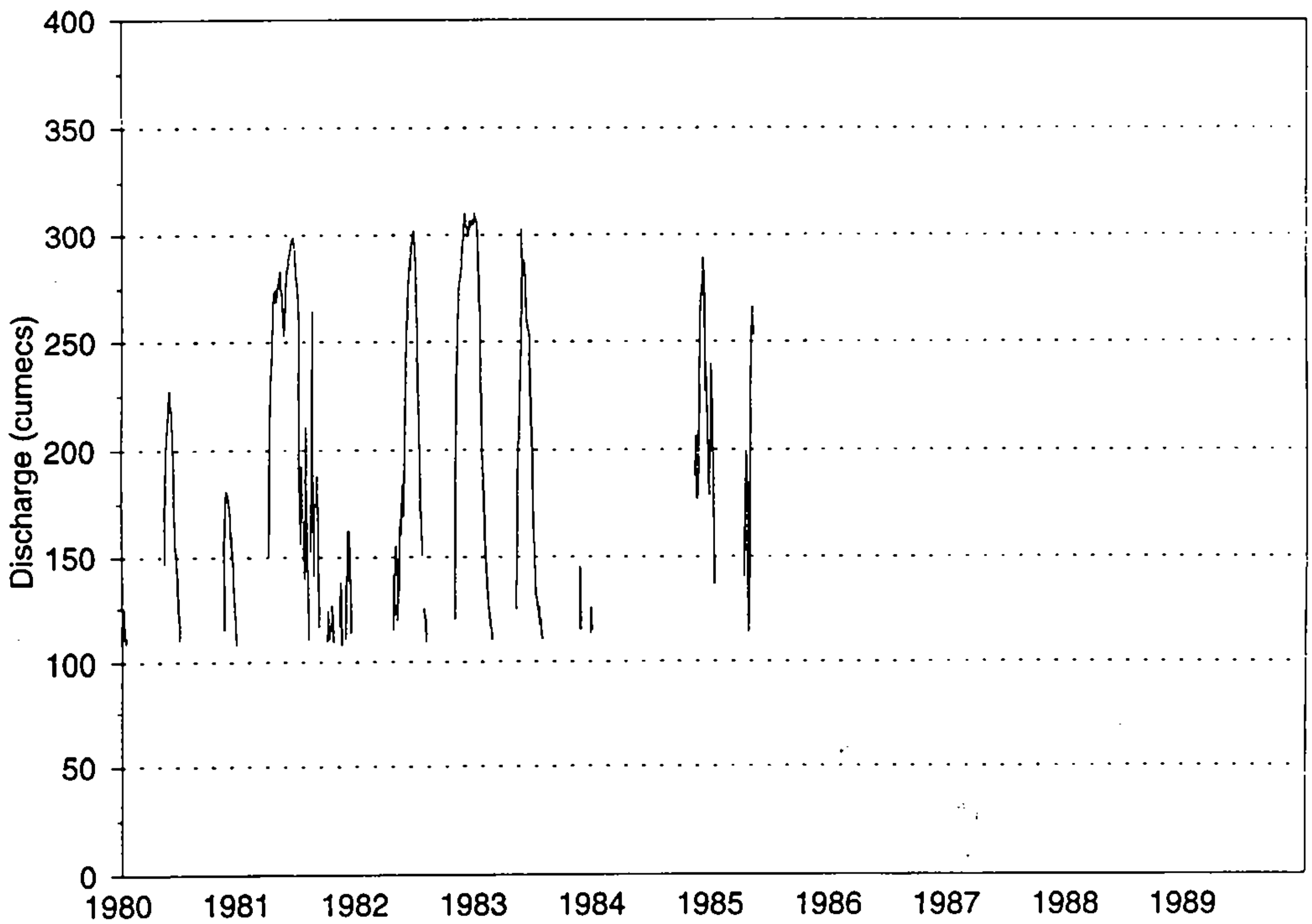


Mean Daily Discharge
4G2- Tana at Garsen
Discharge (cumecs)
400
350
300
250
200
150
100
50
0
1960
1961
1962
1963
1964
1965
1966
1967
1968
1969



Mean Daily Discharge
4G2- Tana at Garsen
Discharge (cumecs)
400
350
300
250
200
150
100
50
0
1970
1971
1972
1973
1974
1975
1976
1977
1978
1979

Mean Daily Discharge
4G2- Tana at Garsen



B.2 Comparison of mean monthly discharges

Figure B.5 - Mean Monthly Flows
Tana at Grand Falls

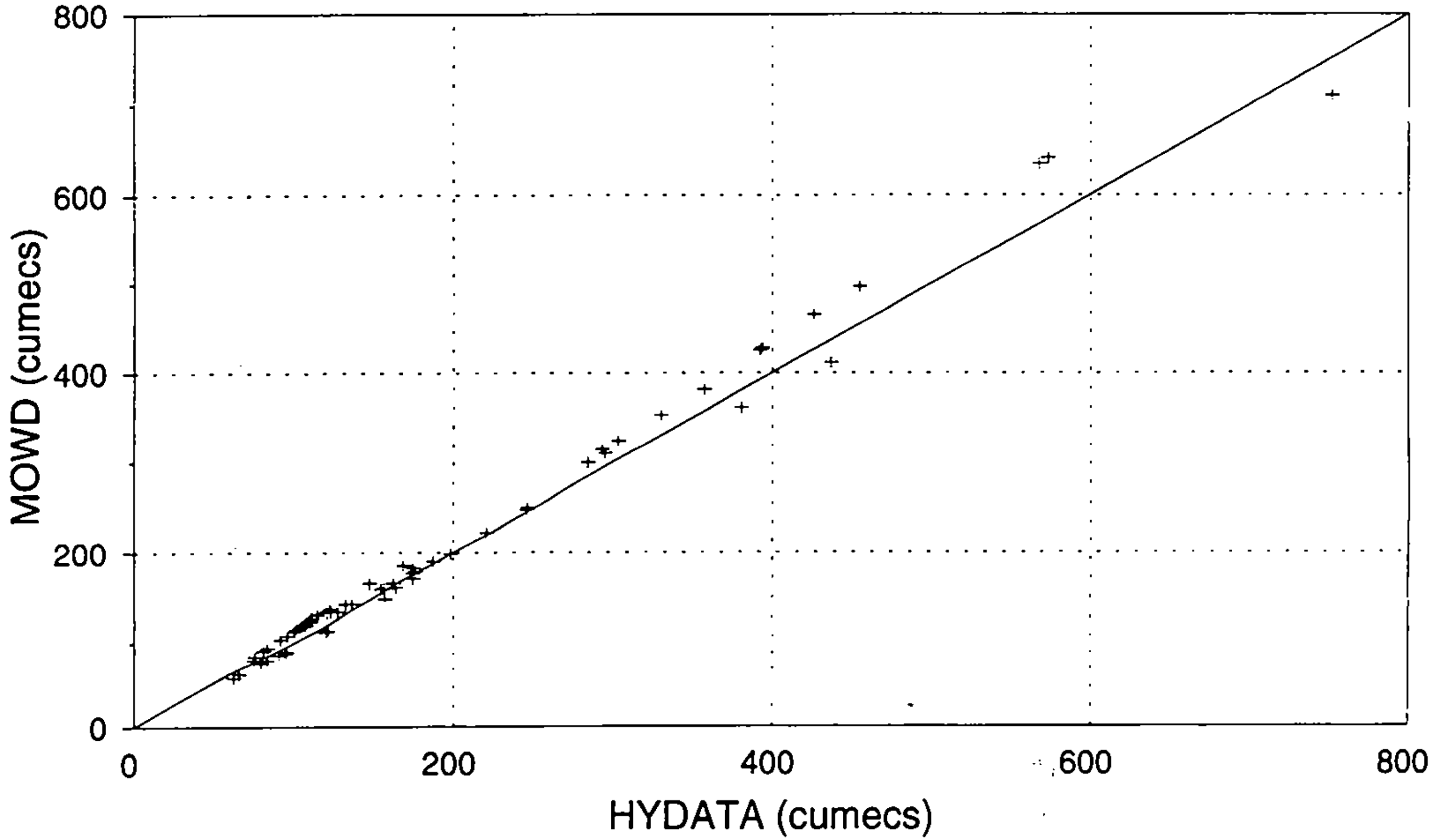
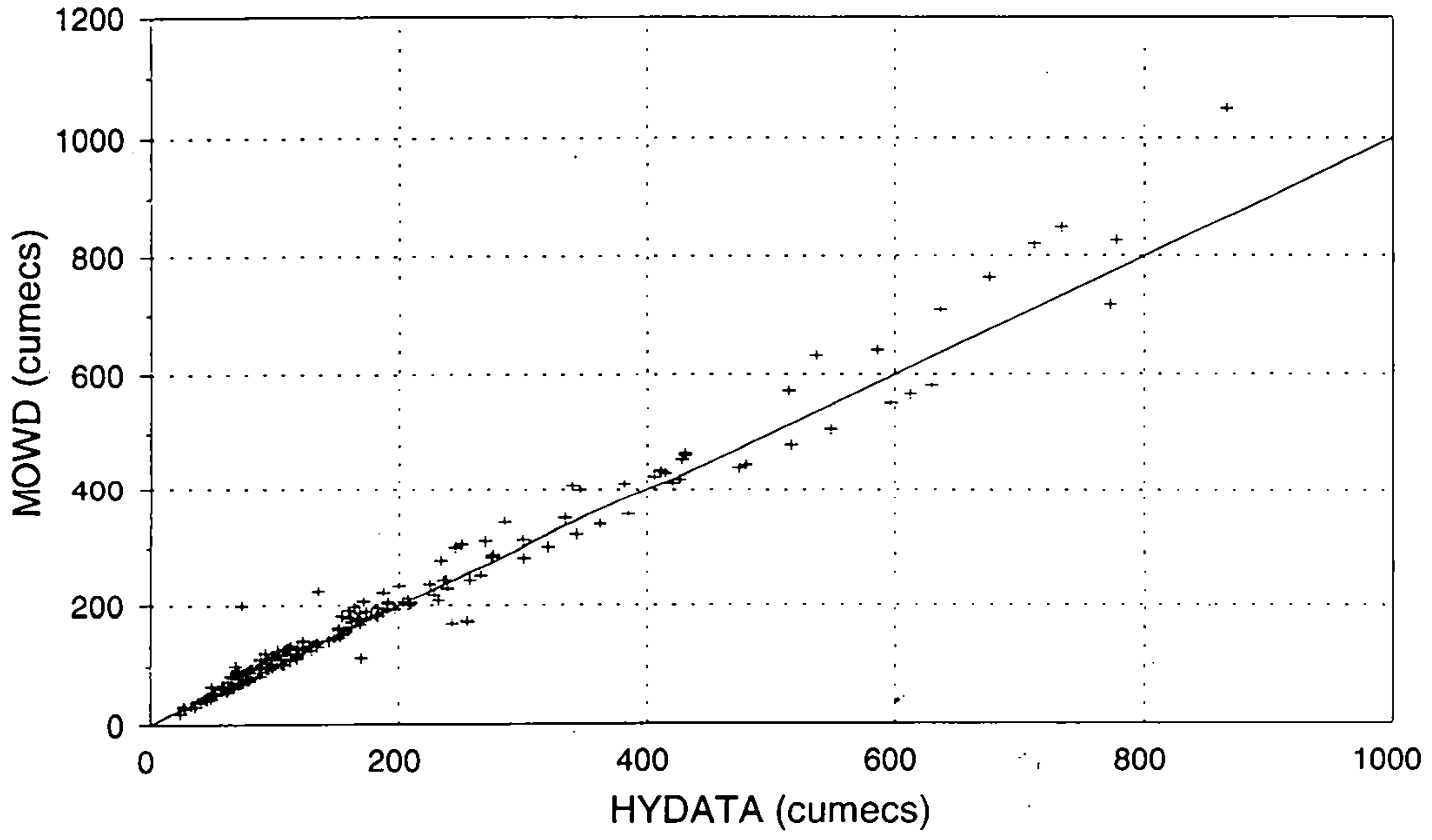


Figure B.6 - Mean Monthly Flows
Tana at Garissa



Appendix C - Characteristics of Flood Events Analysed

C.1 Characteristics of floods > 500 cumecs at Garissa

Start Date	Peak flow (cumecs)	Duration (days)	Cum vol (MCM)
24/04/63	894.65	29	1638.64
06/12/63	701.74	5	277.66
10/04/64	506.18	3	130.1
17/04/64	982.56	25	1591.26
14/04/66	693.32	6	317.3
24/04/66	740.03	18	991.53
02/11/66	978.7	11	660.77
06/05/67	1247.31	22	1554.13
10/11/67	657.6	2	113.08
19/11/67	1097.15	22	1307.82
01/03/68	798.6	3	167.92
24/03/68	594.86	3	142.65
05/04/68	1119.5	47	3208.59
30/05/68	504.73	2	86.97
06/06/68	608.73	5	243.49
10/04/70	733.27	3	160.57
25/04/70	1010.81	8	509.66
06/05/70	657.19	10	446.7
22/04/71	686.53	5	247.56
29/04/71	946.75	8	422.91
20/05/71	616.68	6	254.81
01/11/72	1089	29	1968.38
07/04/77	963.85	10	623.85
27/04/77	1054.72	23	1378.54
12/11/77	1032.09	17	1095.94
31/03/78	1088.05	47	3070.38
29/10/78	648.09	5	201.54
02/02/79	528.32	1	167.23
10/04/79	845.78	10	546.55
26/04/79	835.4	9	507.93
01/05/79	958.49	21	1186.92
24/05/79	860.45	26	1477.53
11/11/79	1004.48	6	436.33
24/05/81	700.25	7	365.41
19/05/82	740.02	18	960.85
28/11/82	840.04	6	322.46
08/12/82	770.92	7	334.39
09/11/84	1631.48	9	620.35
16/05/85	519.26	1	87.81
19/05/85	678.13	1	58.59
21/05/85	750.41	6	341.6
24/04/88	1626.2	1	874.35
20/11/88	1029.75	6	360.09
23/12/88	525.21	1	85.08
27/12/88	830.77	2	115.15
17/11/89	1173.61	27	1948.68
05/01/90	716.38	4	220.22
04/04/90	1061.15	26	1901.33
01/05/90	680.54	7	348.86
10/05/90	680.54	14	668.97
14/12/92	551.13	1	47.62
19/12/92	562.67	1	48.61

C.2 Characteristics of floods events at Grand Falls and Garissa

Start Date at Garissa	Grand Falls flood statistics Peak flow (cumecs)	Duration (days)	Cum vol (MCM)	Lag (days)	Garissa flood statistics Peak flow (cumecs)	Duration (days)	Cum vol (MCM)
Type A floods							
14/04/66	1476.7	6	617.4	1	693.3	6	317.3
13/05/67	2377.9	15	1350.9	3	1247.3	15	1014.1
22/11/68	2720.14	12	1616.1	2	1332.5	12	1138.4
04/12/68	3570.4	21	1916.9	2	1479.6	21	1756
10/04/70	1108.8	4	264	2	733.2	4	198.4
09/04/77	1554.3	8	581.8	1	963.9	8	523.1
01/05/77	1436.9	9	717.3	2	1054.7	9	615.8
10/05/77	854.7	10	579.8	2	780.4	10	545.3
06/04/78	1342.6	19	1415.4	1	1002.7	19	1249
26/04/78	1460.1	21	1570.5	1	1088.1	21	1410.1
26/04/79	1306.2	8	518.8	1	835.4	8	461.8
Type C floods							
02/11/66	1208	11	692.5	2	978.7	11	660.8
19/11/67	1523.8	20	1198.5	2	1097.2	20	1192.5
25/04/70	1342.6	8	520.6	1	1010.8	8	509.7
06/05/70	559.9	5	224.8	2	504.9	5	217.2
13/05/70	774.7	3	156.6	2	657.2	3	144.7
12/11/77	993.6	4	214.8	1	703.4	4	203.2
16/11/77	1417.2	13	895.8	1	1032.1	13	869.9
09/05/79	1355.5	14	729.9	1	958.5	14	795.9
11/11/79	1085.3	6	376.2	1	1004.5	6	436.3
24/05/81	681.4	7	336.6	1	700.3	7	365.4
22/05/82	769.7	15	857.1	1	740	15	813.2
09/12/82	671.9	8	358.1	2	770.9	8	374.7
Type D floods							
01/11/72	1085.3	9	578	1	1089	9	626
14/11/72	802.7	16	864	1	910.6	16	974
11/06/79	655.3	8	375.4	2	641.3	8	387.3
28/11/82	671.9	6	243.8	2	840	6	322.5
09/11/84	506.3	9	249.2	1	1631.5	9	620.4

Appendix D - Characteristics of Rainfall Events Analysed

D.1 Rainfall event characteristics

Start date of flood at Garissa	Nyambene Hills Duration (days)	Peak rainfall (mm)	Total rainfall (mm)	Mean per day (mm)	Nyambene Foothills Duration (days)	Peak rainfall (mm)	Total rainfall (mm)	Mean per day (mm)	d/s Grand Falls Duration (days)	Peak rainfall (mm)	Total rainfall (mm)	Mean per day (mm)	Garissa Duration (days)	Peak rainfall (mm)	Total rainfall (mm)	Mean per day (mm)
Type A floods																
14/04/66	5	84.7	184.9	37.0	8	2.1	2.1	0.3	8	9.9	24.2	3.0	5	15.1	16.1	3.2
13/05/67	8	62.8	177.7	22.2	m	m	m	m	m	m	m	m	8	54.1	65.8	8.2
22/11/68	9	78.1	394	43.8	m	m	m	m	m	m	m	m	9	0	0	0.0
04/12/68	6	113.3	444.1	74.0	m	m	m	m	m	m	m	m	6	50.7	158.4	26.4
10/04/70	4	43.1	111.7	27.9	m	m	m	m	m	m	m	m	4	14.1	38.2	9.6
09/04/77	4	77.5	245.8	61.5	4	0	0	0.0	m	m	m	m	4	13.7	15.5	3.9
01/05/77	4	71.9	231.7	57.9	4	42.3	110.65	27.7	4	39.9	57.3	14.3	4	106.9	106.9	26.7
10/05/77	6	75.7	226.6	37.8	6	12.8	26.6	4.4	6	15	42.1	7.0	6	1.4	1.4	0.2
06/04/78	3	55.9	150.5	50.2	3	0	0	0.0	3	4	4	1.3	3	0	0	0.0
26/04/78	15	53.9	423.3	28.2	15	24.1	69.5	4.6	15	20	39.5	2.6	15	0	0	0.0
26/04/79	4	19.4	59.3	14.8	4	44.3	47.6	11.9	4	18.2	22.1	5.5	4	0	0	0.0
Type C floods																
02/11/66	3	69.8	163.9	54.6	3	19.6	55.8	18.6	3	27.4	41.6	13.9	3	25.8	38.3	12.8
19/11/67	3	6.8	9.8	3.3	3	0	0	0.0	3	2.7	3.6	1.2	m	m	m	m
25/04/70	2	26.6	51.7	25.9	2	20.3	30.9	15.5	m	m	m	m	2	6.7	11.4	5.7
06/05/70	9	137.4	627.5	69.7	m	m	m	m	m	m	m	m	9	65.8	96.9	10.8
13/05/70	17	100.4	550.9	32.4	m	m	m	m	m	m	m	m	17	46.9	206.4	12.1
12/11/77	3	71.9	139.7	46.6	3	24.3	32.5	10.8	m	m	m	m	3	0	0	0.0
16/11/77	3	5.6	10.3	3.4	3	0	0	0.0	m	m	m	m	3	0	0	0.0
09/05/79	3	21	21	7.0	3	0	0	0.0	m	m	m	m	3	0	0	0.0
11/11/79	3	84.6	165.2	55.1	3	19.7	24.3	8.1	m	m	m	m	3	3.6	4.2	1.4
24/05/81	12	47	312.5	26.0	12	44.9	133.8	11.2	3	14	18.3	6.1	12	12.6	32	2.7
22/05/82	10	70.6	103.6	10.4	10	0	0	0.0	12	87.7	230.6	19.2	10	0	0	0.0
09/12/82	11	34.9	127.3	11.6	11	0.6	1.9	0.2	11	2.7	4.9	0.4	11	0	0	0.0
Type D floods																
01/11/72	4	41.1	97.9	24.5	4	25.5	46.5	11.6	4	74.2	124.7	31.2	4	40	52.3	13.1
14/11/72	7	134.4	369.1	52.7	7	93.8	141	20.1	m	m	m	m	7	9.5	23.7	3.4
11/06/79	15	46.7	253.9	16.9	15	53.3	61.8	4.1	m	m	m	m	15	5.5	8.8	0.6
09/11/84	10	75.2	351.7	35.2	10	53.6	141.5	14.2	10	80.6	205.2	20.5	10	89.6	154.5	15.5

D.2 Median rainfall characteristics

	Nyambene Hills				Nyambene Foothills				d/s Grand Falls				Garissa			
	Duration (days)	Peak rainfall (mm)	Total rainfall (mm)	Mean per day (mm)	Duration (days)	Peak rainfall (mm)	Total rainfall (mm)	Mean per day (mm)	Duration (days)	Peak rainfall (mm)	Total rainfall (mm)	Mean per day (mm)	Duration (days)	Peak rainfall (mm)	Total rainfall (mm)	Mean per day (mm)
Common events																
Type A	4.5	63.9	205.8	37.4	5	18.5	37.1	4.5	5	16.6	31.9	4.3	4.5	0.7	0.7	0.1
Type C/D	10	58.4	145.6	25.3	10	22.6	51.2	11.4	7	50.8	83.2	16.5	10	19.2	35.2	7.7
All events																
Type A	5	71.9	226.6	37.8	4	12.8	26.6	4.4	5	16.6	31.9	4.3	5	13.7	15.5	3.2
Type C	3	58.4	133.5	25.9	3	10.1	13.1	4.1	3	14.0	18.3	6.1	3	3.6	4.2	1.4
Type D	8.5	61.0	302.8	29.8	8.5	53.5	101.4	12.9	7	77.4	165.0	25.8	8.5	24.8	38.0	8.2

Grand Falls Dam

Morphological Model Studies

1 Introduction

The catchment of the Tana River stretches between the Kenya Highlands and the Indian Ocean and has an area of approximately 95,000 km^2. The total length of the river is approximately 1,000 km. The rainfall pattern is bi-annual with most of the rainfall occurring in the upper and middle parts of the catchment. In this area the tributaries of the river are perennial. Lower in the catchment the rainfall decreases significantly and tributaries only flow seasonally.

In the past a number of reservoirs have been constructed in the upper catchment which have had the impact of regulating flows in the river.

The present study considers the morphological impact of the proposed Lower Grand Falls dam on the morphology of the river downstream. By the nature of reservoirs, sediment is trapped in the reservoir itself, denying sediment to the reach downstream, while the river flows downstream of the reservoir are also modified. These alterations lead to changes in the morphology of the river. The typical impact of reservoirs is to cause degradation of the river bed downstream. This degradation continues until a new equilibrium is established. This may take decades to achieve, or in some cases even centuries. To predict the morphological impact of reservoirs it is now common to use numerical models which simulate the movement of water and sediment in the river.

A tributary of the Tana River, the Kathita enters the proposed reservoir a short distance upstream of the dam. It has been suggested that the sediment from this catchment could be diverted around the reservoir so that instead of entering the reservoir it is diverted to the river downstream. This would enhance the sediment load in the river downstream and so reduce the morphological impact of the reservoir. This option was investigated using the numerical model.

2 Description of numerical model

The numerical model used in this study was Flumorph. Flumorph is a computational model developed by HR which will predict the long-term bed level changes in rivers as the result of engineering works.

2.1 Hydraulic equations used in the model

The model is based on the St Venant flow equations together with sediment transport equation to determine the quantity of sediment in motion and a sediment continuity equation to determine the changes in bed level. The differential equations are solved in the numerical model using finite-difference approximations to the differential equations. The model is a time-stepping one, that is, on the basis of knowing the bed levels in the river at one time the model calculates the new bed level after a short time interval or timestep. By repeating this process it is possible to predict bed levels up to any time in the future.

2.2 Boundary conditions applied in the model

In the model the topography of the river is described by a number of cross-sections. The discharges in the river are described as boundary conditions. The discharge in the river is specified together with any tributary flows and also flow losses through evaporation or seepage. The sediment on the bed of the river is characterised by its size and specific gravity. At the downstream end of the model a flow boundary condition is applied. For this study as the effect of the reservoir was not expected to propagate as far as the Indian Ocean the model was truncated some 135 km from the sea. The downstream flow boundary condition that was applied was normal flow.

2.3 Time-stepping procedure

At each time-step the model calculates the velocity, depth and water surface slope at each cross-section. From this information and data on the sediment properties, the model calculates the quantity of sediment passing each cross-section during the timestep. By using a sediment continuity equation applied to adjacent cross-sections the change in bed level at each cross-section during the timestep is determined. The process is then repeated for the next timestep.

2.4 Sediment transport calculations

To calculate the sediment transport the Ackers and White sediment transport relations were used (Ackers and White,1973). In extensive tests on a wide range of data these equations have been shown to provide satisfactory predictions of sediment transport rates (White, Milli and Crabbe,1973). They are applicable to the size of sediment found in the Tana River and are appropriate for the present study as they include a threshold of motion criterion in which for sufficiently low flows no sediment motion is assumed. Ackers and White recommend that to represent the size of the sediment the D_{35} sediment size is used, that is, the size which is exceeded 35% of the time. This is the size that was used in the numerical model.

3 Data

3.1 General data sources

To carry out this study data has been collected from a number of sources. Delft Hydraulics carried out an extensive study of the morphology of the Tana River in the period from 1983 to 1986. This provided much background information on the sediment processes in the Tana River. As part of the present studies Nippon Koei and the Institute of Hydrology studied different aspects of the hydrology of the catchment. Also as part of the present study Professor Mavuti took sediment measurements in the river in both the dry and the wet seasons. All this data has been reviewed as part of the present work and the data used in the study of the morphology as appropriate.

3.2 Hydrology

Nippon Koei provided time series discharge data for 35 years at the dam site for three conditions:

a) existing conditions,
b) with the proposed dam,
c) with the proposed dam but with artificial flood releases downstream.

As part of their studies in 1983 to 1986, Delft Hydraulics investigated the variation of discharge along the river. By studying the stage records at

Grand Falls,
Saka,
Garissa,
Nanigi,
Hola,
Garsen and
Ngao

and converting them into discharges using rating curves, DH were able to study the change in discharge along the Tana River. It was concluded that no significant change in discharge took place between Saka and Garissa. Downstream of Garissa, their study showed that the discharge in the river reduced significantly as one progressed down the river. This was attributed to seepage and evaporation losses. On the basis of their studies they proposed an equation to describe the spatial variation of discharge along the river. In the absence of any further data, this equation was used in the present study.

3.3 Topography

In the numerical model the topography of the river is described using cross-sections. DH, as part of their data collection exercise, measured cross-sections of the river approximately every 5 km. In the absence of any further topographic data these were used to describe the shape of the river. In all 95 cross-sections were used in the model.

3.4 Sediment data

In the numerical model the properties of the sediment in the river are described by the sediment size and specific gravity. During their data collection work, DH took and analysed sediment data from along the river. This showed variation from section to section but there was an overall trend for the sediment size to reduce in the downstream direction. To carry out the sediment transport calculations in the numerical model the Ackers and White sediment transport relationship was used. This is based on the sediment D35 size. On the basis of the DH data a D35 sediment size of 0.3mm was selected to represent the sediment in the reach of the river immediately downstream of the proposed Lower Grand Falls dam.

Sediment yield

To determine the morphology of the river it is important to specify the sediment that is entering the reach under consideration from the upstream end. The quantity of sediment entering the reach was estimated by,

a) on the basis of previous HR experience, assessing the sediment yield from the catchment upstream ,
b) carrying out sediment transport calculations using flow characteristics from the upstream sections.

On the basis of this an upstream incoming sediment load of 2.5 million tonnes of sediment per year was assumed. This is comparable with sediment yields determined from the sediment information that was derived from the data for Garissa gauging station. This data showed annual sediment yields which varied significantly from year to year within the range 0.2 to 36 million tonnes. This latter data included wash load whereas the figure used as input to the numerical model excluded wash load, being limited to bed material load.

To investigate that impact of diverting sediment from the Kathita catchment around the reservoir to the river downstream, it was necessary to estimate the amount of sediment coming from the catchment of the Kathita. It was assumed that the sediment yield of the Kathita was similar to that of the rest of the catchment. If this option is to be pursued then it is recommended that further work is carried out to confirm this assumption.

4 Numerical model calibration

The numerical model was run to simulate existing conditions. The assumption was that under existing conditions there is little or no morphological change. The model was run with the existing river bed levels as initial conditions. The flow sequence used was derived from the flow records for the last 34 years. The incoming sediment load corresponded to that from the present upstream catchment. During the calibration process the incoming sediment load was adjusted.

Figure 1 shows a longitudinal bed profile of the initial conditions and the predicted bed level after 34 years. Comparison of the two profiles indicates that the model predicts little or no bed level change during this period. This is consistent with our knowledge of the present situation.

5 Model predictions

5.1 Lower Grand Falls and Mutonga Dam

The impact of the Lower Grand Falls on the river downstream is two fold. The presence of the storage modifies the flows in the river downstream, while the reservoir also traps a significant proportion of the sediment load and so modifies the quantity of sediment that is passed downstream. These effects are represented in the model by modifying the two boundary conditions describing the flow and the incoming sediment load.

Nippon Koei had carried out a simulation of the reservoir and had predicted a 34 year sequence of daily flows with the assumption of the reservoir in place. A new flow exceedance curve was derived from these daily flows. From the parameters of the proposed reservoir an overall trapping efficiency of the reservoir was estimated. This indicated that the reservoir would trap approximately 94% of the incoming sediment load. To simulate the impact of the reservoir on sediment input to the reach, therefore, the incoming sediment load was reduced by 94%. The model was then used to simulate the morphological development of the river for 34 years after the dam is constructed.

The impact of the reservoir is to reduce bed levels in the river downstream. This reduction would normally start at the dam itself and progress downstream. Immediately downstream of the dam the river is constrained by the local geology and therefore degradation will not take place in this location. Downstream of Koreh Rapids, however, the river enters the alluvium and it will then have the potential to degrade.

Figure 2 compares the initial bed levels with those predicted after 34 years with the dam in place. The chainage shown in the figure is restricted to the upper part of the river as no significant change has taken place further downstream. Figure 3 shows the change in bed level over the 34 year period as a function of chainage. The figure shows that the largest amount of degradation will occur in the neighbourhood of the Koreh Rapids and then will reduce in the downstream direction. After 34 years the reduction in bed levels immediately downstream of the Rapids will be approximately 11m. For locations further downstream there will be a delay in the onset of degradation but then the bed will begin to degrade. As one progresses downstream the delay in the onset of degradation will increase and the absolute magnitude of the degradation will reduce.

The reduction in bed levels will also influence water levels. Figures 4 and 5 show longitudinal profiles of water levels for discharges of 750 and 90 cumecs, respectively, while Figure 6 shows the change in water level as a result of the reservoir as a function of chainage. The results show that after 34 years there will be a reduction in water levels immediately downstream of Koreh Rapids of approximately 11m. This will reduce as one progresses downstream. After 34 years the impact on water levels extends approximately 40 km downstream from the Rapids.

5.2 Impact of artificial flood releases

There is a proposal to use artificial flood releases from the reservoir to mitigate some of the environmental impacts of the reservoir and to help to maintain the flood plain environment. This would involve a different pattern of discharges released from the dam. The morphological impact of this different pattern of reservoir releases was also investigated with the numerical model. Nippon Koei provided a 34 years simulated time series of releases from the reservoir. This was analysed to provide corresponding flow exceedance data which was then used in the numerical model to make predictions.

Figure 7 shows a longitudinal profile of initial bed levels and predicted bed levels after 34 years. It can be seen that the impact of the flood releases does not have a major effect on the pattern of morphological change. The amount and extent of degradation is very similar to that shown in Figure 2. Figure 8 shows the change in bed level against chainage. The pattern is similar to that in Figure 3. Approximately 11m of degradation occurs immediately downstream of Koreh Rapids and the degradation extends for approximately 40 km downstream. Figures 9 and 10 show the water levels corresponding to discharges of 750 and 90 cumecs respectively. The change in water levels as a result of the reservoir are shown in Figure 11.

5.3 Diversion of sediment load from Kathita catchment

It has been proposed that to reduce the morphological impact of the proposed the reservoir, sediment from the Kathita catchment that might otherwise enter the reservoir should be diverted around the reservoir to enter the river downstream. The morphological impact of this option was investigated using the numerical model. To represent the diversion of the sediment from the Kathita catchment an estimate was made of the sediment load presently coming from the catchment. This sediment load was added to that estimated to be discharged from the dam following its construction. The model was then re-run with this modified sediment load.

Figure 12 shows a longitudinal profile showing the initial bed levels and the bed levels after 34 years, while Figure 13 shows the change in bed level as a function of chainage. It can be seen that the impact of diverting the sediment from the Kathita is to reduce the amount of degradation from approximately 11m to approximately 9m during this period. There is a corresponding impact on water levels which is shown in Figures 14,15 and 16.

It should be noted that the feasibility of and engineering works required to divert the sediment load were not considered. If it is considered worth pursuing this option further then these aspects would have to be considered in some detail. This would require detailed information on channel size, bed levels and sediment sizes in the lower part of the Kathita and the topographic relationship of the Kathita to the reservoir and the river downstream.

6 Discussion of results

The Tana river in the reach downstream of the proposed reservoir presently carries a significant sediment load. The impact of the dam will be to significantly reduce the sediment input to the river downstream. In many situations the sediment in rivers contains a wide range of sediment sizes and it is then described as graded. In such situations the presence of a large range of sediment sizes acts to inhibit degradation. The finer sediment is preferentially removed and the bed of the river is covered with the larger sizes of sediment. As these are more difficult to move than the finer sediment, the degradation is reduced. The sediment in the Tana River is relatively uniform and so there is no similar mechanism to inhibit degradation. The result of the large reduction in sediment load and the uniformity of the sediment is that a large amount of degradation will take place. This will take place over a long time period and will eventually affect a significant length of the river downstream of Koreh Rapids.

The large predicted reduction in bed level downstream of Koreh Rapids will have an effect on water levels, as demonstrated in Figures 6 and 11. It will also affect the conveyance of the channel and hence bankfull flows. It is expected that as the bed level reduces, the discharge required to give bankfull flow will increase. This will also affect the frequency and severity of overbank flooding. It is expected that flooding onto the floodplain will occur less frequently and that, when it does occur, the depth of flooding will be less. This will have an impact on those aspects of the environment that rely on flooding on the floodplain. It is also expected that as the water levels in the channel reduce, the surrounding groundwater levels will reduce. This will also have an impact on those aspects of the environment that rely on groundwater.

The numerical model predictions are based on the assumption that the overall shape of the channel cross-sections remains approximately constant. In the reach immediately downstream of Koreh Rapids, however, the numerical model predicts reductions in bed level up to 11m. It is unlikely that the present river banks will be able to withstand such a large reduction in bed level. The reduced bed level will have a number of effects. It will tend to de-stabilise the banks of the river. This will lead to changes in the shape of the channel cross-sections. It will also lead to the injection of sediment into the river from the banks. This effect is not represented in the numerical model and will tend to slow the actual morphological change in comparison with the rate of change predicted in the model. It will not affect, however, the final equilibrium that will be achieved, only the time taken to achieve it.

The plan form of a river depends upon the balance between the equilibrium slope of the river, as determined by the flow and sediment characteristics, and the valley slope, as determined by the topography of the land (Bettess and White,1983). The impact of the dam will be to alter the sediment load in the river. This will affect the equilibrium slope of the river, hence resulting in the reduction in bed levels discussed above. A further impact of this change in the equilibrium conditions will be on the plan form of the river. The reduction in equilibrium slope will reduce the discrepancy between the equilibrium slope and the valley slope. The impact will be that in those reaches were the river presently has a braided character, the degree of braiding will reduce and the river may become meandering in character. In those reaches were the river is already meandering, the sinuosity of the river will reduce. This change in plan form could have a significant impact on any infrastructure associated with the river or river banks.

7 Conclusions

A numerical model study has been carried out to determine the morphological impact of the proposed Lower Grand Falls and Mutonga dams. The study has assumed that due to the nature of the river between the proposed dam site and the Koreh Rapids no significant morphological change will take place in this reach. The numerical model indicates that downstream of Koreh rapids significant degradation will occur.

After 34 years the degradation will be of the order of 11m immediately downstream of Koreh rapids. The degradation will extend approximately 40 km downstream, reducing in magnitude as one progresses downstream. Further degradation will take place after 34 years.

It is currently proposed to release artificial floods from the reservoir. This will not have a significant impact on the morphology in comparison with the normal dam releases.

It has been suggested that the sediment from the Kathita catchment should be diverted around the reservoir to enter the river downstream. The impact of this is to reduce the amount of degradation from approximately 11m to approximately 9m. In this study the feasibility of diverting the sediment was not considered nor the engineering works required to achieve this. If this option were to be pursued then more detailed studies of these aspects would have to be considered.

The reduction in bed levels would tend to destabilise the banks of the river, leading to changes in the shape of the channel cross-section and the injection of sediment into the river. Neither of these effects have been included in the present model. They are likely to slow the actual rate of change in comparison with the model predictions but are unlikely to affect the final equilibrium value.

The reduction in bed levels leads to a corresponding reduction in water levels. This will reduce the frequency of overbank flooding and lead to a reduction in the groundwater levels adjacent to the river. This is likely to have an impact on the local environment.

The change in the equilibrium conditions of the river will also induce plan form changes. Those reaches which are presently braided are likely top become less braided and may change to a meandering plan form. The sinuosity in those reaches that are presently meandering may reduce. This will have an impact on any infrastructure along the banks of the river.

8 References

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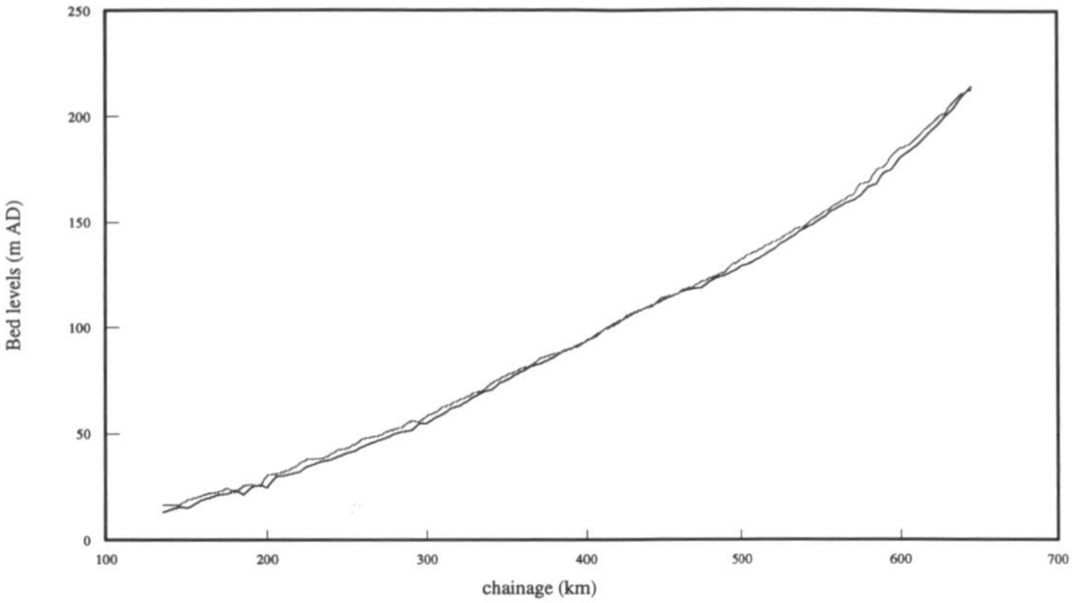
Bettess R and WR White, 1983, Meandering and braiding of alluvial channels, Proc Instn Civ Engrs, Part2,75,Sept,pp525-538

White WR, H Milli, AD Crabbe,1973, Sediment transport: an appraisal of available methods, Hydraulics Research Station Report INT119, Wallingford

Figures

Tana river: Without dam : 34 years



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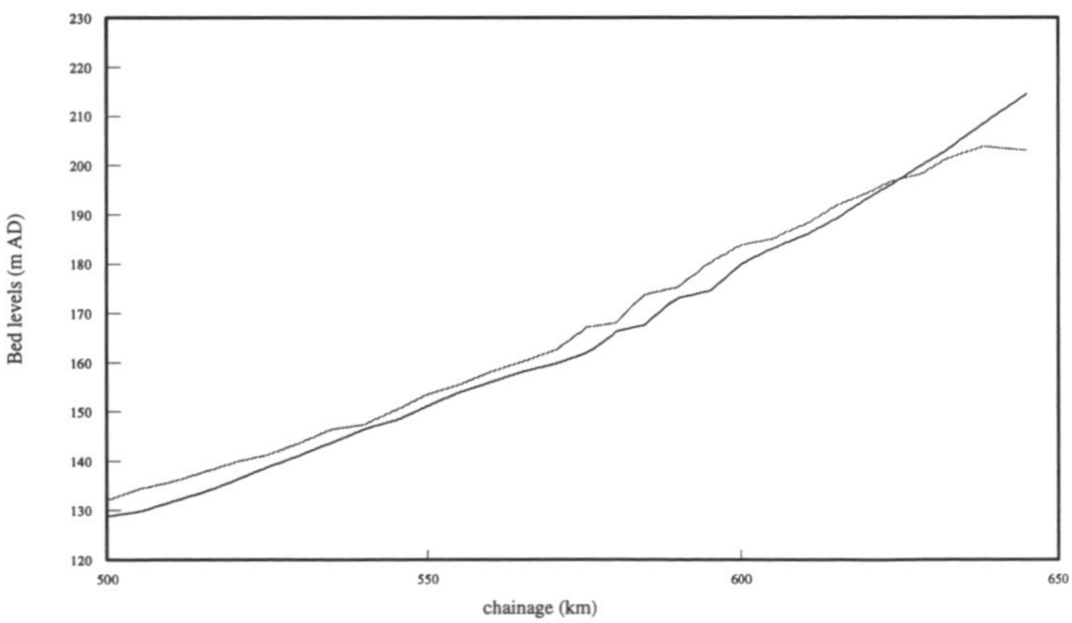

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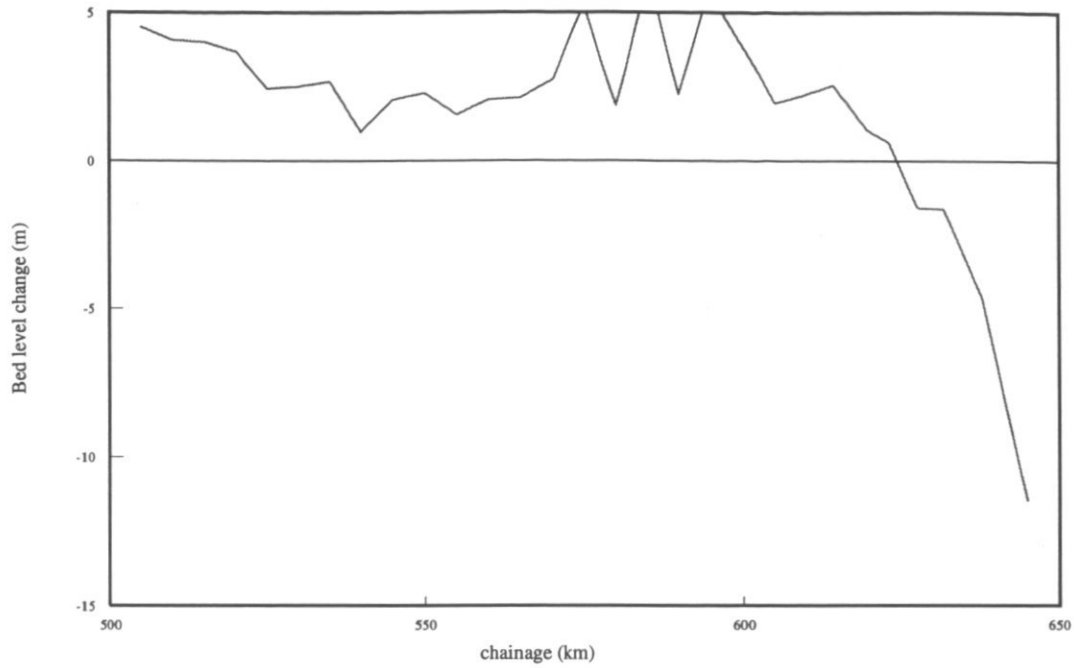

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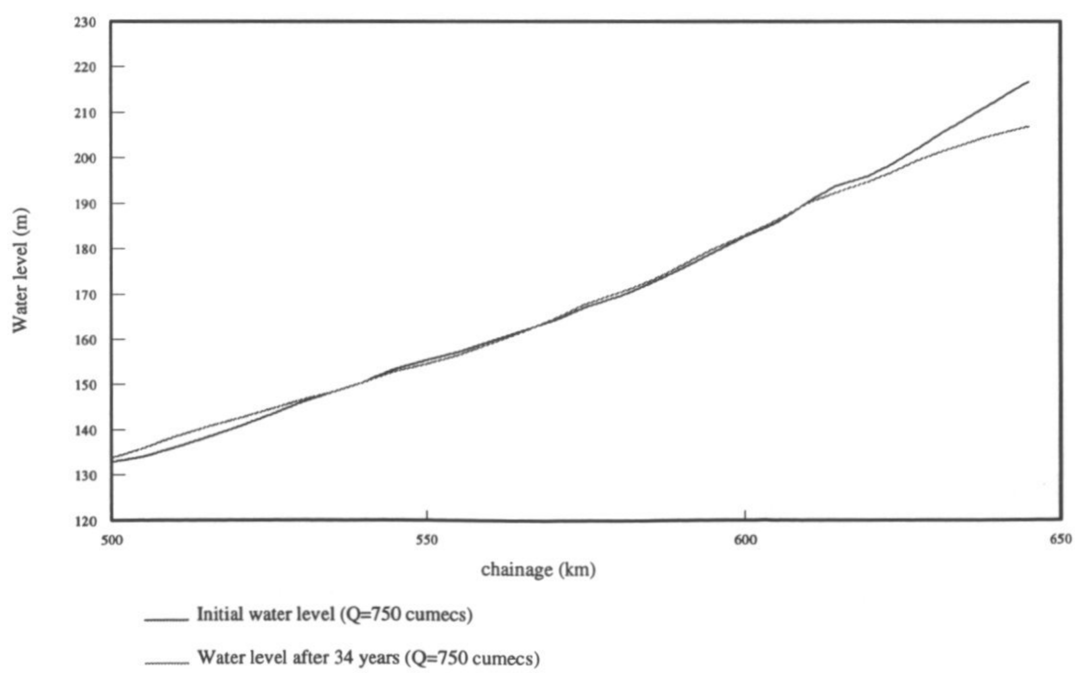

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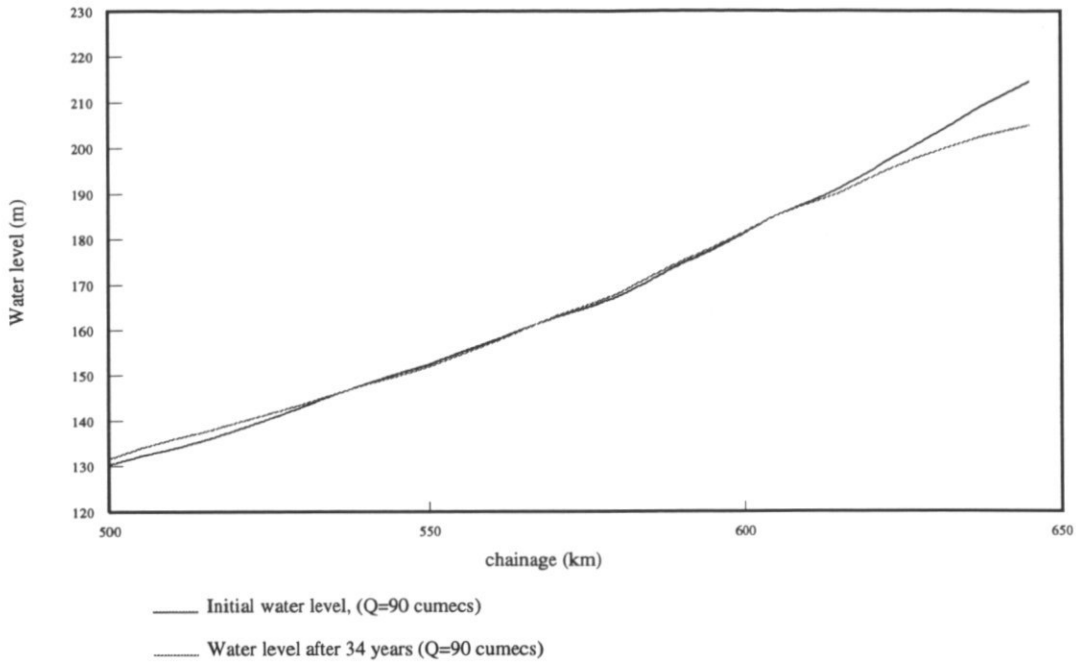

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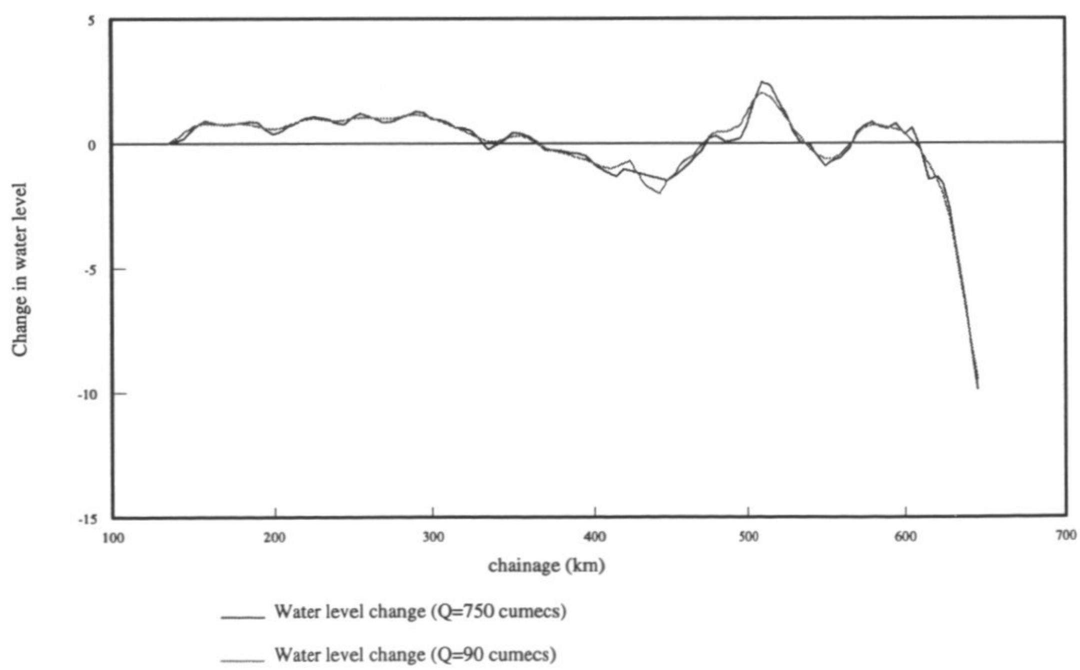
Tana river: Lower Grand falls dam : 'Normal' flow : 34 years



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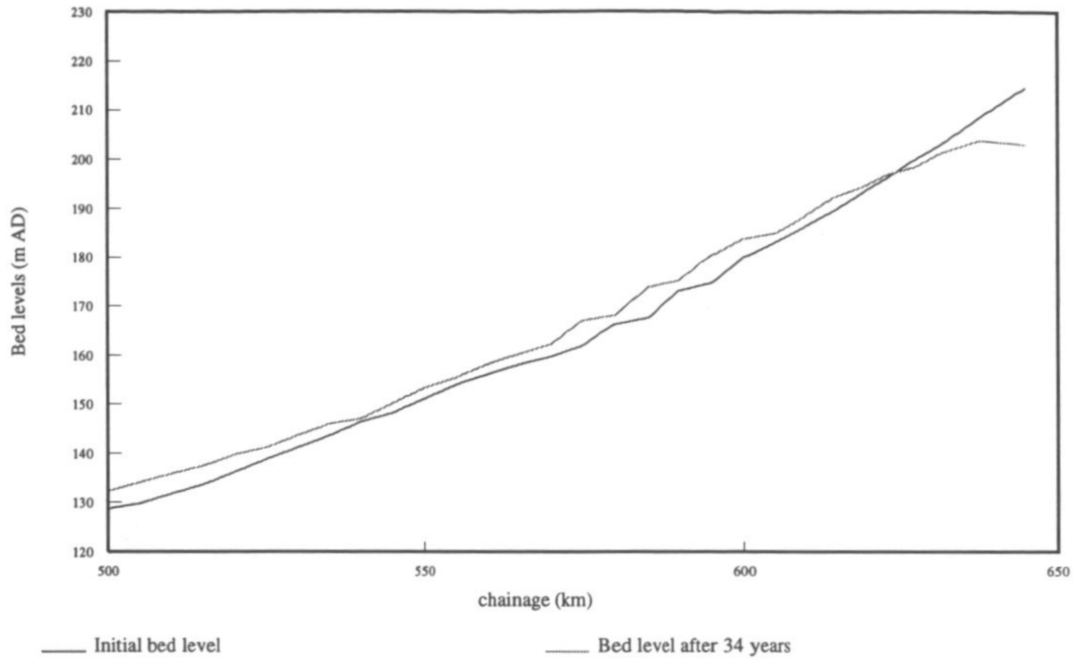
Tana river: Lower Grand falls dam - 'flood' flow : 34 years



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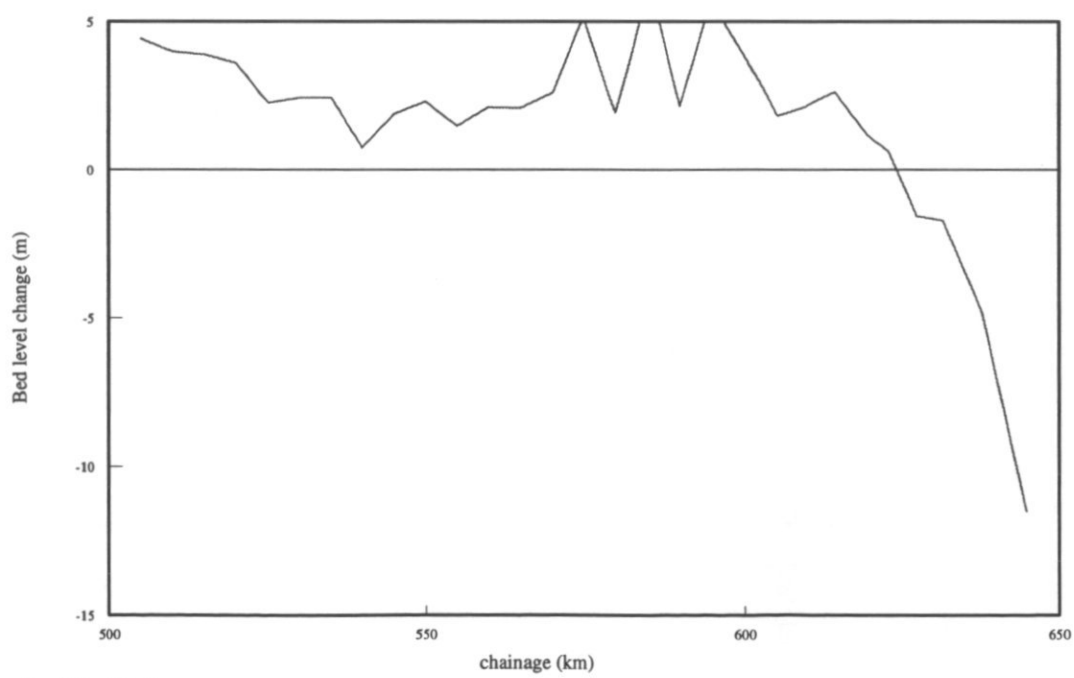

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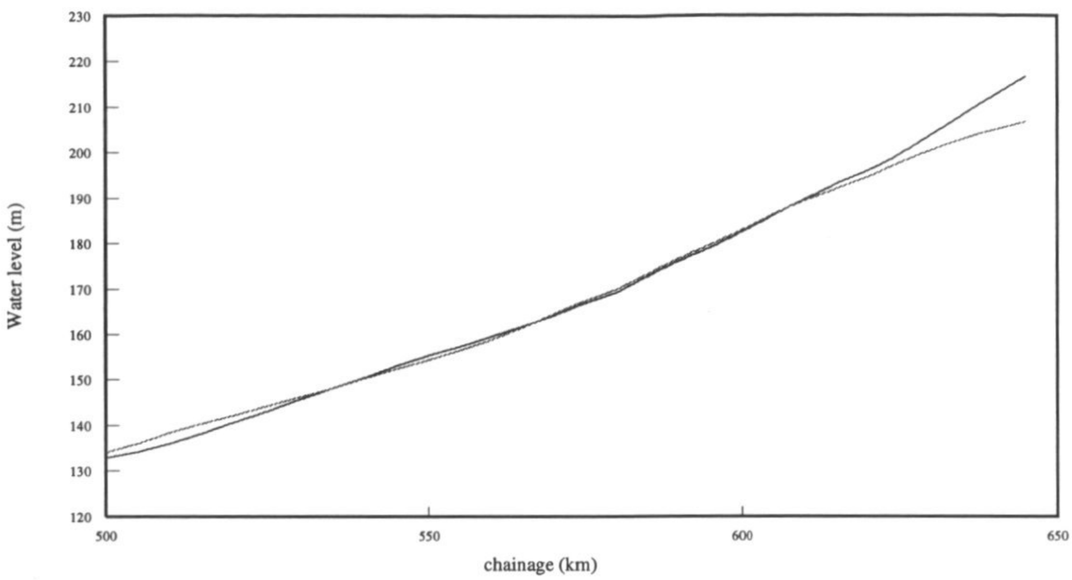

Initial water level (Q=750 cumecs)

Water level after 34 years (Q=750 cumecs)

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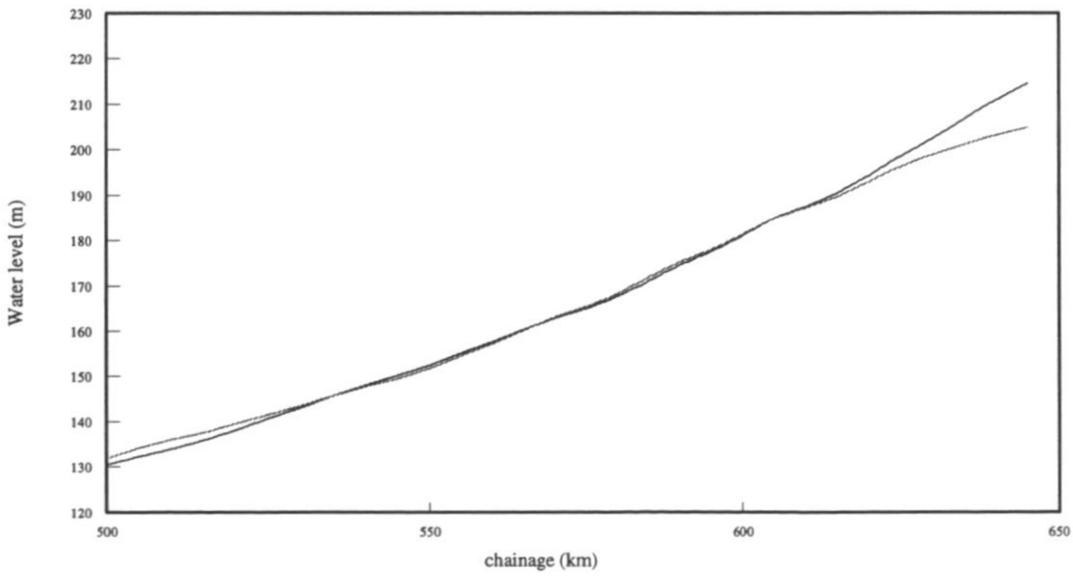

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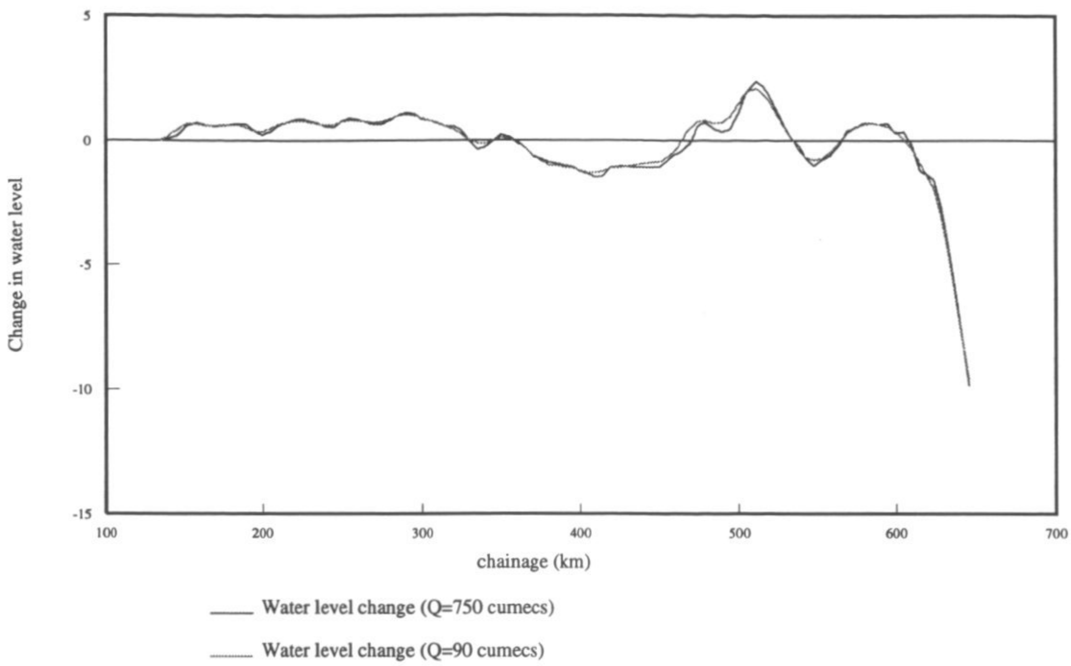

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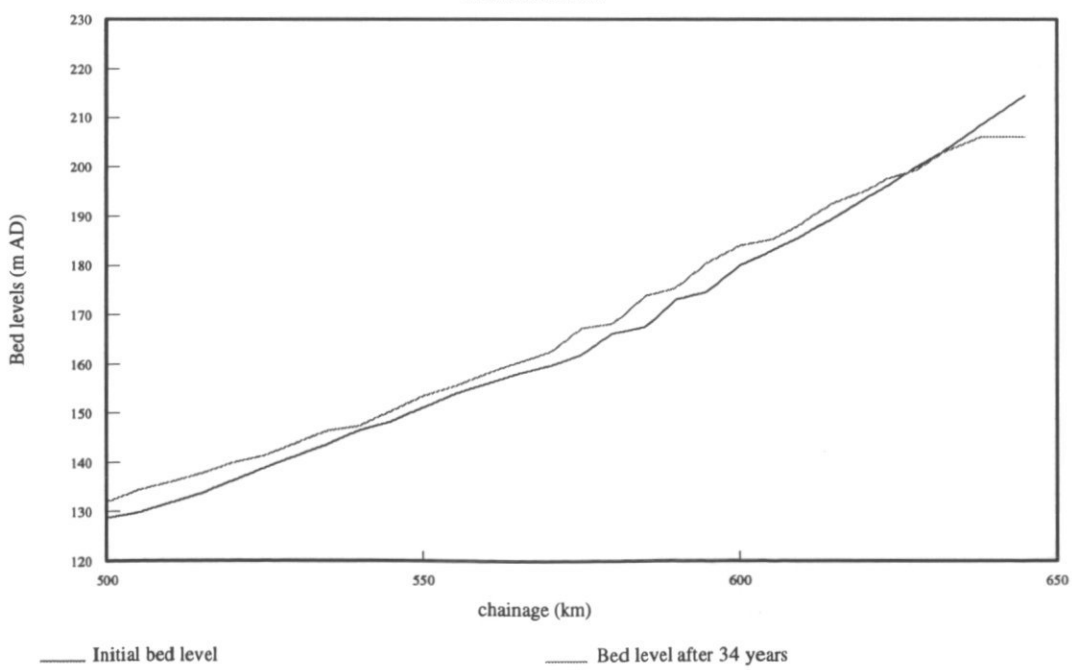
Kathita sediment



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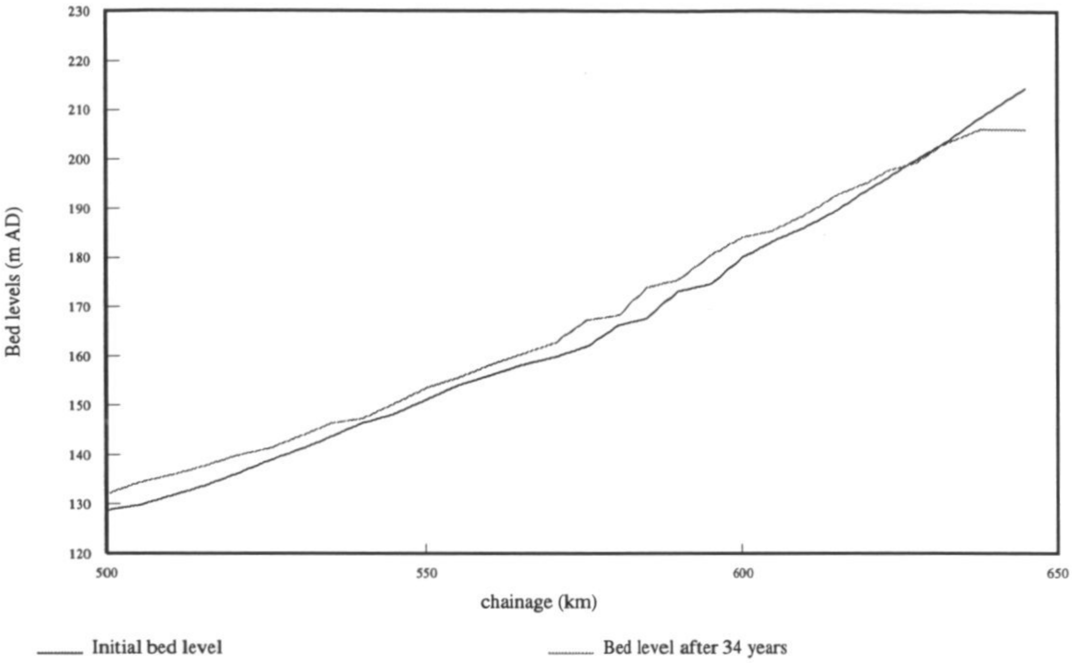
Kathita sediment



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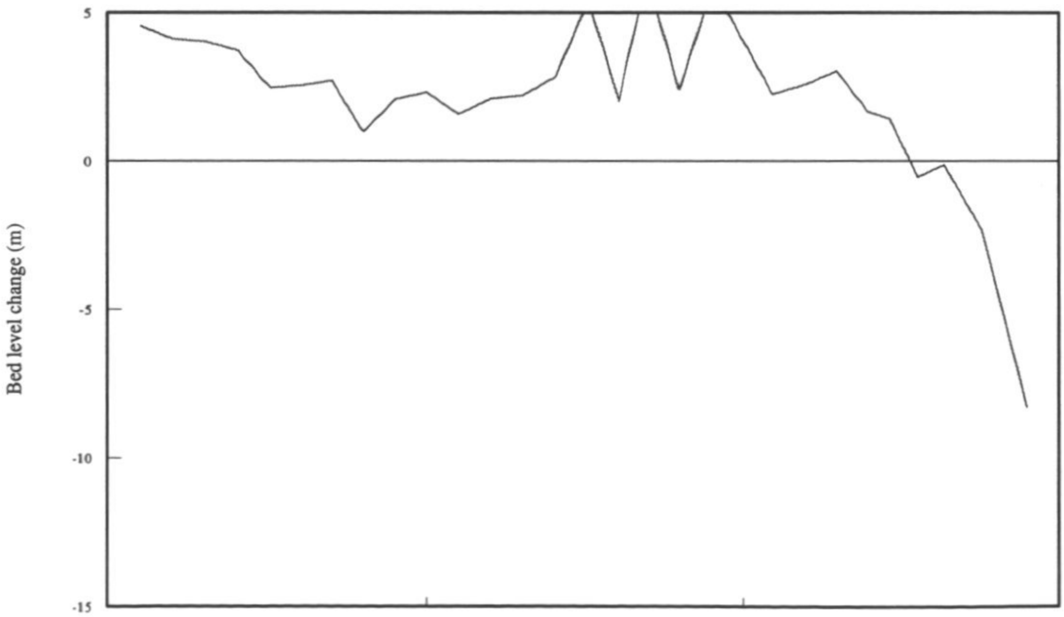
Kathita sediment



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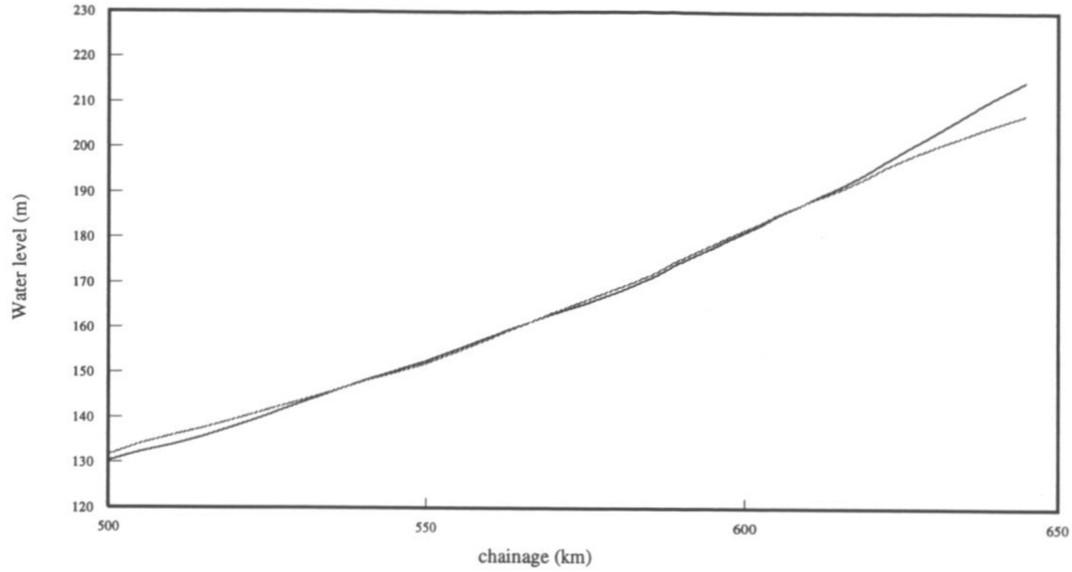
Tana river: Lower Grand Falls dam : 'Normal' flow :34 years
Kathita sediment



Initial water level, (Q=90 cumecs)

Water level after 34 years (Q=90 cumecs)

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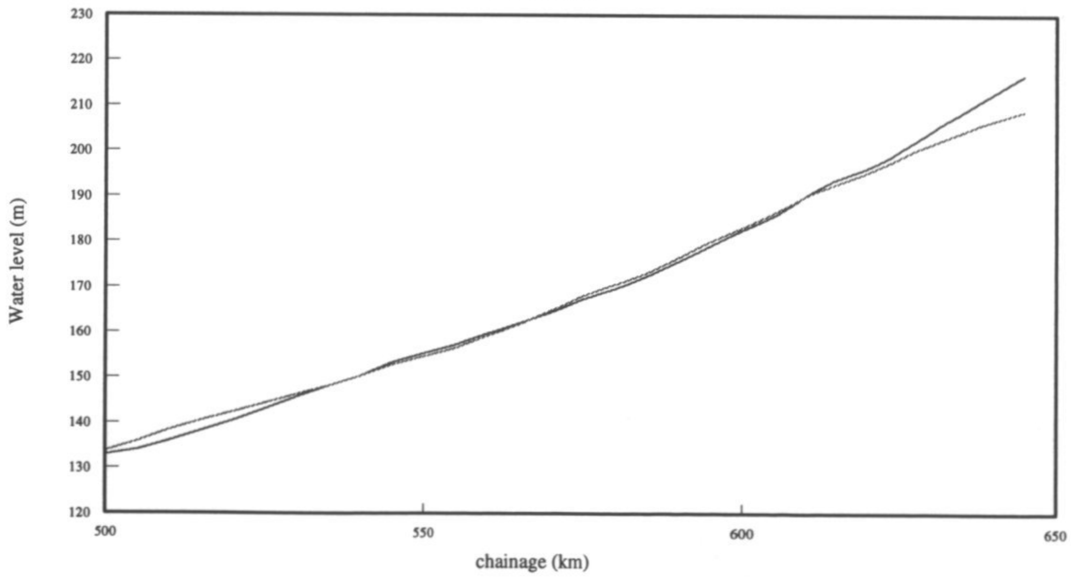
Tana river: Lower Grand Falls dam : 'Normal' flow :34 years
Kathita sediment



Initial water level (Q=750 cumecs)

Water level after 34 years (Q=750 cumecs)

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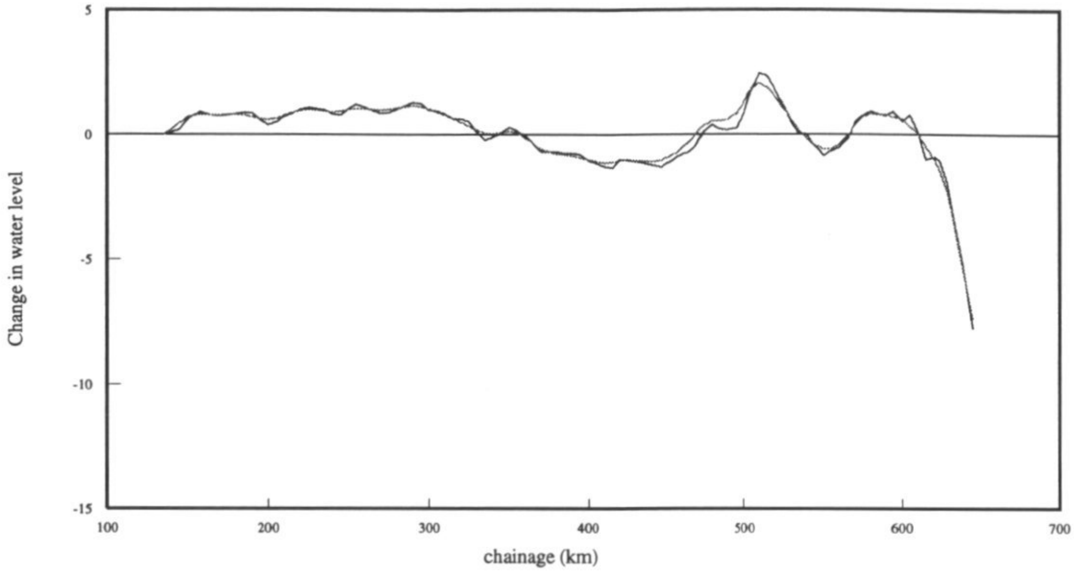
Tana river: Lower Grand Falls dam : 'Normal' flow :34 years
Kathita sediment



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16

Summary

Phase 3
Mutonga/Grand Falls Hydropower Project Environmental Impact Assessment

Water quality and flushing of nutrients and particulate matter through the proposed reservoirs

Report EX 3375
February 1996

This report forms a series of reports that will be accompanied by an overview report covering the potential impacts of proposed dam construction for hydropower production on the Tana River.

The report describes an assessment of the dry and wet season water quality in the Tana, Mutonga and Kathita Rivers and within the existing Kiambere Reservoir in September and November 1995. It also describes the application of a deterministic three-dimensional segmented and layered model, which was used to predict the water quality and flushing of nutrients and particulate matter through the proposed Mutonga and Low Grand Falls Reservoirs.

The 3D models of the Mutonga and Grand Falls reservoirs were run in series - one flowing into the other - and were used to simulate typical wet and dry season conditions with steady 20 and 80 percentile fluvial flows, respectively.

The analysis of the Kiambere reservoir data indicated that it trapped about 15% of the wash load of clay particles, which are weakly flocculated by the presence of natural salts in solution (75ppm) and settle at a rate estimated to be about 5 x 10^{-6}m/s.

The models predicted that about 60% and 85% of the suspended load of clay particles and the associated phosphate and organic matter would be trapped, mainly in the Low Grand Falls reservoir during typical wet and dry season conditions, respectively. The latter figure may be overestimated as a result of using a constant settling velocity. During floods from the Mutonga and Kathita rivers, much higher, but as yet unquantified, masses of suspended silts and clay will pass rapidy through the L.G. Falls reservoir, as a cold density current, scouring the soft bed and will settle in the dead zone below the out take or pass downstream through the turbines.

The models predicted that the two reservoirs operating in series would trap about 40% and 55% of the daily influx of dissolved nitrate, mainly in the Low Grand Falls Reservoir, during typical wet and dry season conditions with recycling of organic nitrogen from settling detritus.

If conditions in the bed allowed optimum rates of recycling of organic nitrogen from settled algal detritus the rates would be expected to fall to about 25% and 40% in the wet and dry seasons, respectively.

The model predicted that algal growth in the surface layers would not be significantly effected by recycling of dissolved available inorganic nitrogen into the lower layers of the reservoir.

Summary continued

The particulate phosphorous trapped in the settled mud and detritus will not be recycled easily and will not be available to phytoplankton in the photic zone. The model predicted that the reservoirs would trap about 95% of the relatively small incoming loads of dissolved available phosphorous and that the surface algae blooms in the surface layers would be limited by lack of phosphorous.

The model predicted a 2-4m deep photic zone with variable and an acceptable range of chlorophyll-a concentrations (ie 5-15 mg/m3) depending on light penetration, the horizontal flux of nutrients. The model also predicted a moderate DO sag in the deeper layers of both reservoirs. However, the DO sag could deepen further with time as a result of an accumulation of settled decaying organic matter raising the benthal oxygen demand in the dead zones of the reservoirs.

The model predictions are sensitve to the factors affecting the growth of the specific algae species in the Tana River reservoirs which is not available, but could be obtained from new research by HR and Dr Mavuti. The coefficients should be tested by simulating conditions in the existing Kiambere reservoir.

There is a need to construct rating curves for the flux of suspended mud, organic matter and particulate and dissolved nutrients for the Mutonga and Kathita Rivers. There is also a need for a daily record of meteorological conditions and synthesised sediment and pollution loads so that the models can be run for a number of years including solar heating, and wind effects.

There is a need to study the detailed behaviour of the passage of sediment laden floods from the Mutonga and Kathita Rivers through the reservoirs, using a fine-gridded 3D model.

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Invasion of reservoirs and their associated waterways by aquatic weeds has seriously reduced fish yields both upstream and downstream of dams.

1.1.2 Impact on water supply and sanitation

The rural communities living around the lakes tend to use water drawn directly from the lakes for their drinking needs and all domestic activities. The results of the analyses performed as part of the previous studies (Roggeri, 1985) indicated that the characteristics of all the waters of the Tana River reservoirs were similar.

- the rate of turbidity was found to be high
- the population of coliform bacteria were highly developed and presence of E Coli indicated the existence of faecal pollution
- the oxygenation rate indicated that the organic decomposition activity was low.
- there was no indication of any traces of industrial pollution and the content of toxic elements was found to be at an acceptable level.
- due to lack of analysis of water quality when the dams were built, it was not possible to determine whether their quality had deteriorated
- the waters in Lakes Masinga, Kamburdu, Kindaruma were found not to be fit for human consumption
- the use of the water for domestic purpose was judged to be risky and was being increased by the lack of adequate sanitary installation

1.1.3 Eutrophication

Initial studies of pollutants from the upper catchment undertaken in the phase 2 study indicated potential problems of deteriorating water quality, largely from agro-industrial processes and urban and peri-urban settlements. Increasing nutrient load in the water may lead to eutrophication. High nutrient load may lead to high weed growth, potentially impairing the functioning of the reservoir. Problems associated with deteriorating water quality are likely to increase with larger reservoir options, due to longer retention time. Suggestions included clearance of vegetation prior to inundation, control of land use and waste water discharges within the upper catchment, and provision of multi-level releases. Further studies and specific monitoring of pollutant levels will be required, leading to a catchment management strategy.

1.1.4 Sedimentation

Phase 2 studies indicated that the economic life of the proposed reservoir options is not decreased by present sediment loads. In the area immediately adjacent to the reservoir, increased land pressure resulting from resettlement is likely to lead to increased erosion. Impacts will be reduced through active management of the buffer zone and direct and indirect interventions through the extension service to promote conservation farming systems.

More general management of sediment load may be possible through sediment release or diversion structures, although the critical factor remains control of land use in the upper catchment. Further sampling of dry season and rainy season sediment loads would give a better indication of total and seasonal variations.

For a complete seasonal picture and for indications of trends in sediment load, further studies and a full monitoring programme will to be necessary.

1.1.5 Annual flooding downstream

The major potential negative downstream impacts are all related to the changes that could occur as a result of changed flow patterns, associated with storage reservoirs. The natural river flow pattern includes bi-annual high flow or flood periods, associated with the rains in the upper catchment. The effect has been the creation of a flood plain in which the natural and socio-economic environments have adapted to and rely on flooding and associated nutrients for their existence.

The only potential mitigation is the deliberate release of water, partially replicating the natural flooding conditions. The proposed reservoir designs will be adapted to include the potential for high flow release, or for diversion of river flow past the reservoir.

The Phase 3 Studies are being undertaken to establish more clearly the "natural" flood conditions, and the release volumes and periods that can replicate them.

Further studies will be required to establish the downstream flood dynamics, including hydraulic modelling of the floodplain.

Monitoring of rainfall and flow levels will be needed to ensure optimum management of the system, balancing flood requirements with maximised power output.

2 Terms of Reference

HR Wallingford, was required to forecast the likely trophic state of the proposed reservoirs by data analysis and the use of 3D mathematical models to simulate flushing, potential anoxic conditions, effects of settling organic matter and recycling of nutrients, and the flux of nutrients and sediment through the reservoirs.

To aid understanding of the behaviour of the proposed reservoirs, HR Wallingford commissioned Professor Mavuti to supervise a water sampling survey of the Kiambere Hydropower Reservoir upstream in the Tana River at the same time as the river survey. The full results of these survey became available to HR on 24 January 1996.

HR were also provided with the following data:-

(I) A digital ground level data set of the proposed reservoirs based on contours at 10m intervals and 44 1: 5000 scale plans based on contours at 2m intervals

(ii) Forecast daily flows with proposed hydropower plants and reservoir working in an optimised mode.

1 Introduction

On 21 August 1995 Acropolis Kenya Ltd commissioned HR Wallingford Ltd to undertake several tasks as part of Phase 3 of an Environmental Impact Assessment for the proposed Mutonga and Grand Falls Hydro Power Project.

This report forms part of a series of reports that will be accompanied by an overview report covering the potential impacts of proposed dam construction for hydropower production on the Tana River. (Figure 1.1).

Together these reports will be presented as an input to the JICA Study Team, working on behalf of the Japanese International Co-operation Agency who are funding the Feasibility Study on the Mutonga/Grand Falls Hydropower Project. The JICA Study Team will be responsible for the production of a final report based on these draft reports.

The conclusion of the JICA Study Team will be presented at a Workshop due to be held in March 1996. It is expected that the Workshop will be open to both local and international government and aid agencies, NGOs and other interested parties.

The Study is being managed through Nippon Koei Co Ltd.

1.1 Background

(I) The Tana River is the largest river in Kenya and contains potential for water resources development. Hydro power generation has been developed along the River to utilise river flow discharge and water head. Power plants have been in service from 1968. Recent reports - National Power Development Plan (NPDP), 1992, KPLC/WB and National Water Master Plan (NWMP), 1992 MOWD/JICA - identified two new dam schemes in above Grand Falls.

(ii) The Japan International Co-operation Agency (JICA) to Kenya and Nippon Koeo Co Ltd are undertaking the feasibility study for the Tana and Athi River Development Authority (TARDA). According to the scope of work so prepared under the discussions of two agencies, the main objective of the Study is to formulate an optimum development scenario and make conclusions and recommendations for the Mutonga/Grand Falls Hydropower Development Project.

(iii) The Study has been undertaken in three phases. Phase 1 (Initial Environmental Examination), Phase 2 (Selection of Definitive Plan/Pre-Feasibility) and Phase 3 (Feasibility Study). Phase 1 commenced in February 1994. Workshop 1 was held to discuss the study results of the Stage 1 at Embu during September 1994. The Workshop identified negative impacts resulting from the project which required further study in subsequent stages to establish appropriate mitigation measures.

Phase 2 which commenced in September 1995 included a preliminary examination of the environmental impact of the dams on water quality and flushing of nutrients and fine sediment through the proposed reservoirs. Neither the Mutonga or low Grand Falls Dam was shown to have any significant capacity for flood control. The larger low Grand Falls Dam had some capacity for releases of small artificial floods.

Table 1.1 Reservoir operating characteristics used in this study

	Mutonga	Low Grand Falls	Kiambere built 1988
Reservoir Surface Area (km^2)	11	66	25
Reservoir Volume ($10^6 m^3$)	132	1,261	585
Rated Power Output (MW)	60	120	144
Firm Output (MW)	30.3	62.6	92
Monthly Inflow:			
Average (m^3/sec)	171	191	137
Max (m^3/sec)	823	861	
Min (m^3/sec)	93	93	
Power Outflow:			
Average (m^3/sec)	136	147	
Max (m^3/sec)	200	210	122
Min (m^3/sec)	65	75	
Monthly Spill out:			
Average (m^3/sec)	34	39	
Max (m^3/sec)	643	662	
Min (m^3/sec)	0	0	0
Average monthly evaporation (m^3/s)	0.78	4.74	

1.1.1 Reservoir water quality

The Phase 2 report (October 1995) concluded that the reservoir water quality will be determined by both the upstream inputs of pollutants and by processes within the reservoir body. Increasing population within the upper catchment, accompanied by increasing urbanisation will lead to increased levels of pollutants. The larger the reservoir the greater trap effect on pollutants. Nutrient levels within the reservoir are likely to be high; this not only has the potential to support active fisheries, but also to stimulate the growth of aquatic weeds.

Initial assessments of possible fisheries benefits were based on the output from the upstream reservoir, although with potentially over twice the surface area of Masinga, and with higher temperatures and nutrient load, productivity is likely to be greater.

Trapped silt which was previously washed downstream as the river flowed unimpeded to the sea. The trapped silt contains nutrients which are vital to the survival of fisheries in the lower reaches of a river and in the sea beyond.

3 Methodology

The small amount of existing water quality data collected in phase 2 was assessed and a water quality survey of the Kiambere Reservoir was specified in collaboration with Professor Mavuti. Professor Mavuti also carried out a parallel survey of water quality and sediment loads in the rivers specified for other purposes.

The river surveys on three occasions were used to define the pollution loads coming into the reservoirs as described in Chapter 4.

The surveys of Kiambere Reservoir were used to evaluate various processes described in Chapter 5 and to design the models.

The topographical maps and information on the design of the dams and the observed pattern of water quality in Kiambere Reservoir were used to set up separate schematic 3D models of the Mutonga and Low Grand Falls Reservoirs in terms of a series of in-plan segments and horizontal layers of variable thickness. The Mutonga Reservoir was divided into eight (8) segments, seven of which represented the submerged Tana River Valley (Figure 3.1). The Mutonga model had 9 layers. The base of the top layer was set at 548m, two meters below the FSL spilling level. The lower layers were 2, 2, 2, 2, 4, 4, 10 and 30 metres thick (Figure 3.2).

The flow to the turbines was extracted from between 520 and 530m (layer 8). The segment boundaries were orthogonal to the existing river channel and spaced at intervals of between 2-3km as shown in (Figure 3.1). The FSL level is 550m. The sections were located where the flow cross-section was constrained by geological ridges in the sides of the canyon. The geometry of the model cells formed by the intersection of the layers and segments were evaluated in terms of plan areas and widths at the cross-sections between segments. The overall shape of the model was checked by reference to the surface area and volume functions published in the phase 2 reports (Figure 3.3).

The low Grand Falls Reservoir was schematised into 19 segments (Figure 3.4) and 8 layers. The top base of the layer was set at 510m, 2m below the FSL level. The lower layers were 2, 3, 5, 10, 10, 20 and 25 metres thick. The flow to the turbines was extracted from between 480 and 490m in layer 6 (Figure 3.5).

The theory behind the models and the particular assumptions made for this study are given in Appendix I. The main assumptions are defined in Chapter 6.

The models were then set up to simulate steady state typical wet and dry season conditions as a means of predicting the water quality in the reservoirs and the trapping and flushing of dissolved and particulate pollutants.

The wet season conditions were selected so that the reservoir was full and the flow to the turbines was maximised (200 m^3/s and 220 m^3/s for Mutonga and Low Grand Falls, respectively.) This was approximately a 20 percentile flow for the Tana and Mutonga Rivers. The results are described in Chapter 7.

The exercise was repeated on the dry season assuming discharges of 65 m^3/s and 75 m^2/s through the turbines on the Mutonga and Low Grand Falls Dams, representing an 80 percentile flow condition. The results are described in Chapter 8.

The understanding of the behaviour of the suspended solids in the reservoir is considered to be a key issue because it controls the light penetration and the transport of particulate nutrients.

4 *Sources of water, mud and pollutants to the proposed reservoirs*

4.1 Water

The heavily regulated outflow of the Tana River from Kiambere Reservoir and the uncontrolled perennial flow of the Mutonga River are the main sources of water and pollutants to the Mutonga Reservoir.

Mutonga Reservoir will hardly modify the flow of the Tana and Mutonga Rivers, into low Grand Falls Reservoir which accepts flow from the Kathita (Kazita) River, another perennial steam fed from the slopes of Mount Kenya.

Table 4.1 Flow and mud transport statistics

Catchment	Tana at Kiambere Tailrace	Mutonga at 4EA7	Kathita at 4FI9
Average flow (m^3/s)	111	29	16
5% percentile (m^3/s)	330	160	100
90% percentile (m^3/s)	35	10	5
Average daily mud load (tonnes/day)	340	[100]	[55]
5% percentile	(4000)	[550]	[350]
95% percentile	50	[35]	[15]
Water temperature °C	25	21	21

(Estimate based on 90ppm)
[estimate based on 40ppm]

The Mutonga and Kazita Rivers are relatively more flashy than the larger but heavily regulated Tana River.

The quality and trophic state of the two proposed reservoirs will be determined by the influx and rate of flushing or trapping of nutrients and fine clay particles.

4.2 Mud (clay) inflows

An analysis of Professor Mavuti's 1995 river sampling exercise at the outflow from the Kiambere Dam showed only mud (fine clay particles) and no sand or silt. Further more the mud concentrations only varied from 30-40 ppm for a three fold change in discharge for 65 to 210 m^3/s. (ie 170 - 730 tonnes/day). (Figure 4.1).

The total annual inflow of mud into Mutonga Reservoir is probably in the range of 0.2 - 0.3 million dry tonnes per year from the outflow of the Tana River from Kiambere Reservoir. The trapping efficient of Kiambere Reservoir is assessed below (Table 4.2).

The Mutonga River has a steep catchment and is fed by snow melt as the water is relatively cold (21°C) compared to the Tana River (25°C).

The 1995 analysis of the sediment yield of the Mutonga River did not separate deflocculated clays from sands and silt. The 1995 surveys appeared to show that less than 1% of the particles were finer than 25μ. Mud and clay particles are less than 10μ. Normally, one would expect the ratio of loads of sand and silt and clay particles to vary differently with the discharge, the sand load varying with a higher power.

However, the turbidity (measured in NTU's) which is a good indicator of the concentration of clay particles, was only 35 with a discharge of 83 m^3/s on the Mutonga River and a reported suspended solids concentration of 20,000 ppm. This implies a suspended mud concentration of only 40 ppm, which is less than 1%.

At present one can only conclude that the mud load of the Mutonga and Kazita rivers are very small and that most of the sediment is granular sand and silt. This needs to be checked.

The Mutonga and Kathita rivers flow into the Mutonga and Low Grand Falls reservoirs relatively close to the dam so one would expect the sand fractions to settle out and form a delta in the reservoir which might encroach on the bellmouth to the turbines.

The relatively cool silt and sand laden Mutonga water would flow as a density turbidity current directly into the deep water behind the dam and the suspended matter would be drawn into the turbines out of the reservoir in preference to the warmer Tana water. Likewise for the Kathita River. Neither the mud load or nutrients and pollutants from the Mutonga River is likely to have a significant impact on the Mutonga Reservoir. The capacity of the turbines is about 200 m^3/s which is greater than the 5%ile flow of the Mutonga River. As a result, the low Grand Falls Reservoir will normally have to adsorb the full unmodified nutrient and suspended sediment load of the Mutonga river.

An analysis of Professor Mavuti's observations of suspended sediment loads, which consisted almost entirely of clay particles and some organic matter, downstream of Kindaruma and Kiambere Dams in the one month long dry and wet season surveys indicate that an average 15% of the incoming fine sediment is trapped in Kiambere Reservoir.

Table 4.2 Mud transport through Kiambere Reservoir

	Kindaruma Tailrace		Kiambere Tailrace		
	Mean daily outflow m^3/s	Mean daily suspended load t/d	Mean daily outflow m^3/s	Mean daily load t/d	Trapping efficiently %
Dry season period (7/9/95 - 5/10/95)	94	313	78 (94)	222 (267)	(15)
Wet season period (29/10/95 - 27/11/95)	116	406	118	341	16

(Bracketed values scaled to match inflow)

In pure distilled water the individual clay particles (< 2μm) repel each other and form a colloidal solution with a negligible settling velocity. However, the presence of cations in solution of salts found in natural river water weaken the repelling forces and allow small groups of individual particles to stick together and form small low density flocs which have a finite settling velocity.

Table 4.3 Dissolved Salts (mg/l) in the wet season (28/11/95)

River Site	Tana at Irira	Lower Mutonga	Lower Kathita	Grand Falls
Ca	6	6	6	(11)
Mg	2	3	4	2
Na	11	14	14	12
K	3	4	5	5
Cl -	6	4	2	6
$CaCO_3$	44	46	56	48
SO_4	6	0	5	4
Fe	1	2	3	(0.03)
Discharge(m^3/s)	89	83	10	330
Total dissolved salts	73	74	89	77
Conductivity (μs/cm)	100	100	115	110

The above concentrations are considered to be sufficient to cause small flocs to form.

The flows through Kiambere Dam were unsteady during both seasons. In the dry season the reservoir was filling and in the wet season the outflow doubled during the period.

One might expect the trapping of slowly settling mud flocs to be directly proportioned to the retention time in a reservoir of similar shape. The average retention time in the Kiambere Mutonga and Low Grand Falls Reservoirs with a flows of 100 and 1000 m^3/s are as follows. The estimated trapping efficiency refers to clay particles travelling the full length of the reservoir.

Table 4.4 Estimated mud trapping efficiency of the reservoirs

	Kiambere	Mutonga	Low Grand Falls
Volume ($10^6 m^3$)	585	132	1261
Retention time at 100m^3/s (days)	68	15	146
Retention time at 1000 m^3/s (days)	7	1.5	14.6
Trapping efficiency at 100 m^3/s	15% (observed)	≈ 5%	≈ 30%
Trapping efficiency at 1000 m^3/s	1.5%	≈ 0.3%	≈ 3%

The observations of turbidity in the Kiambere Reservoir showed that the surface waters were clear compared to the bed water at the deep end of the reservoir, which indicates that the clay particles do settle within the reservoir.

The average settling velocity of the clay flocs (groups of particles) can be estimated approximately from the mean depth of Kiambere Reservoir which is 35m and the time of travel of 68 days at 100 m^3/s. So the settling velocity of the clay particles is of the order of 5 x 10^{-6} m/s. A typical value for fully flocculated mud is 10^{-3} m/s.

The above estimates of the trapping efficiency combined with the flow duration curve and estimates of the mud concentrations in the inflowing water at different discharges indicate that each year about 40,000 tonnes of mud, 20% of the annual influx, is trapped permanently or temporarily in the Kiambere Reservoir. The estimated trapping efficiency of the clay particles varied from 60% at the 10%ile flow to 3% at the 5%ile flow. However mud settling in the deeper water near the dam can be re-eroded by turbulence caused by the flow into the turbine.

4.3 Water quality of the river water

Professor Mavuti successfully organised three water quality sampling surveys of the Tana, upstream and downstream of Kiambere Reservoir at Irira, the lower Mutonga River, the lower Kathita River and Grand Falls in the dry season (26-27/9/95), the beginning of the wet season (28/10/95 - 13/11/95) and the middle of the wet season (25-27/11/95). The observed water quality is shown in Tables 4.5 a-c.

The dissolved oxygen (DO) values were all close to saturation values, BOD_5 was in the range 2-5 mg/l. The dissolved available inorganic nitrogen (DAIN) (NO_2 + NO_3 + NH_4) was observed to be nil in the Kiambere tailrace in the dry season. However, at the same time it was observed to be 0.4 at Irira downstream.

Table 4.5a Dry Season River Survey 26 - 27 September 1995

Dry Season 1995	Discharge m3/s	Temp °C	DO mg/l	BOD_5	DAIN mg/l	DAIP mg/l	Turbidity NTU
Kiambere inflow KS1 (27/9)	≈ 80	25	9	2.0	0.0	0.02	30 (Brown)
Kiambere KS2 outflow (27/9)	80	25	8.6	2.4	0.0	0.02	35 (Brown)
Tana at Irira (26/9)	86	25.0	9.0	4.5	0.4	0.01	60
Mutonga River inflow (26/9)	4.5	21.5	10.2	2.8	0.11	0.01	20
Kathita (26/9)	2	20.0	9.0	2.2	0.11	0.01	15
Grand Falls (26/9)	96.4	25.0	9.0	5.0	0.02	0.01	5

Table 4.5b Early Wet Season Survey 28 October - 13 November 1995

1995 wet season	Discharge m3/s	Temp °C	DO	BOD_5	DAIN	DAIP	Turbidity NTU
Kiambere inflow 13/11/95	117	25.0	8.4	3.1	0.16	0.05	50 (Brown)
Kiambere outflow 13/11/95	≈100	26.0	9.3	3.5	0.16	0.5	60 (Brown)
Tana at Irira 28/10/95	89.4	25.0	10.3	4.5	1.67	0.01	40
Mutonga River 28/10/95	(117)	21.0	9.4	4.3	1.58	0.01	35
Kathita 28/10/95	10.0	23.0	8.7	4.5	1.04	0.01	32
Grand Falls 28/10/95	330	25.0	8.6	3.8	1.04	0.01	45

Table 4.5c **Wet Season River Survey 25 - 27 November 1995**

Wet Season 1995	Discharge m3/s	Temp °C	DO	BOD_5	DAIN	DAIP	Turbidity NTW
Kiambere inflow 27/11/95	114	25.5	8.6	3	0.16	0.05	30 (Brown)
Kiambere outflow 27/11/95	194	25.0	9.6	3.5	0.21	0.05	30 (Brown)
Tana at Irira 25/11/95	198	25.0	9.2	2.0	0.41	0.03	40
Mutonga River 25/11/95	20.5	20.8	9.8	3.6	0.11	0.01	38
Kathita River 25/11/95	11.5	24.0	9.2	2.0	0.11	0.01	33
Grand Falls 25/11/95	391	25.5	9.9	3.9	0.31	0.04	45

There were no measurements of chlorophyll a, but values observed in the reservoir suggest a value of 1 mg/m^3 might be appropriate in the Tana River downstream of Kiambere.

5 Analysis of conditions in Kiambere Reservoir

HR Wallingford commissioned Professor Mavuti to undertake three surveys in Kiambere Reservoir simultaneously with the river water quality surveys in September, October and November 1995.

The results as longitudinal sections of the temperature, DO, BOD_5, total Solids, nitrate and Chlorophyll a are illustrated in Figure 5.1a-c.

5.1 Late dry season survey - 27 September 1995

The water level in the reservoir was 6m below the FSL level, because of low antecedent river flows. The flow through the reservoir was about 80 m^3/s close to the 40%ile value. The condition was one of weak flushing with a retention time of about 60 days. The reservoir was strongly layered as regards water quality but there was only a weak (4°C) thermocline near the surface. The body of the reservoir had a constant temperature of about 24°C. There was no evidence of significant vertical mixing by wind driven currents or waves during the surveys. The observations were made during the day, a period of strong solar heating in the 2m surface layer. The Secchi disc depth was less than 2m. Very strong cooling at night could generate an instability and cause mixing between the surface layer and those below. However, there was no evidence of such mixing.

The observation of 21.5°C at the surface in the entrance to the reservoir was probably observed early in the morning. The concentration of the water quality variables in the plunge pool indicate that the penstock was withdrawing water from a layer about 40m below the water surface. However, the observations reported a whirling undercurrent at a depth of 75m, 1km from the dam. This suggests that the turbines could draw in water from all layers below 40m at higher discharges. The Secchi disc depth of 1.8m indicates appreciable light penetration and productivity to a depth of about 2 metres. The surface layers were super saturated with oxygen in the day time. The DO dropped to 60% of the saturated value in the bed layer near the dam.

The BOD_5 concentrations were all in the range 2 - 3.5 ppm, which may have been close to limit of detection of the methods used. Oxidation of settling algal detrital carbon is unlikely to add to BOD values significantly. Theoretically, the inflowing BOD_5 of 2ppm could reduce the DO value from 9.0 mg/l at the inlet to 7.0 mg/l at the outlet. The DO value of 5.1 mg/l in the bed layer near the dam indicates a relatively small benthal oxygen demand in the reservoir of less than 1 $g/m^2/day$ assuming a plan area of 20 km^2.

The suspended clay flocs in the water column settle by about 30m over the 60 day retention time which is equivalent to a settling velocity of about 5×10^{-6} m/s in the absence of vertical turbulent exchange. The month long sediment survey indicated a trapping efficiency of 15% with a discharge of about 80-100 m^3/s in the Tana River.

However on the 27 September 1995, the concentration of suspended solids in the outflow were slightly higher than at the inlet and compatible with selective withdrawal from a level about 40m below the water surface.

The DAIN (NO_2 + NO_3 + NH_4) concentrations were relatively uniform in the reservoir at a level exceeding 14 mmol/m^3 (0.2 mg/l) at all depths, which may be considered to be nutrient rich.

There was little evidence of nutrient trapping in the reservoir, despite the zero value of nutrients observed in the plunge pool. Higher values were observed downstream at Irira on 26 September 1995 (Table 4.4a). The chlorophyll-a values hardly exceeded 5 mg/m^3 at midday. The light intensity in the surface layer may exceed the optimum level for growth resulting in photo-inhibition. Chlorophyll a concentrations in the slack bed layer near the dam were about 1 mg/m^3.

5.2 Early wet season survey - 13 November 1995

The Tana River discharges were slightly higher at about 115m^3/s during the survey on 13 November 1995, the 50%ile flow. The whole flow passed through the turbines without spilling over the dam.

The BOD_5, suspended solids and DAIN patterns were similar to the dry season survey. There was a deeper and more eutrophic (Chl a > 15 mglm^3) surface layer extending to a depth of more than 5 metres with high levels of super-saturation (140%). The chlorophyll-a concentrations were also higher in the deep water.

5.3 Mid wet season survey - 27 November 1995

The inflow and outflow on the second wet season survey were higher still with an inflow of about 200m^3/s.

The temperature, BOD_5 and suspended solids patterns were unchanged. There was a greater DO sag (24%) in the deepest part of the reservoir below the penstock intake. The DAIN concentrations were more variable with concentrations in the surface layer as low as 0.03 mg/l. However, chlorophyll-a concentrations at the surface were higher at up to 18 mg/m^3.

6 Assumptions

The following assumptions were made in applying the 3D model.

6.1 Solar radiation

The solar radiation was assumed to average 1.4 m Joules/m^2 hr between 0600 and 1800 hrs and to be zero outside this period.

This value was based on the theoretical value at the equator of 600 cal/cm^2/day, an average transmission coefficient of 0.8 and an average of 8 hours sunshine per day.

This is equivalent to 33.5 cal/m^2/hr, which is twice the optimum of 17 cal/m^2/hr for maximum algal growth used in the model.

There was insufficient data on local mereological conditions to predict diurnal temperatures fluctuations in temperature in the surface layer. The buoyancy effect was simulated by assuming negligible vertical turbulence exchange across the thermocline at about 2m. Otherwise, the waters of different temperatures were allowed to mix assuming no net gain or loss of thermal energy. As a result, the model therefore predicted an outflow temperature based on the weighted mean of the inflowing rivers. Observations in the Kiambere Reservoir indicated that the natural equilibrium temperature of water in this part of the Tana Valley is about 25°C throughout the year.

The Mutonga River, and Kathita rivers are fed by snow melt on Mt Kenya. As a consequence, their temperature is only about 18-21°C when they join the Tana River just upstream of the proposed dams.

The Mutonga and Kathita inflows were assumed to enter at the surface, which caused a density inversion and strong vertical mixing in the relevant model segment. The resulting temperature was less than 25°C and caused the water to sink to fill the deep in front of the dam.

In reality, the cooler inflow would flow down the submerged valley as a density current, entraining overlying water in the process and sink into the deep in a slightly less diluted form. However, the process of selective withdrawn would still result in outflow having the same temperature.

6.2 Oxygen balance and nutrients

The rivers were assumed to be saturated with oxygen. The BOD was assumed evenly split between fast and slowly oxidising fractions. The rate of re-aeration, and loss of oxygen to the atmosphere in the case of supersaturation, was assumed to be 37mm/hr which is equivalent to calm conditions. The settled detrital carbon was assumed to apply a benthal oxygen demand based on its mass per unit area. The total available dissolved inorganic nitrogen was assumed to be present as oxidised nitrogen, based on the assumption that the rivers would have largely neutralised the fast acting oxygen demands from sources of urban pollution upstream in terms of ammoniacal nitrogen from raw sewage.

Algal growth was based on the theory in Appendix 1. The rivers were seeded with a chlorophyll a concentration of 1.0 mg/m^3.

6.3 Bacteria

Bacteria were not simulated in the model because there was no information on their mortality which is very low in freshwater.

However, the turbidity of the reservoir and shading by the algal blooms at the surface will severely limit the penetration of light into the water column of the reservoir and allow the bacteria to survive or even multiply during their long residence in the reservoir.

6.4 Settling velocity of mud flocs

The mud particles (clay flocs) were assumed to settle at 5 x 10^{-6} m/s based on an observation of the depth of clear water and travel times observed in the Kiambere Reservoir. The particles were assumed to settle on the bed if the velocity near the bed fell below 0.02 m/s, based on the low trapping efficiency expected in the Mutonga Reservoir. (See Table 4.4).

By comparison, the values for much larger and stronger fully flocculated marine mud are 0.3 m/s and 0.2 m/s.

7 Wet season predictions

The models were set up to simulate conditions in the proposed reservoirs during typical wet season conditions. The Mutonga Reservoir was full with steady inflows of 130 m^3/s from the Tana River and 70 m^3/s from the Mutonga River and an outflow of 200 m^3/s via the turbines. The Low Grand Falls Reservoir, which has an addition inflow of 20 m^3/s from the Kathita River, discharged 220 m^3/s via the turbines. The water quality of the incoming flows was based on the observations as follows:-

Table 7.1 River flows and loads for typical wet season conditions

	Tana	Mutonga	Kathita
Discharge (m^3/s)	130	70	20
percentile flow	22	27	60
Water temperature (°C)	25	21	20
Suspended mud (ppm)	60	120	120
DO (mg/l)	8.4	9.0	8.5
Fast BOD (mg/l)	1.25	2.0	2.0
Slow BOD (mg/l)	1.25	2.0	2.0
NO_3 (mg/l)	0.25	1.5	1.0
PO_4 (mg/l)	0.05	0.01	0.01
Chl a (mg/m^3)	1.0	1.0	1.0

The models were set up to simulate steady conditions starting with no pollutants in the reservoirs. The models were run to a dynamic diurnal equilibrium. This was done to assist in evaluating trapping and flushing efficiencies.

The model was run for 100 days which is much longer than the wet season residence time of 11 days for Tana river water in the Mutonga Reservoir and 73 days for Tana and Mutonga water in the Low Grand Falls Reservoir.

7.1 Mutonga Reservoir

The results at midnight, when DO levels would be expected to be low, are shown in Table (7.2) in the form of a section along the reservoir. The outflow of 200 m^3/s was withdrawn from between 520-530m which is the 8th layer in segment 1.

The water quality of the outflow and the trapping efficiency of the reservoir was as follows:-

Table 7.3 The water quality of the outflow and the trapping efficiency of Mutonga Reservoir - wet season

	Outflow	Inflow	Loss
Temperature (°C)	23.6		-
Mud concentration (ppm)	74.6	(81.0)	8%
DO (%)	82		
Fast BOD (mg/l)	0.5	(1.5)	67%
Slow BOD (mg/l)	1.1	(1.5)	27%
NO_3 (mg/l)	0.64 [0.64]	(0.69)	10% [8]
NH_4 (mg/l)		neg	-
PO_4 (mg/l)	0.028	(0.036)	25%

(Bracketed figures based on incoming loads)

[unrestricted recycling of nitrogen from bed sediments]

The model predicted that the Mutonga water would sink and fill lower depths of the reservoir but otherwise have a short residence time in the reservoir. The temperature of the outflow would be 23.6°C which is lower than the natural equilibrium temperature of the Low Grand Falls Reservoir of 25°C.

The 2m surface layer would rise to about 28°C or more during the day, a process not simulated in the model. However, the damping effect of the thermocline on vertical mixing was allowed for.

The model predicted that 8% of the mud would be trapped in the reservoir. However, this value is sensitive to the prescribed settling velocity and critical shear for deposition.

The DO saturation in the reservoir varied from more than 115% in the surface layer to 66% near the bed at midnight, without an outflow of 82%. The benthal oxygen demand exerted by settled algal detritus was only about 1.5 g/m^2/day. There was no evidence that the BOD load of the river would cause anaerobic conditions in any part of the reservoir. However, it is possible that a small pocket of stagnant anaerobic water could form below the level of the penstock intake at 520m at the base of the dam.

The model predicted that 90% of the total available dissolved organic nitrogen mostly in the form of nitrate, would pass through the reservoir. The remaining 10% was stored in the reservoir. In reality, one would only expect a loss by denitrification in anaerobic conditions in the organic deposits at the bottom of the reservoir. The model showed that the reservoir would not cause a significant reduction in the dissolved nitrogen load carried by the rivers in the wet season (11 tonnes day). No account was taken of particulate nitrogen bound into small quantities of suspended particulate organic matter attached to the river muds.

The model predicted that 25% of the dissolved phosphorus would be trapped in the slowly decaying settled algal detrital matter. It is likely that this will be re-mineralised into the water column given time. However, the model predicted that 85% or more of the clay particles would pass through the reservoir.

The model predicted a continuous diurnally varying algal bloom in the 2m deep surface layer. Chlorophyll a values of 13 mg/m^3 and 115% DO saturation values were persisting at midnight. The bloom was limited by the strong sunlight in the day and maintained by the suppression of vertical mixing caused by the thermocline.

NO_3 in the surface layer fell locally to 0.04 mg/l and 0.004 mg/l, respectively, indicating local nutrient limitation.

The resulting detrital carbon settled onto the bed in the widest parts of the reservoir towards the dam generating a peak benthal oxygen demand of about 1.5 g/m^2/day - not sufficient to cause a serious oxygen sag in the lower layers.

Adjustment of the vertical mixing between the top 4 surface layers (8m) showed that waves, wind stirring or thermal instability and local overturning at night would mix the algae downwards and dilute the algal concentrations. This limited the chlorophyll a and oxygen saturation values in the surface layer to about 5 mg/l m^2 and 100%, respectively. In calm conditions, the effective Secchi disc depth was predicted to be about 2m.

7.2 Low Grand Falls Reservoir

The outflow and associated suspended matter, nutrients and pollutants were input into the head of the Low Grand Falls Reservoir. The water temperature of the outflow was assessed to rise rapidly to 250°C - the natural water temperature in the Tana Valley locally.

The results are shown in Table (7.4) in the form of parallel sections northward along the reservoir. The outflow of 220m^2/s was withdrawn from between 480 and 490m, which is the 6th layer in segment 20 (east of segment 2). The model was run for 100 days, greater than the flushing times of Tana River water in the Reservoir.

Table 7.5 Water quality of the outflow and trapping efficiency of the Low Grand Falls Reservoir - wet season

	Outflow	Inflow	Loss
Temperature (°C)	24.9		-
Mud concentration (ppm)	36.20	(78.7)	54%
DO%	71.1		
Fast BOD (mg/l)	0.01	(0.64)	98%
Slow BOD (mg/l)	0.16	(1.18)	87%
NO_3 (mg/l)	0.44	(0.66)	26%
NH_4 (mg/l)	neg		-
PO_4 (mg/l)	0.01	(0.026)	95%

(Bracketed figures based on incoming loads)

The model predicted that 46% of the influx of suspended clay particles (1418 tonnes/day) would settle in the wider part of the reservoir. The suspended mud concentrations in the surface layers in this part of the reservoir fall to less than 10ppm causing greater light penetration.

However, the surface chlorophyll-a concentrations peaked at only about 5 mg/m^3 near the head of the reservoir and reduced to about 2mg/m^3 in the 4m deep surface layer in the widest part of the reservoir. Nitrate concentrations remain high at about 0.5 mg/l. Phosphate concentrations were below 0.001 mg/l in the surface layers. (Half saturation constant 0.014mg/l). The algal bloom was limited by excessive light and lack of dissolved available phosphate. However, winds were not imposed during the period, which would increase vertical mixing.

The model predicted a minimum DO of 70% of the saturated value over most of the water column and a DO of 100% saturation in the 4m deep surface layers. Benthal oxygen demand was predicted to be only 0.3 g/m^2/d.

The model predicted a 26% loss in nitrate and a 95% loss of dissolved phosphorus, both bound into detrital matter settling on the bed.

8 Dry Season Predictions

The models were set up to simulate conditions in the proposed reservoirs during typical dry season conditions. The Mutonga Reservoir was full with steady inflows of 47 m^3/s from the Tana River and 18 m^3/s from the Mutonga River and an outflow of 65 m^3/s via the turbines. The Low Grand Falls Reservoir gained an additional flow of 10 m^3/s from the Kathita River and discharged 75 m^3/s via the turbines.

The model of the Mutonga Reservoir was run for 100 days which was greater than the residence time of 32 days for Tana water in the reservoir. The model of the Low Grand Falls Reservoir was run for 230 days which is greater than the residence time of 224 days of the Tana and Mutonga rive water in the reservoir doing the dry season.

Table 8.1 River flows and load for typical dry season conditions

	Tana	Mutonga	Kathita
Discharge (m^3/s)	47	18	10
percentile	75	80	80
Water temperature (°C)	25	21.5	20
Suspended mud (ppm)	40	40	40
DO (mg/l)	8.4	9.1	9.2
Fast BOD (mg/l)	2.2	1.5	1.5
Slow BOD (mg/l)	2.2	1.5	1.5
NO_3 (mg/l)	0.4	0.1	0.1
PO_4 (mg/l)	0.02	0.02	0.02
Chl a (mg/m^3)	1.0	1.0	1.0

The models were again run to dynamic equilibrium.

8.1 Mutonga Reservoir

The 3D steady state velocities and concentrations are shown in Table (8.2) in the form a section along the reservoir. The quality of the outflow and the trapping efficiency are listed below.

Table 8.3 The water quality of the outflow and the trapping efficiency of Mutonga Reservoir - dry season

	Outflow	Inflow	Loss
Temperature (°C)	24.0		-
Mud concentration (ppm)	24.9	(40.0)	38%
DO%	71.0		
Fast BOD (mg/l)	0.13	(2.0)	93%
Slow BOD (mg/l)	0.76	(2.0)	62%
NO_3 (mg/l)	0.25 [0.27]	(0.32)	22% [16]
NH_4 (mg/l)	neg		-
PO_4 (mg/l)	0.01	(0.2)	95%

(Bracketed figures based on incoming loads)
[unrestricted recycling of nitrogen from the bed]

The Mutonga reservoir behaved in a similar fashion to the wet season condition except that the residence times for the Tana water was nearly three times longer at 32 days.

As a result, the model predicted that 57% of the mud would settle in the reservoir causing mud concentrations to decrease towards the dam. The DO values in the reservoir did not rise above 100% in the surface layer and fell to a minimum of 55% in the bed layer.

The fast and slow oxidising BOD loads fell by 93% and 62%, respectively, and the benthal demand averaged about 0.7 g/m^2/day. However, the model probably under estimated the DO sag near the dam, which was only 30%.

The model predicted that the reservoir would trap 22% of the available nitrate, and 95% of the dissolved phosphate, much of which might be re-mineralised and flushed out by higher river discharges.

The photic zone was deeper and the peak chlorophyll-a concentrations in the surface layers at midnight were much lower than the wet season at about 5 mg/m^3. There was no evidence of a lack of nitrate in the photic zone. However, phosphate concentrations fell to 0.001 mg/l indicating local nutrient limitation, in the surface layers.

The level of eutrophication appears to be suppressed by photo-inhibition.

8.2 Low Grands Fall Reservoir

The outflow from the Mutonga Reservoir model was input to the Low Grand Falls model. The 3D steady state results are listed in Table 8.4 Outflow from Mutonga Dam was input at the head of the Low Grand Falls Reservoir, except that the water temperature was assumed to rise rapidly to 25°C - the natural water temperature in the Tana River Valley.

Table 8.5 Water quality of the outflow and trapping efficiency of the Low Grand Falls Reservoir - dry season

	Outflow	Inflow	Loss
Temperature (°C)	24.5		-
Mud concentration (ppm)	5.6	(26.9)	79%
DO%	80.9 [79.3]		
Fast BOD (mg/l)	neg	(0.21)	≈ 100%
Slow BOD (mg/l)	0.02	(0.86)	98%
NO_3 (mg/l)	0.12 [0.16]	(0.23)	48% [32]
NH_4 (mg/l)	neg		-
PO_4 (mg/l)	0.003	0.011	≈ 73%

(Bracketed figures based on incoming loads)
[unrestricted recycling of nitrogen from the bed]

The residence time of Tana and Mutonga water entering the head of the reservoir increased for 75 days to about 225 days, the length of the test.

The model predicted at nearly 80% of the incoming load of suspended clay particles (174 tonnes/day) would be trapped evenly over the bed of the reservoir. Suspended mud concentrations were generally about 5ppm throughout the reservoir allowing considerable light penetration and a deeper and weaker diurnal thermocline - not modelled except by suppression of vertical mixing.

Predicted surface chlorophyll a concentrations were low, averaging only about 0.4 mg/l in the 7m deep surface layer. Dissolved nitrate and phosphate concentrations averaged 0.13 mg/l and 0.003 mg/l, respectively. The letter indicating limitation.

The minimum DO was only 80% of the saturated value which prevailed in the surface layer.

The model predicted a loss of 48% incoming dissolved nitrate (0.7 tonnes/day) and a loss of 73% (the incoming dissolved phosphate) (0.05 tonnes/day).

Unrestricted recycling of nitrogen from the bed reduced nitrate trapping from 48% to 32% per day after 230 days.

9 *Discussion*

9.1 Method of using the models

Unlike the earlier forecasts of expected water quality in the proposed Mutonga and Low Grand falls reservoirs, which were based on relatively sparse data from existing reservoirs upstream - the present study was based on a deterministic predictive mathematical model using field data to provide dissolved and suspended input loads to the new reservoirs. Because of the need to make the new observations during the dry and second wet season in September and

November 1995, the necessary data only became available in January 1996. As a result, the water quality modelling had to be completed in a few weeks.

The present study was based on three sets of simultaneous observations of flow and river quality in the rivers that will feed into the new reservoirs (Tables 4.5a-c). These were used to estimate typical equivalent steady dry and wet season inflows (Tables 7.1 and 8.1). The models of the Mutonga and Low Grand Falls reservoir were run in series (one feeding the other) for periods exceeding their water retention times (10-220 days) so that they approached a state of dynamic (diurnal) equilibrium. This was done to allow a rapid estimation of the percentage of solids, decaying organic matter, and nutrients that are likely to be trapped in the reservoirs.

9.2 Fluvial mud (clay) loads

The magnitude of the load of clay particles and it's associated organic matter has an important influence on the eutrophic conditions in the lake and the flux of nutrients passing downstream. The suspended clay particles control light penetration and traps nutrients in the bed. It also contains slowly oxidising organic detritus which adds to the benthal oxygen demand in time. The model simulated the depth of the photic zone to be between 2-4m in both reservoirs.

One of the main uncertainties was the percentage of the observed suspended sediment load of the Mutonga and Kathita Rivers in the wet season that was in the clay size range. The present study was based on the assumption that the percentage of clay in the wet season were relatively small as reported in the draft report on sediment load field studies by Prof K M Mavuti.

The models are capable of predicting the effect of a real annual hydrograph if one could establish approximate rating curves for the flux of the clay fractions and associated nutrients and organic matter at stations 4EA7 on the Mutonga River and 4F19 on the Kathita River.

9.3 Large episodic fluvial floods

Large (>200m^3/s) sand, silt and mud-laden-cold water-floods from the Mutonga River are likely to flow directly into the bottom of the Mutonga Reservoir as a density current. The turbines would withdraw the Mutonga water preferentially compared to the warmer less dense Tana River water - as soon as the flood water had submerged the outtake at 530m. The volume of the dead zone, below the outtake, is 16 x 10^6 m^3 (Figure 3.3).

This volume is equivalent to 1 day at 200m^3/s. Mutonga floods of a lesser volume will be trapped in this dead zone (Figure 3.2). The still cold, mud-laden flood water for the Mutonga River that passed through the turbines would flow down the length of the Grand Falls Reservoir as a density current entraining overlying water and eroding the soft bed deposits. These effects can only be simulated in a fine gridded 3D model, which can only be used to simulate a few days at a time, and is outside the scope of the present study.

Large, cold, sediment-laden flows from the Kathita River would behave in the same fashion. However, the volume of the dead zone below the out-take at 490m in the Grand Falls Reservoir, is about 260 x 10^6 m^3 - much larger than for the Mutonga Reservoir. This dead zone is likely to silt up with silt and mud from both the Kalhita and Mutonga rivers. The coarser sandy fractions will form a delta in the original submerged valleys of the two tributaries.

Turbulence near the out-take may help keep fine sediments in suspension in the dead zone (Figures 5.1-5.3). It might be practical to install a low level outlet to help flush the dead zone. Once the dead zones are filled in, the cold, sediment-laden flood waters of the Mutonga and Kathita river will tend to erode soft muds from the bottom of the reservoir and carry it through the turbines thereby flushing organic muds out of the reservoir.

The predictions presented in this report do not show the effect of episodic floods on the water quality of the reservoirs, mainly because of the lack of data to estimate the clay and nutrient loads during floods.

9.4 Settling velocity of mud flocs

An analysis of the fluxs and distribution of relatively dilute suspension of mud in the Kiambere Reservoir indicate that there were sufficient salts in solution (Table 4.3) to cause the individual clay particles to form into small flocs with a very low but significant settling velocity estimated to be about 5×10^{-6} m/s. This value was used in the model, and largely determines the trapping efficiency of the reservoir. The second factor is the velocity which prevents deposition from suspension.

The mud (clay) trapping efficiency of the Mutonga Reservoir was estimated roughly from the observed trapping efficiency of the existing Kiambere Reservoir (Table 4.4) in typical dry and wet season conditions (Table 4.2) by consideration of their relative residence times (Table 4.4).

The critical velocity to allow deposition was found by trial and error to be about 20mm/s. In other words, it was adjusted to give the Mutonga reservoir a realistic trapping efficiency compared to that observed in the Kiambere reservoir . The mud trapping efficiency of the new reservoirs during typical dry and wet season conditions were predicted as follows:-

Table (9.1) Predicted mud trapping efficiencies of the reservoirs

	Mutonga	L.G Falls	Combined
Wet Season			
Trapping efficiency	8%	54%	60%
Influx (t/d)	1400	1496	1728
Outflow (t/d)	1290	690	690
Dry season			
Trapping efficiency	38%	79%	86%
Influx (t/d)	224	174	258
Outflow (t/d)	140	36	36

The trapping efficiency of the two reservoirs in the dry season may have been over predicted because the model assumed that the mud flows would have a constant settling velocity, when in reality it probably decreases with decreasing mud concentrations because of the reduced probability of collisions between suspended flocs.

The model assumed that the mud would settle on the submerged side slopes of the reservoir which are steep in places. In reality, one might expect significant quantities of settled mud to slump or flow into the bottom of the reservoir. This would increase the thickness of the deposits and increase the local benthal oxygen demand in the lowest layers of the water column if the sediment contained a significant percentage of decaying organic matter.

9.5 Recycling of nitrogen from settled detrital matter

The basic predictive tests simulated the recycling of nitrogen from slowly settling decomposing algae detritus. The rate of decomposition was assumed to be similar to that of slow BOD, namely 0.046 d^{-1}. The resulting dissolved slow organic nitrogen was assumed to hydrolise to ammoniacal nitrogen at a rate of 0.046 d^{-1}, which was in turn oxidised to nitrate at 0.26 d^{-1}. However, the process takes so long that the detritus settled on the bed before there was any significant recycling of nitrogen.

Once on the bed, the detrital nitrogen was assumed to be locked into the bed. The basic tests therefore simulated a condition of minimum recycling of nitrogen within the reservoir.

However, since the model predicted that during the first few years the settled deposit would have a relatively low benthal oxygen demand, the overlying water would be reasonably well-oxygenated water and the deposits are likely to have a low density - it is quite likely that the organic nitrogen will diffuse through the organic muddy ooze into the water column above without being reduced to nitrogen. In ideal conditions, averaged over the long term, one could expect the rate of vertical diffusion of organic nitrogen from the bed to balance the rate of deposition of detrital nitrogen.

To test the effect of this ideally efficient rate of recycling, the model of the Low Grand Falls Reservoir was re-run assuming that all nitrogen would be released in time from the decaying benthal detritus back into the water column in the form of soluble slow organic nitrogen. The effect was to increase nitrate concentrations in the hypolimnion and the outflow by 26% compared to the base line tests as shown in Table (9.2). [The sinking algae detritus and recycled nutrients may be the cause of the discoloured water at depth in Kiambere Reservoir (Figures 5.1-5.3)]. After 230 days, starting from a clear reservoir, the only 30% of the daily inflow of nitrate nitrogen was trapped in the L.G. Falls reservoir. There was also a small increase in the daily outflow of ammoniacal nitrogen and organic nitrogen.

The algal bloom in the surface layer was totally unaffected by the recycling of nitrogen form the settled deposit, because of the lack of vertical mixing. Dissolved oxidised nitrogen (nitrate) usually comprises 95% of the dissolved available inorganic nitrogen. Ammoniacal ammonia concentrations are usually low.

The nitrate trapping efficiency of the new reservoirs during typical dry and wet conditions were predicted as follows:-

Table (9.2) **Predicted nitrate trapping efficiency of the reservoir**

	Mutonga	L.G. Falls	Combined
WET SEASON	100 days	100 days	
No benthal recycling			
Trapping efficiency	10%	26%	38%
Influx (t/d)	11.9	12.5	13.6
Outflow (t/d)	10.7	8.4	8.4
With benthal recycling			
Trapping efficiency	8%		
Influx	11.9		
Outflow	10.9		
DRY SEASON	100 days	230 days	
no benthal recycling			
Trapping efficiency	22%	48%	55%
Influx	1.8	1.5	1.8
Outflow	1.4	0.8	0.8
With benthal recycling			
Trapping efficiency	17%	32%	42%
Influx	1.8	1.6*	1.9
Outflow	1.5	1.1*	1.1

*Adjusted to allow for recycling in Mutonga Reservoir

9.6 Phosphorous

The model was run using estimated loads of dissolved available inorganic phosphorous.

The concentrations of dissolved phosphorous in the rivers varied from 0.01 - 0.05mg/l (Table 7.1 and 8.1) Observations in the November 1995 wet season at Station 4EA7 on the Mutonga River indicated concentrations of particulate phosphorous averaged about 2ppm of the average dry weight of all suspended solids of 12000ppm. This is equivalent to a concentration of phosphorous of 0.024mg/l. In aerobic conditions, particulate phosphorous is strongly locked onto the clay particles and is not available to phytoplankton and it was assumed to be trapped in the bed sediments.

9.7 Changes with the age of the reservoirs

Over time, one would expect the accumulative settlement of particulate organic matter from the Mutonga and Kathita Rivers to raise the benthal oxygen demand in the dead zones of both reservoirs. This will reduce DO levels which may become anoxic on some occasions.

Pacini (1994) used field data from the Kindaruma, Kamburu, Gitaru, Masinga and Kiambere Reservoirs to postulate that their N/P ratios increased from 10 to 100 over a period of 25 years. This implies an increase in phosphorous limitation and a change of dominant algae species in time. There is also the effect of accumulative trapping of nutrients; clay and organic matter in the cascade of reservoirs. However, the Grand Falls Reservoir will be fed by the undiluted fluxes of nutrients and organic matter from the Mutonga and Kathita Rivers.

9.8 Primary production

Professor Mavuti (1996) reported that the following plankton species were found in Kiambere Reservoir.

Nitschia sp.	Microcystis auriginosa
Synedra sp.	Melosira sp
Botryococus sp	Ceratium sp.
Cyclotella sp.	Cryptonomas sp.
Rhodomonas spp	

However, no data exists on algae growth rates for any water bodies in Kenya. There is also no information on the rate of predation by the numerous zooplankton and larvae fishfry.

The theory used to predict algae growth in the model is given in Appendix I. The reaction coefficients are given in Table 9.3. The half saturation nutrient concentrations permitting 50% of maximum productivity were as follows:-

Nitrate	0.1mg/l
Phosphorous	0.014mg/l
Silica	0.0mg/l

Table 9.3 Reaction constants

0.23	4.7	0.2	BOD: rate const., t coeff., rate of decay
0.23	4.7	0.2	Fast Org N: rate const., t coeff., rate of decay
0.26	4.7		Nitrification AM: rate const., t coeff
0.0	4.7		De-nitr. Of ox.nitrogen: rate const., t coeff
0.037			Oxygen exchange coeff (m/hr)
1.6	0.5		Reaeration coeff. And rate
0.1	0.16		Nitrate: Half-sat.n constant, N-Carbon phytopl. ratio
0.014	0.024		Phosphate: Half-sat.n constant, P-Carbon ratio
0.00	0.00		Silica: Half-sat.n constant, SI-Carbon ratio
0.037	-1.564		Gradient & Intercept parameters for max production
17.0			Light intensity for max productivity (cal/cm2/hr)
0.02	2.2		Max respiration rate (gC/day), respirat.n param
1.7	0.85		Light extinction coeffs : phytopl. & detritus
0.35			Mortality of phytoplankton
0.046	4.7		Detritus: Decay rate, temp. Coeff of decay
0.001	0.1		Settling velocity of phytoplankton & detritus (mm/s)

The light intensity for maximum productivity was 17 cal/cm²/hr, which might be too low for African conditions. The phytoplankton mortality rate was set at a constant 0.35 d^{-1}.

The model predictions in terms of Chlorophyll-a and DO concentrations in the surface layers depends on these constants. The could be optimised by trial and error by simulating observed conditions in Kiambere Reservoir.

9.9 Diurnal heating

The analysis of the theoretical clear sky solar radiation shows that it varies slightly throughout the year and that the values used in the model were representative of any time in the year. However, it was not possible to assess the density of the observed cloud cover.

The model has the capability of simulating the diurnal heating and cooling of the surface layers, which may cause instability and deepening of the surface layer at night. But there was insufficient data to do a complete thermal balance, which has to take into account evaporation losses etc.

The effect of diurnal heating is to raise the mean average daily water temperature of the surface layer compared to the body of the reservoir. This in turn causes a stable density gradient which almost totally suppresses vertical turbulent exchange between the photic zone and the much larger water body below. This effect was simulated by assuming negligible vertical mixing between the top flow layers of the reservoir.

9.10 Wind effects

The observed wind speeds at the Kindaruma Fisheries Station average 65 miles/day through the year, which is only 1.2m/s, and would hardly effect the reservoir. However, values in excess of about 5m/s would drag the buoyant surface layer down wind and cause upwelling and vertical mixing. Strong episodic wind effects could therefore disrupt the normal stable thermal stratification and bring nutrient rich waters to the surface thereby causing a sudden large algae bloom. The reservoir would then return to its normal stable conditions. The model is capable of simulating such episodic events, but if they are rare they will not affect the nutrient balance of the reservoirs.

9.11 Local pollution

The reported problems of high bacterial counts preventing the local population from using the Tana reservoirs for drinking purposes may be related to local urban pollution in poorly flushed bays within the reservoirs.

9.12 Comparison with phase 2 predictions

Mavuti (1994) used the observed water quality in the existing Tana River hydropower reservoirs to predict conditions in the Mutonga and Low Grand Falls reservoirs. He expected the nitrate and phosphate concentrations to be medium to high, and the Chl.a biomass to be low in Mutonga Reservoir and medium in Low Grand Falls Reservoir. The suspended solids were expected to be in the range 20 - 30 mg/l and the Secchi depth to be 0.3 - 1.5m.

The conclusions of the present modelling study is that nitrate concentrations will be generally in the range of 0.1 - 1.0 mg/l, which is relatively low but will hardly limit algal growth. However, concentrations of dissolved available phosphate in the warmer 2-4m deep photic zone are likely to fall below 0.01 ppm and will limit the algal biomass (chl-a) in much of the downstream parts of the reservoirs in calm conditions to between about 5-15 mg/m^3. Suspended solids concentrations will be considerably lower in the surface than the bed layers. The DO sag at depth is likely to deepen in time but to remain aerobic.

10 Summary and Conclusions

This report forms a series of reports that will be accompanied by an overview report covering the potential impacts of proposed dam construction for hydropower production on the Tana River.

The report describes an assessment of the dry and wet season water quality in the Tana, Mutonga and Kathita Rivers and within the existing Kiambere Reservoir in September and November 1995. It also describes the application of a deteministic three-dimensional segmented and layered model, which was used to predict the water quality and flushing of nutrients and particulate matter through the proposed Mutonga and Low Grand Falls Reservoirs.

The 3D models of the Mutonga and Grand Falls reservoirs were run in series - one flowing into the other - and were used to simulate typical wet and dry season conditions with steady 20 and 80 percentile fluvial flows, respectively.

The analysis of the Kiambere reservoir data indicated that it trapped about 15% of the wash load of clay particles, which are weakly flocculated by the presence of natural salts in solution (75ppm) and settle at a rate estimated to be about 5 x 10^{-6}m/s.

The models predicted that about 60% and 85% of the suspended load of clay particles and the associated phosphate and organic matter would be trapped, mainly in the Low Grand Falls reservoir, during typical wet and dry season conditions, respectively. The latter figure may be overestimated as a result of using a constant settling velocity. During floods from the Mutonga and Kathita rivers, much higher, but as yet unquantified, masses of suspended silts and clay will pass rapidy through the L.G. Falls reservoir, as a cold density current, scouring the soft bed and will settle in the dead zone below the out take or pass downstream through the turbines.

The models predicted that the two reservoirs operating in series would trap about 40% and 55% of the daily influx of dissolved nitrate, mainly in the Low Grand Falls reservoir, during typical wet and dry season conditions with recycling of organic nitrogen from settling detritus, but not from the bed.

If conditions in the bed allowed optimum rates of recycling of organic nitrogen from settled algal detritus, the trapping rates would be expected to fall to about 25% and 40% during typical wet and dry seasons, respectively.

The model predicted that algal growth in the surface layers would not be significantly effected by recycling of dissolved available inorganic nitrogen into the lower layers of the reservoir, unless strongwinds caused upwelling.

The particulate phosphorous trapped in the settled mud and detritus will not be recycled easily and will not be available to phytoplankton in the photic zone. The model predicted that the reservoirs would trap about 95% of the relatively small incoming loads of dissolved available phosphorous and that the surface algae blooms in the surface layers would be limited by lack of phosphorous.

The model predicted a 2-4m deep photic zone with variable and an acceptable range of chlorophyll-a concentrations (ie 5-15 mg/m^3) depending on light penetration, the horizontal flux of nutrients. The model also predicted a moderate DO sag in the deeper layers of both reservoirs. However, the DO sag could deepen further with time as a result of an accumulation of settled decaying organic matter raising the benthal oxygen demand in the dead zones of the reservoirs.

10.1 Further studies

The model predictions are sensitve to the factors affecting the growth of the specific algae species in the Tana River reservoirs which is not available, but could be obtained from new research by HR and Dr Mavuti. There is also a lack of knowledge of the rate of recycling of nitrogen from settled mud and detrital matter. The coefficients should be tested by simulating conditions in the existing Kiambere reservoir.

There is a need to construct rating curves for the flux of suspended mud, organic matter and particulate and dissolved nutrients for the Mutonga and Kathita Rivers. There is also a need for a daily record of meteorological conditions and synthesised sediment and pollution loads so that the models can be run for a number of years including solar heating, and wind effects.

There is a need to study the detailed behaviour of the passage of sediment laden floods from the Mutonga and Kathita Rivers through the reservoirs, using a fine-gridded 3D model.

11 References

N Pacini Coupling of land and water phosphorous fluxes in the Upper lana River Catchment, Kenya. Ph D. Thesis. Department of Zoology Leicester University, May 1994.

K Mavuti Draft report on water quality of Kiambere Dam/Reservoir prepared for HR Wallingford December 1995.

K Mavuti Mutonga Grand Falls Hydropower Plan 3 Study Sediment Load and Release Studies. Draft report December 1995.

K Mavuti Grand Falls Hydropower Project Stage 2. Draft report on Limnology and Fisheries, December 1994.

Tables

Table 7.2 Typical wet season conditions - Mutonga Reservoir

TYPICAL WET SEASON CONDITIONS IN MUTONGA RESERVOIR

U-VELOCITY east-west (m/s)

8
-.2882E-01
-.2405E-01
-.1559E-01
-.1070E-01
0.5740E-02
0.1954E-01
0.6242E-01
0.8139E-01
0.

7	6	5	4	3	2	1
0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.1667
0.	0.	0.	0.	0.	0.	0.

V-VELOCITY north-south (m/s)

8
0.
0.
0.
0.
0.
0.
0.
0.
0.

7	6	5	4	3	2	1
0.	0.1561	0.2029	0.5100E-01	0.4899E-01	0.7051E-01	0.9456E-03
0.	0.1687	0.1926	0.5204E-01	0.4242E-01	0.6635E-01	0.9277E-02
0.	0.1765	0.1775	0.5092E-01	0.3641E-01	0.4825E-01	0.2103E-01
0.	0.1626	0.1661	0.4910E-01	0.2708E-01	0.4439E-01	0.2271E-01
0.	0.1334	0.1418	0.4528E-01	0.1856E-01	0.2517E-01	0.2549E-01
0.	0.	0.	0.4491E-01	0.1572E-01	0.1926E-01	0.1864E-01
0.	0.	0.	0.2107E-01	0.3539E-02	0.6559E-02	0.2320E-02
0.	0.	0.	0.	0.	-.2079E-01	-.1276E-01
0.	0.	0.	0.	0.	0.	0.

VERTICAL VELOCITY down: -ve (m/s)

8
-.1415E-03
-.2042E-03
-.2822E-03
-.4030E-03
-.6159E-03
-.7914E-03
-.1302E-02
0.
0.

7	6	5	4	3	2	1
-.7207E-03	-.1029E-04	-.1084E-04	0.1060E-04	0.1788E-06	-.1489E-04	0.7663E-05
-.5252E-03	-.9609E-05	-.2417E-04	0.1979E-04	0.2553E-05	-.2818E-04	0.9950E-05
-.3386E-03	-.9723E-05	-.3947E-04	0.2809E-04	0.3009E-05	-.2681E-04	-.2477E-05
-.1578E-03	-.7691E-05	-.6019E-04	0.3317E-04	0.6782E-05	-.2414E-04	-.1864E-04
0.	0.	-.9229E-04	0.3622E-04	0.9060E-05	-.1304E-04	-.4338E-04
0.	0.	-.6485E-04	0.2839E-04	0.1242E-04	0.5956E-06	-.9157E-04
0.	0.	0.	0.	0.2263E-04	-.3115E-05	-.2271E-03
0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.

TYPICAL WET SEASON CONDITIONS IN MUTONGA RESERVOIR

X-DISCHARGES east-west (cumec)

8
-24.64
-18.33
-10.51
-6.281
2.669
13.29
48.69
65.12
0.

7	6	5	4	3	2	1
0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	200.0
0.	0.	0.	0.	0.	0.	0.

Y-DISCHARGES north-south (cumec)

8
0.
0.
0.
0.
0.
0.
0.
0.
0.

7	6	5	4	3	2	1
0.	39.84	35.24	23.51	38.53	38.90	9.590
0.	30.37	31.20	20.66	30.20	34.57	15.46
0.	25.07	25.55	17.82	23.19	23.40	32.48
0.	20.32	21.43	15.37	14.95	19.71	29.68
0.	14.40	16.59	12.22	8.576	9.915	26.68
0.	0.	0.	21.29	11.63	12.48	25.50
0.	0.	0.	19.12	2.920	3.818	2.276
0.	0.	0.	0.	0.	-12.79	-11.67
0.	0.	0.	0.	0.	0.	0.

Z-DISCHARGES down: -ve (cumec)

8
-94.64
-113.0
-123.5
-129.8
-127.1
-113.8
-65.12
0.
0.

7	6	5	4	3	2	1
-90.16	-4.603	-11.72	15.01	0.3696	-29.31	15.05
-59.79	-3.776	-22.26	24.56	4.737	-48.41	17.92
-34.72	-3.292	-29.99	29.92	4.943	-39.33	-4.055
-14.40	-2.186	-36.05	29.50	9.704	-29.36	-27.46
0.	0.	-40.41	25.86	11.04	-12.59	-56.81
0.	0.	-19.12	16.20	11.89	0.4300	-95.60
0.	0.	0.	0.	12.79	-1.112	-146.6
0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.

TYPICAL WET SEASON CONDITIONS IN MUTONGA RESERVOIR

VOLUMES m3

						8
						0.1453E+07
						0.1222E+07
						0.9908E+06
						0.7595E+06
						0.5283E+06
						0.7003E+06
						0.5814E+06
						0.3000E+06
						0.
7	6	5	4	3	2	1
0.2621E+06	0.9506E+06	0.2327E+07	0.3011E+07	0.4340E+07	0.4189E+07	0.4092E+07
0.2390E+06	0.8404E+06	0.2003E+07	0.2657E+07	0.3922E+07	0.3686E+07	0.3765E+07
0.2164E+06	0.7316E+06	0.1681E+07	0.2306E+07	0.3498E+07	0.3185E+07	0.3438E+07
0.1938E+06	0.6229E+06	0.1359E+07	0.1955E+07	0.3074E+07	0.2683E+07	0.3110E+07
0.1713E+06	0.5141E+06	0.1037E+07	0.1603E+07	0.2650E+07	0.2181E+07	0.2783E+07
0.	0.	0.1465E+07	0.2569E+07	0.4352E+07	0.3375E+07	0.4707E+07
0.	0.	0.2064E+07	0.3190E+07	0.4567E+07	0.3237E+07	0.5068E+07
0.	0.	0.	0.	0.5043E+07	0.3333E+07	0.4879E+07
0.	0.	0.	0.	0.	0.	0.8883E+06

X-1D-DISCHARGES (cumec)

						8
						70.00
7	6	5	4	3	2	1
0.	0.	0.	0.	0.	0.	200.0

Y-1D-DISCHARGES (cumec)

						8
						0.
7	6	5	4	3	2	1
0.	130.0	130.0	130.0	130.0	130.0	130.0

LATERAL INFLOWS (cumec)

						8
						70.00
7	6	5	4	3	2	1
130.0	0.	0.	0.	0.	0.	0.

TYPICAL WET SEASON CONDITIONS IN LOW GRAND FALLS RESERVOIR DAY 100

VOLUMES m3

19	18	17
0.3717E+07	0.4369E+07	0.3184E+07
0.3419E+07	0.4086E+07	0.2641E+07
0.4321E+07	0.5504E+07	0.3205E+07
0.5049E+07	0.7507E+07	0.5635E+07
0.4207E+07	0.7508E+07	0.
0.5031E+06	0.1046E+07	0.
0.	0.	0.
0.	0.	0.

16	15	14	13	12	11	10	9	8	7	6
0.6542E+06	0.2807E+07	0.1030E+08	0.9751E+07	0.1311E+08	0.1682E+08	0.1619E+08	0.1059E+08	0.6438E+07	0.6336E+07	0.2132E+07
0.5383E+06	0.2445E+07	0.9357E+07	0.9035E+07	0.1238E+08	0.1599E+08	0.1559E+08	0.1053E+08	0.6300E+07	0.5762E+07	0.1660E+07
0.5956E+06	0.3168E+07	0.1230E+08	0.1235E+08	0.1720E+08	0.2242E+08	0.2208E+08	0.1558E+08	0.9041E+07	0.7342E+07	0.1922E+07
0.4278E+06	0.3946E+07	0.1589E+08	0.1739E+08	0.2502E+08	0.3317E+08	0.3333E+08	0.2540E+08	0.1398E+08	0.8767E+07	0.1688E+07
0.	0.3311E+07	0.1911E+08	0.2331E+08	0.3606E+08	0.4982E+08	0.5207E+08	0.4573E+08	0.2016E+08	0.7708E+07	0.
0.	0.	0.	0.9349E+07	0.1680E+08	0.2772E+08	0.3091E+08	0.3267E+08	0.8086E+07	0.1119E+07	0.
0.	0.	0.	0.	0.	0.	0.2176E+08	0.1274E+08	0.1724E+07	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.7847E+06	0.	0.	0.

5	4	3
0.9724E+06	0.7238E+07	0.4678E+07
0.7565E+06	0.7141E+07	0.4245E+07
0.8390E+06	0.1039E+08	0.5526E+07
0.6095E+06	0.1647E+08	0.6964E+07
0.1166E+06	0.2789E+08	0.7246E+07
0.	0.1922E+08	0.1775E+07
0.	0.8562E+07	0.
0.	0.1954E+07	0.

2	1	20
0.3181E+07	0.2541E+07	0.3181E+07
0.3103E+07	0.2294E+07	0.3103E+07
0.4514E+07	0.3004E+07	0.4514E+07
0.7147E+07	0.3842E+07	0.7147E+07
0.1247E+08	0.4481E+07	0.1247E+08
0.9314E+07	0.1757E+07	0.9314E+07
0.4557E+07	0.4085E+06	0.4557E+07
0.2110E+07	0.	0.3014E+07

TYPICAL WET SEASON CONDITIONS IN LOW GRAND FALLS RESERVOIR DAY 100

X-DISCHARGES east-west (cumec)

19	18	17
4.701	6.514	1.970
3.836	5.049	0.9993
-2.461	1.632	0.4730
-6.622	-1.619	-1.174
-6.184	-5.787	0.
-.6792	-.6474	0.
0.	0.	0.
0.	0.	0.

16	15	14	13	12	11	10	9	8	7	6
0.	0.	0.	0.	0.	0.	6.372	27.53	0.8034E-01	0.	0.
0.	0.	0.	0.	0.	0.	5.236	26.49	0.4433	0.	0.
0.	0.	0.	0.	0.	0.	3.176	28.57	1.929	0.	0.
0.	0.	0.	0.	0.	0.	2.513	42.45	2.270	0.	0.
0.	0.	0.	0.	0.	0.	1.539	62.64	1.503	0.	0.
0.	0.	0.	0.	0.	0.	0.	18.12	0.1031	0.	0.
0.	0.	0.	0.	0.	0.	0.	-8.575	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	-2.389	0.	0.	0.

5	4	3
0.	23.54	0.6177
0.	22.61	0.6535
0.	26.38	1.596
0.	39.94	2.185
0.	60.96	3.011
0.	30.56	0.4967
0.	7.867	0.
0.	-.4197	0.

2	1	20
30.95	0.	0.
28.40	0.	0.
26.71	0.	0.
35.84	0.	0.
44.50	0.	0.
31.58	0.	220.0
21.41	0.	0.
0.6098	0.	0.

TYPICAL WET SEASON CONDITIONS IN LOW GRAND FALLS RESERVOIR DAY 100

Y-DISCHARGES north-south (cumec)

19	18	17
0.	3.323	0.8219
0.	2.366	0.1900
0.	1.251	-.3909
0.	0.4543	1.647
0.	0.1614E-01	0.
0.	0.	0.
0.	0.	0.
0.	0.	0.

16	15	14	13	12	11	10	9	8	7	6
0.	50.05	37.61	41.46	40.75	44.11	35.13	17.76	1.833	3.748	-2.992
0.	45.05	33.71	36.80	37.54	40.40	32.85	16.06	0.8485	2.015	-3.758
0.	54.53	37.95	34.83	31.77	31.83	30.34	20.13	-2.224	-1.402	-5.947
0.	50.37	45.66	41.27	40.57	39.98	42.58	29.20	-5.484	-6.862	-7.304
0.	0.	45.07	45.63	42.75	39.04	48.12	55.45	-12.21	-14.93	0.
0.	0.	0.	0.	6.624	4.632	10.98	28.83	-3.681	-4.842	0.
0.	0.	0.	0.	0.	0.	0.	13.73	-.1617	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.

5	4	3
0.	0.2000	-6.248
0.	-.4839E-01	-5.699
0.	4.773	-1.414
0.	5.672	0.6831
0.	8.240	9.258
0.	0.	5.650
0.	0.	0.
0.	0.	0.

2	1	20
0.	-.6974E-01	0.
0.	-1.071	0.
0.	-4.357	0.
0.	-5.028	0.
0.	-2.576	0.
0.	2.281	0.
0.	2.261	0.
0.	0.	0.

TYPICAL WET SEASON CONDITIONS IN LOW GRAND FALLS RESERVOIR DAY 100

Z-DISCHARGES down : -ve (cumec)

19	18	17
8.023	4.013	1.148
14.22	6.887	1.957
13.01	6.877	2.821
6.847	6.451	0.
0.6792	0.6474	0.
0.	0.	0.
0.	0.	0.
0.	0.	0.

16	15	14	13	12	11	10	9	8	7	6
-150.0	-12.44	3.858	-.7143	3.357	-8.978	-11.00	6.904	-4.518	-8.710	-17.01
-104.9	-23.79	6.950	0.1813E-01	6.222	-16.53	-22.55	14.34	-7.958	-15.48	-13.25
-50.37	-40.36	3.829	-3.039	6.283	-18.02	-29.58	23.02	-6.839	-20.50	-7.304
0.	-45.07	-.5625	-3.741	5.697	-15.43	-40.45	37.41	-4.327	-19.77	0.
0.	0.	0.	-6.624	1.992	-6.347	-31.59	38.58	0.2489	-4.842	0.
0.	0.	0.	0.	0.	0.	-13.73	24.86	-.1617	0.	0.
0.	0.	0.	0.	0.	0.	0.	2.389	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.

5	4	3
-6.172	-10.43	6.785
-11.46	-19.96	12.69
-9.861	-28.34	13.77
-6.701	-35.84	13.01
0.	-36.50	5.256
0.	-18.41	0.
0.	-1.969	0.
0.	0.	0.

2	1	20
7.336	-.5480	-30.95
12.06	-.1301	-59.35
8.030	2.630	-86.06
-1.097	5.474	-121.9
-20.13	5.038	-166.4
-16.83	2.261	22.02
-1.030	0.	0.6098
0.	0.	0.

TYPICAL WET SEASON CONDITIONS IN LOW GRAND FALLS RESERVOIR DAY 100

U-VELOCITY east-west (m/s)

19	18	17
0.1073E-02	0.1904E-02	0.1751E-02
0.8879E-03	0.1507E-02	0.1234E-02
-.3935E-03	0.3425E-03	0.5390E-03
-.6740E-03	-.2232E-03	-.1044E-02
-.5089E-03	-.6273E-03	0.
-.2515E-03	-.2698E-03	0.
0.	0.	0.
0.	0.	0.

16	15	14	13	12	11	10	9	8	7	6
0.	0.	0.	0.	0.	0.	0.4783E-02	0.6284E-02	0.2861E-04	0.	0.
0.	0.	0.	0.	0.	0.	0.4593E-02	0.6047E-02	0.1716E-03	0.	0.
0.	0.	0.	0.	0.	0.	0.2139E-02	0.4349E-02	0.6011E-03	0.	0.
0.	0.	0.	0.	0.	0.	0.1340E-02	0.3877E-02	0.6342E-03	0.	0.
0.	0.	0.	0.	0.	0.	0.1026E-02	0.2976E-02	0.5726E-03	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.1330E-02	0.6876E-03	0.	0.
0.	0.	0.	0.	0.	0.	0.	-.9581E-03	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	-.1593E-02	0.	0.	0.

5	4	3
0.	0.5549E-02	0.4134E-03
0.	0.5379E-02	0.4777E-03
0.	0.4253E-02	0.8958E-03
0.	0.3968E-02	0.9710E-03
0.	0.3429E-02	0.1217E-02
0.	0.2355E-02	0.7358E-03
0.	0.5959E-03	0.
0.	-.1998E-03	0.

2	1	20
0.9278E-02	0.	0.
0.8916E-02	0.	0.
0.5976E-02	0.	0.
0.5390E-02	0.	0.
0.4495E-02	0.	0.
0.4821E-02	0.	0.3359E-01
0.2817E-02	0.	0.
0.1682E-03	0.	0.

TYPICAL WET SEASON CONDITIONS IN LOW GRAND FALLS RESERVOIR DAY 100

V-VELOCITY north-south (m/s)

19	18	17
0.	0.1792E-02	0.3722E-03
0.	0.1448E-02	0.9146E-04
0.	0.6842E-03	-.1394E-03
0.	0.3274E-03	0.2150E-03
0.	0.4610E-04	0.
0.	0.	0.
0.	0.	0.
0.	0.	0.

16	15	14	13	12	11	10	9	8	7	6
0.	0.1023	0.3621E-01	0.1225E-01	0.1157E-01	0.1033E-01	0.5426E-02	0.3630E-02	0.4662E-03	0.1233E-02	-.1813E-02
0.	0.1065	0.3497E-01	0.1191E-01	0.1098E-01	0.9789E-02	0.5181E-02	0.3369E-02	0.2227E-03	0.6818E-03	-.2495E-02
0.	0.1024	0.2895E-01	0.8335E-02	0.6478E-02	0.5358E-02	0.3258E-02	0.3006E-02	-.4136E-03	-.3378E-03	-.3247E-02
0.	0.8157E-01	0.2502E-01	0.7171E-02	0.5356E-02	0.4327E-02	0.2839E-02	0.2936E-02	-.6802E-03	-.1113E-02	-.3819E-02
0.	0.	0.2003E-01	0.5384E-02	0.4042E-02	0.2834E-02	0.1949E-02	0.3208E-02	-.9848E-03	-.2073E-02	0.
0.	0.	0.	0.	0.1448E-02	0.7181E-03	0.8058E-03	0.2390E-02	-.6186E-03	-.2690E-02	0.
0.	0.	0.	0.	0.	0.	0.	0.1732E-02	-.1268E-03	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.

5	4	3
0.	0.7777E-04	-.1893E-02
0.	-.2029E-04	-.1743E-02
0.	0.1499E-02	-.2951E-03
0.	0.1333E-02	0.8886E-04
0.	0.2197E-02	0.7392E-03
0.	0.	0.9783E-03
0.	0.	0.
0.	0.	0.

2	1	20
0.	0.1913E-04	0.
0.	-.4297E-03	0.
0.	-.1236E-02	0.
0.	-.9478E-03	0.
0.	-.2961E-03	0.
0.	0.4344E-03	0.
0.	0.1256E-02	0.
0.	0.	0.

TYPICAL WET SEASON CONDITIONS IN LOW GRAND FALLS RESERVOIR DAY 100

VERTICAL VELOCITY down: -ve (m/s)

19	18	17
0.4416E-05	0.1888E-05	0.8075E-06
0.8881E-05	0.3514E-05	0.1605E-05
0.1018E-04	0.4022E-05	0.3077E-05
0.9244E-05	0.4988E-05	0.
0.6749E-05	0.3108E-05	0.
0.	0.	0.
0.	0.	0.
0.	0.	0.

16	15	14	13	12	11	10	9	8	7	6
-.5043E-03	-.9651E-05	0.7859E-06	-.1527E-06	0.5267E-06	-.1094E-05	-.1381E-05	0.1304E-05	-.1410E-05	-.2852E-05	-.1878E-04
-.4355E-03	-.2058E-04	0.1563E-05	0.4160E-08	0.1036E-05	-.2122E-05	-.2960E-05	0.2739E-05	-.2571E-05	-.5718E-05	-.1757E-04
-.3225E-03	-.4222E-04	0.1020E-05	-.7838E-06	0.1150E-05	-.2518E-05	-.4167E-05	0.4469E-05	-.2332E-05	-.9373E-05	-.1386E-04
0.	-.7240E-04	-.2163E-06	-.1215E-05	0.1253E-05	-.2526E-05	-.6489E-05	0.7471E-05	-.1627E-05	-.1498E-04	0.
0.	0.	0.	-.4184E-05	0.7479E-06	-.1646E-05	-.7555E-05	0.9321E-05	0.1814E-06	-.2183E-04	0.
0.	0.	0.	0.	0.	0.	-.6862E-05	0.1038E-04	-.6604E-06	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.1569E-04	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.

5	4	3
-.1478E-04	-.2888E-05	0.3036E-05
-.3382E-04	-.5659E-05	0.6314E-05
-.4472E-04	-.8335E-05	0.8230E-05
-.2874E-03	-.1125E-04	0.1169E-04
0.	-.1527E-04	0.1559E-04
0.	-.1267E-04	0.
0.	-.7610E-05	0.
0.	0.	0.

2	1	20
0.4671E-05	-.4547E-06	-.1971E-04
0.7865E-05	-.1195E-06	-.3872E-04
0.5439E-05	0.2878E-05	-.5829E-04
-.7934E-06	0.8788E-05	-.8818E-04
-.1810E-04	0.1843E-04	-.1496E-03
-.2242E-04	0.2900E-04	0.2933E-04
-.6402E-05	0.	0.3792E-05
0.	0.	0.

TYPICAL WET SEASON CONDITIONS IN LOW GRAND FALLS RESERVOIR DAY 100

X-1D-DISCHARGES (cumec)

							19	18	17	
							-7.410	5.142	2.268	
16	15	14	13	12	11	10	9	8	7	6
0.	0.	0.	0.	0.	0.	18.84	194.8	6.330	0.	0.
						5	4	3		
						0.	211.4	8.560		
							2	1	20	
							220.0	0.	220.0	

Y-1D-DISCHARGES (cumec)

							19	18	17	
							0.	7.410	2.268	
16	15	14	13	12	11	10	9	8	7	6
0.	200.0	200.0	200.0	200.0	200.0	200.0	181.2	-21.08	-22.27	-20.00
						5	4	3		
						0.	18.84	2.231		
							2	1	20	
							0.	-8.560	0.	

LATERAL INFLOWS

							19	18	17	
							0.	0.	0.	
16	15	14	13	12	11	10	9	8	7	6
200.0	0.	0.	0.	0.	0.	0.	0.	0.	0.	20.00
						5	4	3		
						0.	0.	0.		
							2	1	20	
							0.	0.	0.	

TYPICAL WET SEASON CONDITIONS IN LOW GRAND FALLS RESERVOIR DAY 100

FB stream conc.s (ppm)

							19	18	17	
							0.	0.	0.	
16	15	14	13	12	11	10	9	8	7	6
0.4900	0.	0.	0.	0.	0.	0.	0.	0.	0.	2.000
						5	4	3		
						0.	0.	0.		
							2	1	20	
							0.	0.	0.	

SB stream conc.s (ppm)

							19	18	17	
							0.	0.	0.	
16	15	14	13	12	11	10	9	8	7	6
1.080	0.	0.	0.	0.	0.	0.	0.	0.	0.	2.000
						5	4	3		
						0.	0.	0.		
							2	1	20	
							0.	0.	0.	

DO stream conc.s (ppm)

							19	18	17	
							0.	0.	0.	
16	15	14	13	12	11	10	9	8	7	6
7.250	0.	0.	0.	0.	0.	0.	0.	0.	0.	8.500
						5	4	3		
						0.	0.	0.		
							2	1	20	
							0.	0.	0.	

TYPICAL WET SEASON CONDITIONS IN LOW GRAND FALLS RESERVOIR DAY 100

ON stream conc.s (ppm)

							19	18	17	
							0.	0.	0.	
16	15	14	13	12	11	10	9	8	7	6
0.6300	0.	0.	0.	0.	0.	0.	0.	0.	0.	1.000
						5	4	3		
						0.	0.	0.		
							2	1	20	
							0.	0.	0.	

MUD stream conc. (ppm)

							19	18	17	
							0.	0.	0.	
16	15	14	13	12	11	10	9	8	7	6
74.50	0.	0.	0.	0.	0.	0.	0.	0.	0.	120.0
						5	4	3		
						0.	0.	0.		
							2	1	20	
							0.	0.	0.	

AC stream conc.s (ppm)

							19	18	17	
							0.	0.	0.	
16	15	14	13	12	11	10	9	8	7	6
0.8000E-01	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.5000E-01
						5	4	3		
						0.	0.	0.		
							2	1	20	
							0.	0.	0.	

TYPICAL WET SEASON CONDITIONS IN LOW GRAND FALLS RESERVOIR   DAY 100

PH stream conc.s   (ppm)

							19 0.	18 0.	17 0.	
16 0.2800E-01	15 0.	14 0.	13 0.	12 0.	11 0.	10 0.	9 0.	8 0.	7 0.	6 0.1000E-01
						5 0.	4 0.	3 0.		
							2 0.	1 0.	20 0.	

TP stream conc.s   deg. C

							19 0.	18 0.	17 0.	
16 25.00	15 0.	14 0.	13 0.	12 0.	11 0.	10 0.	9 0.	8 0.	7 0.	6 24.00
						5 0.	4 0.	3 0.		
							2 0.	1 0.	20 0.	

TYPICAL WET SEASON CONDITIONS IN LOW GRAND FALLS RESERVOIR DAY 100

INERT S.SOL. PPM

19	18	17
6.900	7.788	9.265
13.54	13.79	14.42
20.75	20.41	20.48
36.28	35.69	35.63
36.45	36.03	0.
36.66	36.27	0.
0.	0.	0.
0.	0.	0.

16	15	14	13	12	11	10	9	8	7	6
77.30	57.68	27.39	19.93	13.73	8.597	6.990	6.699	7.877	13.07	34.37
73.33	65.21	41.71	33.37	25.76	17.84	14.90	13.41	13.77	17.14	30.02
74.64	68.00	46.97	39.69	33.08	25.78	22.91	20.64	20.23	21.33	28.62
70.00	54.65	44.74	41.84	39.77	37.69	36.97	36.21	35.72	35.03	31.23
0.	54.47	44.49	41.84	39.78	37.89	37.29	36.50	36.12	35.65	0.
0.	0.	0.	41.63	39.72	37.84	37.32	36.70	36.40	35.97	0.
0.	0.	0.	0.	0.	0.	37.40	36.78	36.48	0.	0.
0.	0.	0.	0.	0.	0.	0.	36.65	0.	0.	0.

5	4	3
5.974	5.844	6.512
12.20	11.87	12.53
19.08	18.53	19.17
35.81	35.74	35.80
36.41	36.24	36.18
0.	36.43	36.39
0.	36.44	0.
0.	36.42	0.

2	1	20
5.378	5.660	4.962
11.06	11.46	10.12
17.21	17.99	15.48
35.42	35.58	34.71
36.13	36.08	36.08
36.33	36.29	36.16
36.35	36.33	36.22
36.33	0.	36.32

TYPICAL WET SEASON CONDITIONS IN LOW GRAND FALLS RESERVOIR DAY 100

SETTLED MUD (T)

19	18	17
21.57	34.54	122.9
106.0	84.47	108.0
250.9	190.6	231.6
622.1	473.3	1040.
743.1	1243.	0.
117.0	239.3	0.
0.	0.	0.
0.	0.	0.

16	15	14	13	12	11	10	9	8	7	6
0.	0.	0.1169E-02	304.0	186.1	129.4	65.34	0.	8.676	117.6	442.5
0.	0.	0.6361E-03	407.3	349.7	273.4	187.9	27.98	55.48	226.2	179.4
0.	0.	0.1921E-03	754.7	704.4	622.0	454.0	66.72	124.5	420.1	246.5
0.	0.	0.9969E-04	1139.	1206.	1284.	1032.	165.0	310.4	976.9	579.9
0.	0.	201.2	2117.	2481.	2763.	2458.	1011.	1480.	1250.	0.
0.	0.	0.	0.	3466.	4684.	2596.	2030.	1301.	253.3	0.
0.	0.	0.	0.	0.	0.	0.	2611.	282.0	0.	0.
0.	0.	0.	0.	0.	0.	0.	175.9	0.	0.	0.

5	4	3
0.	2.352	51.48
0.	37.08	103.0
0.	90.79	244.1
0.	243.1	639.9
0.	916.4	890.9
0.	1082.	388.5
0.	1377.	0.
0.	296.4	0.

2	1	20
8.087	27.97	0.
15.12	48.49	0.
37.49	119.6	0.
106.2	329.7	0.
310.0	400.2	0.
416.0	224.5	0.
678.2	89.48	676.2
183.4	0.	183.3

TYPICAL WET SEASON CONDITIONS IN LOW GRAND FALLS RESERVOIR DAY 100

BED DETRITUS MGS

19	18	17
0.4113E+08	0.5137E+08	0.1401E+09
0.2706E+09	0.1890E+09	0.2136E+09
0.5202E+09	0.3665E+09	0.4227E+09
0.9689E+09	0.6907E+09	0.1503E+10
0.1182E+10	0.1886E+10	0.
0.1883E+09	0.3700E+09	0.
0.	0.	0.
0.	0.	0.

16	15	14	13	12	11	10	9	8	7	6
0.6147E+07	0.2875E+09	0.1122E+10	0.8547E+09	0.6086E+09	0.4192E+09	0.1879E+09	0.	0.1291E+08	0.9710E+08	0.1771E+09
0.1408E+08	0.2218E+09	0.1329E+10	0.9131E+09	0.9337E+09	0.8500E+09	0.5875E+09	0.7567E+08	0.1250E+09	0.3481E+09	0.1277E+09
0.4488E+08	0.4057E+09	0.2118E+10	0.1444E+10	0.1504E+10	0.1441E+10	0.1048E+10	0.1428E+09	0.2444E+09	0.7004E+09	0.2511E+09
0.1870E+09	0.8186E+09	0.3193E+10	0.2117E+10	0.2242E+10	0.2288E+10	0.1762E+10	0.2589E+09	0.4636E+09	0.1398E+10	0.6993E+09
0.	0.1539E+10	0.7041E+10	0.3889E+10	0.4561E+10	0.4831E+10	0.4168E+10	0.1617E+10	0.2281E+10	0.1861E+10	0.
0.	0.	0.	0.4042E+10	0.6353E+10	0.8106E+10	0.4356E+10	0.3279E+10	0.2042E+10	0.3845E+09	0.
0.	0.	0.	0.	0.	0.	0.3927E+10	0.4224E+10	0.4450E+09	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.2838E+09	0.	0.	0.

5	4	3
0.6860E+08	0.4784E+07	0.8876E+08
0.9963E+08	0.1008E+09	0.2531E+09
0.1952E+09	0.2012E+09	0.5092E+09
0.3568E+09	0.3763E+09	0.9684E+09
0.4321E+08	0.1447E+10	0.1396E+10
0.	0.1725E+10	0.6173E+09
0.	0.2198E+10	0.
0.	0.4731E+09	0.

2	1	20
0.1619E+08	0.5140E+08	0.1467E+08
0.4163E+08	0.1250E+09	0.3870E+08
0.8627E+08	0.2604E+09	0.8385E+08
0.1639E+09	0.4987E+09	0.1622E+09
0.4879E+09	0.6256E+09	0.4867E+09
0.6603E+09	0.3553E+09	0.6538E+09
0.1079E+10	0.1421E+09	0.1070E+10
0.2915E+09	0.	0.2910E+09

TYPICAL WET SEASON CONDITIONS IN LOW GRAND FALLS RESERVOIR DAY 100

BEDLOAD G/M2/DAY

19	18	17
0.8559E-01	0.7664E-01	0.7118E-01
0.2076	0.1875	0.1750
0.2514	0.2291	0.2182
0.2774	0.2556	0.2526
0.2845	0.2678	0.
0.2884	0.2737	0.
0.	0.	0.
0.	0.	0.

16	15	14	13	12	11	10	9	8	7	6
0.3522E-01	0.2285	0.4100	0.3803	0.2946	0.1790	0.1293	0.	0.7788E-01	0.7373E-01	0.9231E-01
0.5687E-01	0.2736	0.4574	0.4550	0.4116	0.3314	0.2793	0.2186	0.1896	0.1653	0.1359
0.1003	0.3270	0.4765	0.4674	0.4265	0.3560	0.3144	0.2601	0.2341	0.2110	0.1745
0.1990	0.3837	0.4275	0.4084	0.3789	0.3361	0.3135	0.2794	0.2624	0.2486	0.2067
0.	0.3864	0.4185	0.4016	0.3730	0.3304	0.3130	0.2866	0.2730	0.2612	0.
0.	0.	0.	0.3938	0.3678	0.3241	0.3079	0.2899	0.2791	0.2672	0.
0.	0.	0.	0.	0.	0.	0.3023	0.2901	0.2799	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.2871	0.	0.	0.

5	4	3
0.8669E-01	0.7792E-01	0.7387E-01
0.2092	0.1955	0.1864
0.2587	0.2467	0.2368
0.2789	0.2721	0.2658
0.2856	0.2803	0.2776
0.	0.2835	0.2822
0.	0.2835	0.
0.	0.2816	0.

2	1	20
0.7065E-01	0.6821E-01	0.6419E-01
0.1832	0.1777	0.1710
0.2405	0.2340	0.2348
0.2688	0.2641	0.2662
0.2782	0.2759	0.2776
0.2814	0.2801	0.2786
0.2818	0.2808	0.2796
0.2792	0.	0.2787

TYPICAL WET SEASON CONDITIONS IN LOW GRAND FALLS RESERVOIR DAY 100

FAST DIS.BOD PPM

19	18	17
0.5099E-01	0.6486E-01	0.8497E-01
0.3431E-01	0.4242E-01	0.5130E-01
0.3067E-01	0.3539E-01	0.3850E-01
0.9723E-02	0.1109E-01	0.1127E-01
0.9704E-02	0.1052E-01	0.
0.8956E-02	0.9428E-02	0.
0.	0.	0.
0.	0.	0.

16	15	14	13	12	11	10	9	8	7	6
0.4885	0.3669	0.1538	0.1074	0.7141E-01	0.4703E-01	0.4223E-01	0.4825E-01	0.6710E-01	0.1341	0.3995
0.4718	0.3525	0.1451	0.9729E-01	0.6342E-01	0.3916E-01	0.3288E-01	0.3383E-01	0.4606E-01	0.9219E-01	0.2700
0.4797	0.3599	0.1356	0.8968E-01	0.5945E-01	0.3828E-01	0.3274E-01	0.3102E-01	0.3803E-01	0.6436E-01	0.1785
0.3681	0.1444	0.4524E-01	0.2833E-01	0.1908E-01	0.1292E-01	0.1128E-01	0.9979E-02	0.1175E-01	0.1940E-01	0.1082
0.	0.1420	0.4357E-01	0.2817E-01	0.1890E-01	0.1256E-01	0.1105E-01	0.9788E-02	0.1067E-01	0.1401E-01	0.
0.	0.	0.	0.2290E-01	0.1779E-01	0.1148E-01	0.9897E-02	0.9003E-02	0.9416E-02	0.1146E-01	0.
0.	0.	0.	0.	0.	0.	0.9234E-02	0.8617E-02	0.8498E-02	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.7850E-02	0.	0.	0.

5	4	3
0.4285E-01	0.4383E-01	0.5135E-01
0.3105E-01	0.3080E-01	0.3500E-01
0.3001E-01	0.2927E-01	0.3081E-01
0.1009E-01	0.9526E-02	0.9499E-02
0.9552E-02	0.9242E-02	0.9201E-02
0.	0.8674E-02	0.8608E-02
0.	0.8399E-02	0.
0.	0.7487E-02	0.

2	1	20
0.4148E-01	0.4375E-01	0.4062E-01
0.2910E-01	0.3002E-01	0.2866E-01
0.2851E-01	0.2814E-01	0.2886E-01
0.9414E-02	0.9053E-02	0.9850E-02
0.9010E-02	0.8900E-02	0.8770E-02
0.8583E-02	0.8464E-02	0.8639E-02
0.8411E-02	0.8174E-02	0.8529E-02
0.7211E-02	0.	0.7150E-02

TYPICAL WET SEASON CONDITIONS IN LOW GRAND FALLS RESERVOIR DAY 100

SLOW DIS.BOD PPM

							19	18	17	
							0.3935	0.4012	0.4171	
							0.3344	0.3368	0.3437	
							0.3525	0.3496	0.3496	
							0.1637	0.1648	0.1649	
							0.1646	0.1648	0.	
							0.1625	0.1622	0.	
							0.	0.	0.	
							0.	0.	0.	
16	15	14	13	12	11	10	9	8	7	6
1.086	0.9766	0.6877	0.6060	0.5243	0.4461	0.4151	0.3960	0.4046	0.4593	0.6672
1.058	0.9373	0.6467	0.5582	0.4772	0.3967	0.3633	0.3380	0.3416	0.3840	0.5443
1.098	0.9989	0.6341	0.5419	0.4682	0.4052	0.3819	0.3573	0.3554	0.3734	0.4487
0.9117	0.4918	0.2651	0.2219	0.1957	0.1775	0.1721	0.1652	0.1677	0.1824	0.3355
0.	0.4866	0.2607	0.2213	0.1951	0.1755	0.1703	0.1652	0.1657	0.1719	0.
0.	0.	0.	0.2078	0.1921	0.1717	0.1662	0.1628	0.1627	0.1663	0.
0.	0.	0.	0.	0.	0.	0.1638	0.1616	0.1597	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.1586	0.	0.	0.
						5	4	3		
						0.3946	0.3878	0.3895		
						0.3349	0.3272	0.3283		
						0.3638	0.3572	0.3515		
						0.1698	0.1662	0.1639		
						0.1653	0.1641	0.1637		
						0.	0.1621	0.1618		
						0.	0.1612	0.		
						0.	0.1574	0.		
							2	1	20	
							0.3837	0.3818	0.3844	
							0.3210	0.3204	0.3180	
							0.3590	0.3515	0.3659	
							0.1677	0.1643	0.1738	
							0.1638	0.1633	0.1636	
							0.1620	0.1616	0.1628	
							0.1615	0.1605	0.1623	
							0.1563	0.	0.1561	

TYPICAL WET SEASON CONDITIONS IN LOW GRAND FALLS RESERVOIR DAY 100

AMMONIA PPM

19	18	17
0.1240E-03	0.1250E-03	0.1264E-03
0.2050E-03	0.2033E-03	0.2018E-03
0.2207E-03	0.2207E-03	0.2207E-03
0.3137E-03	0.3126E-03	0.3126E-03
0.3133E-03	0.3127E-03	0.
0.3141E-03	0.3138E-03	0.
0.	0.	0.
0.	0.	0.

16	15	14	13	12	11	10	9	8	7	6
-.3289E-05	0.1458E-04	0.8039E-04	0.9701E-04	0.1106E-03	0.1173E-03	0.1191E-03	0.1219E-03	0.1234E-03	0.1281E-03	0.1466E-03
0.6325E-05	0.3672E-04	0.1320E-03	0.1596E-03	0.1820E-03	0.1965E-03	0.2002E-03	0.2028E-03	0.2006E-03	0.1931E-03	0.1747E-03
-.1037E-04	0.1366E-04	0.1404E-03	0.1716E-03	0.1948E-03	0.2102E-03	0.2143E-03	0.2185E-03	0.2181E-03	0.2134E-03	0.2027E-03
0.5219E-04	0.1989E-03	0.2811E-03	0.2963E-03	0.3050E-03	0.3102E-03	0.3115E-03	0.3130E-03	0.3115E-03	0.3053E-03	0.2456E-03
0.	0.2007E-03	0.2826E-03	0.2965E-03	0.3052E-03	0.3109E-03	0.3122E-03	0.3131E-03	0.3125E-03	0.3097E-03	0.
0.	0.	0.	0.3015E-03	0.3063E-03	0.3122E-03	0.3135E-03	0.3140E-03	0.3137E-03	0.3119E-03	0.
0.	0.	0.	0.	0.	0.	0.3142E-03	0.3144E-03	0.3147E-03	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.3152E-03	0.	0.	0.

5	4	3
0.1168E-03	0.1178E-03	0.1212E-03
0.1970E-03	0.1985E-03	0.2011E-03
0.2121E-03	0.2134E-03	0.2171E-03
0.3106E-03	0.3119E-03	0.3130E-03
0.3129E-03	0.3131E-03	0.3132E-03
0.	0.3139E-03	0.3140E-03
0.	0.3141E-03	0.
0.	0.3153E-03	0.

2	1	20
0.1152E-03	0.1181E-03	0.1108E-03
0.1957E-03	0.1987E-03	0.1902E-03
0.2093E-03	0.2142E-03	0.2022E-03
0.3108E-03	0.3124E-03	0.3073E-03
0.3130E-03	0.3131E-03	0.3129E-03
0.3137E-03	0.3139E-03	0.3132E-03
0.3139E-03	0.3142E-03	0.3135E-03
0.3155E-03	0.	0.3155E-03

TYPICAL WET SEASON CONDITIONS IN LOW GRAND FALLS RESERVOIR DAY 100

NITRATE PPM

19	18	17
0.5171	0.5245	0.5325
0.4820	0.4862	0.4912
0.5765	0.5750	0.5748
0.4907	0.4914	0.4914
0.4911	0.4914	0.
0.4906	0.4907	0.
0.	0.	0.
0.	0.	0.

16	15	14	13	12	11	10	9	8	7	6
0.6312	0.5936	0.5056	0.4918	0.4888	0.4960	0.5035	0.5150	0.5251	0.5480	0.6190
0.6262	0.6050	0.5599	0.5391	0.5160	0.4874	0.4787	0.4795	0.4855	0.5080	0.5863
0.6342	0.6379	0.6135	0.6050	0.5962	0.5853	0.5806	0.5761	0.5743	0.5733	0.5704
0.6077	0.5456	0.5079	0.5006	0.4961	0.4935	0.4927	0.4913	0.4923	0.4970	0.5398
0.	0.5447	0.5072	0.5005	0.4961	0.4928	0.4920	0.4913	0.4917	0.4937	0.
0.	0.	0.	0.4982	0.4955	0.4920	0.4911	0.4907	0.4908	0.4921	0.
0.	0.	0.	0.	0.	0.	0.4907	0.4904	0.4901	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.4898	0.	0.	0.

5	4	3
0.5148	0.5180	0.5208
0.4712	0.4721	0.4781
0.5728	0.5726	0.5734
0.4933	0.4921	0.4912
0.4915	0.4913	0.4912
0.	0.4907	0.4907
0.	0.4905	0.
0.	0.4896	0.

2	1	20
0.5204	0.5203	0.5235
0.4677	0.4720	0.4614
0.5707	0.5713	0.5676
0.4929	0.4916	0.4953
0.4914	0.4912	0.4914
0.4908	0.4907	0.4912
0.4907	0.4904	0.4910
0.4894	0.	0.4893

TYPICAL WET SEASON CONDITIONS IN LOW GRAND FALLS RESERVOIR DAY 100

DIS.OXYGEN %SAT

							19	18	17	
							99.43	99.14	98.80	
							93.50	93.48	93.33	
							85.51	85.71	85.69	
							70.96	71.15	71.15	
							71.00	71.12	0.	
							70.87	70.91	0.	
							0.	0.	0.	
							0.	0.	0.	
16	15	14	13	12	11	10	9	8	7	6
84.54	91.57	100.8	101.8	101.5	100.8	100.3	99.65	99.21	98.07	93.23
83.97	83.86	84.38	86.07	88.56	92.28	93.54	93.79	93.78	93.20	90.63
84.70	84.39	81.81	81.98	82.68	84.43	85.29	85.85	86.19	86.69	86.93
81.46	74.79	71.42	70.98	70.82	70.94	71.02	71.07	71.33	72.22	80.65
0.	74.70	71.36	70.97	70.80	70.84	70.90	71.04	71.16	71.56	0.
0.	0.	0.	70.68	70.70	70.71	70.78	70.90	70.94	71.18	0.
0.	0.	0.	0.	0.	0.	70.74	70.82	70.76	0.	0.
0.	0.	0.	0.	0.	0.	0.	70.70	0.	0.	0.
						5	4	3		
						99.99	99.78	99.45		
						94.73	94.66	94.11		
						87.30	87.37	86.66		
						71.47	71.34	71.16		
						71.09	71.12	71.11		
						0.	70.99	70.97		
						0.	70.95	0.		
						0.	70.80	0.		
							2	1	20	
							99.83	99.63	100.0	
							95.11	94.65	95.88	
							88.40	87.49	89.97	
							71.57	71.29	72.19	
							71.17	71.15	71.21	
							71.04	71.03	71.15	
							71.00	70.94	71.10	
							70.85	0.	70.85	

TYPICAL WET SEASON CONDITIONS IN LOW GRAND FALLS RESERVOIR DAY 100

DO CONC PPM

							19	18	17	
							8.605	8.582	8.554	
							8.086	8.087	8.075	
							7.396	7.415	7.414	
							6.133	6.149	6.149	
							6.137	6.146	0.	
							6.125	6.129	0.	
							0.	0.	0.	
							0.	0.	0.	
16	15	14	13	12	11	10	9	8	7	6
7.298	7.905	8.704	8.794	8.776	8.717	8.678	8.623	8.588	8.494	8.091
7.249	7.240	7.288	7.435	7.653	7.976	8.087	8.111	8.112	8.067	7.857
7.311	7.286	7.068	7.085	7.147	7.300	7.376	7.426	7.456	7.502	7.530
7.033	6.461	6.171	6.134	6.120	6.130	6.138	6.142	6.165	6.242	6.979
0.	6.453	6.166	6.132	6.119	6.122	6.128	6.139	6.150	6.185	0.
0.	0.	0.	6.108	6.109	6.111	6.117	6.127	6.131	6.152	0.
0.	0.	0.	0.	0.	0.	6.113	6.120	6.116	0.	0.
0.	0.	0.	0.	0.	0.	0.	6.110	0.	0.	0.
						5	4	3		
						8.652	8.635	8.607		
						8.192	8.187	8.141		
						7.551	7.557	7.496		
						6.177	6.166	6.150		
						6.144	6.147	6.146		
						0.	6.135	6.134		
						0.	6.132	0.		
						0.	6.119	0.		
							2	1	20	
							8.640	8.623	8.657	
							8.226	8.187	8.293	
							7.647	7.569	7.783	
							6.186	6.161	6.239	
							6.151	6.150	6.155	
							6.140	6.138	6.150	
							6.136	6.131	6.145	
							6.123	0.	6.123	

TYPICAL WET SEASON CONDITIONS IN LOW GRAND FALLS RESERVOIR DAY 100

TEMPERATURE DEGC

							19	18	17	
							24.84	24.83	24.82	
							24.88	24.87	24.86	
							24.88	24.87	24.86	
							24.93	24.93	24.93	
							24.93	24.93	0.	
							24.93	24.93	0.	
							0.	0.	0.	
							0.	0.	0.	
16	15	14	13	12	11	10	9	8	7	6
25.00	24.99	24.96	24.94	24.92	24.89	24.88	24.85	24.83	24.79	24.68
25.00	24.99	24.97	24.95	24.94	24.92	24.91	24.89	24.87	24.84	24.74
25.00	24.99	24.94	24.93	24.91	24.90	24.89	24.88	24.87	24.85	24.79
24.99	24.96	24.94	24.94	24.93	24.93	24.93	24.93	24.93	24.92	24.85
0.	24.96	24.94	24.94	24.93	24.93	24.93	24.93	24.93	24.92	0.
0.	0.	0.	24.94	24.93	24.93	24.93	24.93	24.93	24.92	0.
0.	0.	0.	0.	0.	0.	24.93	24.93	24.93	0.	0.
0.	0.	0.	0.	0.	0.	0.	24.93	0.	0.	0.
						5	4	3		
						24.85	24.85	24.84		
						24.89	24.88	24.88		
						24.88	24.87	24.87		
						24.93	24.93	24.93		
						24.93	24.93	24.93		
						0.	24.93	24.93		
						0.	24.93	0.		
						0.	24.93	0.		
							2	1	20	
							24.84	24.84	24.84	
							24.88	24.88	24.88	
							24.87	24.87	24.87	
							24.93	24.93	24.92	
							24.93	24.93	24.93	
							24.93	24.93	24.93	
							24.93	24.93	24.93	
							24.93	0.	24.93	

TYPICAL WET SEASON CONDITIONS IN LOW GRAND FALLS RESERVOIR DAY 100

CHLOROPHYLL PPB

							19	18	17	
							0.8297	0.7594	0.7362	
							1.357	1.245	1.179	
							0.3651	0.3635	0.3578	
							0.3526E-01	0.3856E-01	0.3879E-01	
							0.3581E-01	0.3723E-01	0.	
							0.3250E-01	0.3308E-01	0.	
							0.	0.	0.	
							0.	0.	0.	
16	15	14	13	12	11	10	9	8	7	6
1.613	2.946	4.520	4.066	3.019	1.776	1.262	0.8825	0.7631	0.7384	0.7193
1.569	1.492	1.216	1.361	1.598	1.831	1.732	1.414	1.255	1.070	0.6702
1.622	1.238	0.4933	0.3822	0.3391	0.3844	0.4058	0.3922	0.3950	0.4135	0.5035
1.239	0.4699	0.1410	0.8764E-01	0.6002E-01	0.4544E-01	0.4229E-01	0.3776E-01	0.4270E-01	0.6558E-01	0.3045
0.	0.4613	0.1353	0.8687E-01	0.5914E-01	0.4207E-01	0.3856E-01	0.3641E-01	0.3830E-01	0.4813E-01	0.
0.	0.	0.	0.6960E-01	0.5520E-01	0.3783E-01	0.3389E-01	0.3278E-01	0.3344E-01	0.3923E-01	0.
0.	0.	0.	0.	0.	0.	0.3167E-01	0.3145E-01	0.2964E-01	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.2865E-01	0.	0.	0.
						5	4	3		
						0.8676	0.7561	0.7238		
						1.426	1.317	1.247		
						0.4848	0.4691	0.4239		
						0.4920E-01	0.4384E-01	0.3900E-01		
						0.3778E-01	0.3729E-01	0.3688E-01		
						0.	0.3369E-01	0.3343E-01		
						0.	0.3296E-01	0.		
						0.	0.2855E-01	0.		
							2	1	20	
							0.6844	0.6713	0.6343	
							1.250	1.214	1.233	
							0.5166	0.4712	0.5952	
							0.5005E-01	0.4222E-01	0.6780E-01	
							0.3819E-01	0.3753E-01	0.3897E-01	
							0.3456E-01	0.3404E-01	0.3732E-01	
							0.3392E-01	0.3260E-01	0.3605E-01	
							0.2788E-01	0.	0.2773E-01	

TYPICAL WET SEASON CONDITIONS IN LOW GRAND FALLS RESERVOIR DAY 100

ALGAL CARBON PPB

							19	18	17	
							41.49	37.97	36.81	
							67.83	62.25	58.97	
							18.25	18.18	17.89	
							1.763	1.928	1.939	
							1.790	1.862	0.	
							1.625	1.654	0.	
							0.	0.	0.	
							0.	0.	0.	
16	15	14	13	12	11	10	9	8	7	6
80.65	147.3	226.0	203.3	151.0	88.81	63.11	44.12	38.15	36.92	35.97
78.45	74.60	60.82	68.03	79.88	91.54	86.59	70.71	62.73	53.52	33.51
81.09	61.88	24.67	19.11	16.95	19.22	20.29	19.61	19.75	20.68	25.17
61.93	23.49	7.049	4.382	3.001	2.272	2.114	1.888	2.135	3.279	15.22
0.	23.06	6.764	4.343	2.957	2.103	1.928	1.820	1.915	2.406	0.
0.	0.	0.	3.480	2.760	1.891	1.695	1.639	1.672	1.961	0.
0.	0.	0.	0.	0.	0.	1.583	1.573	1.482	0.	0.
0.	0.	0.	0.	0.	0.	0.	1.432	0.	0.	0.
						5	4	3		
						43.38	37.80	36.19		
						71.31	65.83	62.35		
						24.24	23.45	21.19		
						2.460	2.192	1.950		
						1.889	1.864	1.844		
						0.	1.684	1.672		
						0.	1.648	0.		
						0.	1.427	0.		
							2	1	20	
							34.22	33.57	31.72	
							62.52	60.71	61.64	
							25.83	23.56	29.76	
							2.502	2.111	3.390	
							1.910	1.877	1.948	
							1.728	1.702	1.866	
							1.696	1.630	1.802	
							1.394	0.	1.386	

TYPICAL WET SEASON CONDITIONS IN LOW GRAND FALLS RESERVOIR DAY 100

DETRITAL CAR PPB

							19	18	17	
							3.461	3.104	2.879	
							8.927	8.061	7.515	
							11.17	10.17	9.683	
							12.38	11.40	11.27	
							12.66	11.94	0.	
							12.84	12.21	0.	
							0.	0.	0.	
							0.	0.	0.	
16	15	14	13	12	11	10	9	8	7	6
0.7747	9.212	16.86	15.56	11.98	7.224	5.203	3.691	3.146	3.001	3.815
1.736	11.63	20.01	19.82	17.81	14.28	12.01	9.397	8.145	7.101	5.865
3.652	13.73	20.66	20.38	18.71	15.75	13.94	11.55	10.38	9.327	7.654
8.227	16.56	18.71	17.91	16.69	14.90	13.93	12.45	11.70	11.08	9.136
0.	16.67	18.29	17.65	16.44	14.62	13.89	12.76	12.17	11.64	0.
0.	0.	0.	17.28	16.28	14.40	13.68	12.91	12.44	11.91	0.
0.	0.	0.	0.	0.	0.	13.50	12.93	12.48	0.	0.
0.	0.	0.	0.	0.	0.	0.	12.80	0.	0.	0.
						5	4	3		
						3.452	3.117	2.966		
						8.938	8.365	7.986		
						11.46	10.93	10.50		
						12.43	12.13	11.86		
						12.72	12.49	12.37		
						0.	12.64	12.58		
						0.	12.64	0.		
						0.	12.56	0.		
							2	1	20	
							2.814	2.723	2.545	
							7.825	7.596	7.295	
							10.64	10.37	10.37	
							11.99	11.78	11.87	
							12.40	12.30	12.38	
							12.55	12.49	12.43	
							12.57	12.53	12.47	
							12.46	0.	12.44	

TYPICAL WET SEASON CONDITIONS IN LOW GRAND FALLS RESERVOIR DAY 100

PHOSPHATE PPM

19	18	17
0.1316E-02	0.1531E-02	0.1827E-02
0.3036E-02	0.2868E-02	0.2927E-02
0.1111E-01	0.1066E-01	0.1053E-01
0.1560E-01	0.1544E-01	0.1542E-01
0.1559E-01	0.1547E-01	0.
0.1561E-01	0.1551E-01	0.
0.	0.	0.
0.	0.	0.

16	15	14	13	12	11	10	9	8	7	6
0.2802E-01	0.2171E-01	0.6693E-02	0.3788E-02	0.2107E-02	0.1199E-02	0.1058E-02	0.1234E-02	0.1530E-02	0.2487E-02	0.6074E-02
0.2767E-01	0.2492E-01	0.1772E-01	0.1441E-01	0.1063E-01	0.5819E-02	0.3963E-02	0.2956E-02	0.2728E-02	0.3339E-02	0.6759E-02
0.2817E-01	0.2637E-01	0.2027E-01	0.1818E-01	0.1609E-01	0.1339E-01	0.1217E-01	0.1100E-01	0.1041E-01	0.9696E-02	0.8621E-02
0.2585E-01	0.2044E-01	0.1743E-01	0.1678E-01	0.1635E-01	0.1593E-01	0.1577E-01	0.1558E-01	0.1540E-01	0.1498E-01	0.1127E-01
0.	0.2037E-01	0.1736E-01	0.1677E-01	0.1633E-01	0.1592E-01	0.1579E-01	0.1559E-01	0.1548E-01	0.1527E-01	0.
0.	0.	0.	0.1659E-01	0.1630E-01	0.1588E-01	0.1574E-01	0.1561E-01	0.1553E-01	0.1538E-01	0.
0.	0.	0.	0.	0.	0.	0.1571E-01	0.1561E-01	0.1554E-01	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.1557E-01	0.	0.	0.

5	4	3
0.1105E-02	0.1162E-02	0.1309E-02
0.2190E-02	0.2028E-02	0.2353E-02
0.1012E-01	0.9903E-02	0.1019E-01
0.1544E-01	0.1545E-01	0.1548E-01
0.1557E-01	0.1553E-01	0.1552E-01
0.	0.1555E-01	0.1554E-01
0.	0.1554E-01	0.
0.	0.1553E-01	0.

2	1	20
0.1152E-02	0.1195E-02	0.1149E-02
0.1540E-02	0.1840E-02	0.8588E-03
0.9203E-02	0.9646E-02	0.8200E-02
0.1534E-01	0.1543E-01	0.1509E-01
0.1549E-01	0.1549E-01	0.1546E-01
0.1552E-01	0.1552E-01	0.1548E-01
0.1552E-01	0.1552E-01	0.1549E-01
0.1550E-01	0.	0.1550E-01

Table 8.2 Typical dry season conditions Mutonga Reservoir

TYPICAL DRY SEASON CONDITIONS IN MUTONGA RESERVOIR

VOLUMES m3

8
0.1453E+07
0.1222E+07
0.9908E+06
0.7595E+06
0.5283E+06
0.7003E+06
0.5814E+06
0.3000E+06
0.

7	6	5	4	3	2	1
0.2621E+06	0.9506E+06	0.2327E+07	0.3011E+07	0.4340E+07	0.4189E+07	0.4092E+07
0.2390E+06	0.8404E+06	0.2003E+07	0.2657E+07	0.3922E+07	0.3686E+07	0.3765E+07
0.2164E+06	0.7316E+06	0.1681E+07	0.2306E+07	0.3498E+07	0.3185E+07	0.3438E+07
0.1938E+06	0.6229E+06	0.1359E+07	0.1955E+07	0.3074E+07	0.2683E+07	0.3110E+07
0.1713E+06	0.5141E+06	0.1037E+07	0.1603E+07	0.2650E+07	0.2181E+07	0.2783E+07
0.	0.	0.1465E+07	0.2569E+07	0.4352E+07	0.3375E+07	0.4707E+07
0.	0.	0.2064E+07	0.3190E+07	0.4567E+07	0.3237E+07	0.5068E+07
0.	0.	0.	0.	0.5043E+07	0.3333E+07	0.4879E+07
0.	0.	0.	0.	0.	0.	0.8883E+06

X-1D-DISCHARGES (cumec)

8
18.00

7	6	5	4	3	2	1
0.	0.	0.	0.	0.	0.	65.00

Y-1D-DISCHARGES (cumec)

8
0.

7	6	5	4	3	2	1
0.	47.00	47.00	47.00	47.00	47.00	47.00

LATERAL INFLOWS (cumec)

8
18.00

7	6	5	4	3	2	1
47.00	0.	0.	0.	0.	0.	0.

TYPICAL DRY SEASON CONDITIONS IN MUTONGA RESERVOIR

X-DISCHARGES east-west (cumec)

8
-13.23
-9.985
-4.771
-2.884
1.022
7.178
18.73
21.94
0.

7	6	5	4	3	2	1
0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	65.00
0.	0.	0.	0.	0.	0.	0.

Y-DISCHARGES north-south (cumec)

8
0.
0.
0.
0.
0.
0.
0.
0.
0.

7	6	5	4	3	2	1
0.	13.87	14.34	12.89	18.88	19.29	2.301
0.	10.75	12.73	11.06	13.44	16.81	5.540
0.	10.39	9.011	8.658	9.164	8.834	17.63
0.	8.391	7.474	7.213	4.400	7.163	14.72
0.	3.599	3.447	3.744	1.230	1.810	9.135
0.	0.	0.	6.245	1.384	1.358	6.024
0.	0.	0.	-2.806	-1.501	-1.933	-1.985
0.	0.	0.	0.	0.	-6.330	-6.369
0.	0.	0.	0.	0.	0.	0.

Z-DISCHARGES down: -ve (cumec)

8
-31.23
-41.22
-45.99
-48.87
-47.85
-40.67
-21.94
0.
0.

7	6	5	4	3	2	1
-33.13	0.4679	-1.455	5.995	0.4078	-16.99	10.93
-22.38	2.447	-3.122	8.376	3.776	-28.26	15.38
-11.99	1.069	-3.475	8.883	3.446	-19.46	2.517
-3.599	0.1519	-3.736	6.070	6.209	-11.90	-9.321
0.	0.	-3.439	3.556	6.789	-4.575	-19.48
0.	0.	2.806	-1.305	6.762	0.9020E-01	-32.68
0.	0.	0.	0.	6.330	0.3888E-01	-49.43
0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.

TYPICAL DRY SEASON CONDITIONS IN MUTONGA RESERVOIR

U-VELOCITY east-west (m/s)

8
-.1548E-01
-.1310E-01
-.7079E-02
-.4914E-02
0.2197E-02
0.1056E-01
0.2402E-01
0.2743E-01
0.

7	6	5	4	3	2	1
0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.5417E-01
0.	0.	0.	0.	0.	0.	0.

V-VELOCITY north-south (m/s)

8
0.
0.
0.
0.
0.
0.
0.
0.
0.

7	6	5	4	3	2	1
0.	0.5471E-01	0.8280E-01	0.2799E-01	0.2404E-01	0.3500E-01	0.2700E-03
0.	0.5970E-01	0.7856E-01	0.2786E-01	0.1888E-01	0.3226E-01	0.3324E-02
0.	0.7316E-01	0.6258E-01	0.2474E-01	0.1439E-01	0.1821E-01	0.1142E-01
0.	0.6713E-01	0.5794E-01	0.2304E-01	0.7971E-02	0.1613E-01	0.1126E-01
0.	0.3332E-01	0.2946E-01	0.1387E-01	0.2663E-02	0.4594E-02	0.8725E-02
0.	0.	0.	0.1318E-01	0.1871E-02	0.2096E-02	0.4403E-02
0.	0.	0.	-.3092E-02	-.1820E-02	-.3322E-02	-.2023E-02
0.	0.	0.	0.	0.	-.1029E-01	-.6961E-02
0.	0.	0.	0.	0.	0.	0.

VERTICAL VELOCITY down: -ve (m/s)

8
-.4670E-04
-.7451E-04
-.1051E-03
-.1518E-03
-.2319E-03
-.2829E-03
-.4388E-03
0.
0.

7	6	5	4	3	2	1
-.2648E-03	0.1046E-05	-.1345E-05	0.4232E-05	0.1973E-06	-.8631E-05	0.5565E-05
-.1966E-03	0.6227E-05	-.3390E-05	0.6750E-05	0.2036E-05	-.1645E-04	0.8540E-05
-.1169E-03	0.3158E-05	-.4573E-05	0.8339E-05	0.2097E-05	-.1327E-04	0.1537E-05
-.3943E-04	0.5345E-06	-.6239E-05	0.6824E-05	0.4339E-05	-.9786E-05	-.6327E-05
0.	0.	-.7853E-05	0.4981E-05	0.5569E-05	-.4740E-05	-.1487E-04
0.	0.	0.9517E-05	-.2287E-05	0.7064E-05	0.1249E-06	-.3130E-04
0.	0.	0.	0.	0.1121E-04	0.1089E-06	-.7658E-04
0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.

TYPICAL DRY SEASON CONDITIONS IN MUTONGA RESERVOIR

SETTLED MUD (T) Typical dry season conditions

7	6	5	4	3	2	1
0.	0.	0.	12.17	11.38	0.4868	71.23
0.	0.	0.	19.28	180.4	0.9026	104.6
0.	0.	0.	19.10	234.4	127.3	121.9
0.	0.	0.1598E-07	27.66	247.2	174.7	133.6
0.	0.	0.	234.9	231.5	219.4	134.5
0.	0.	0.	191.5	285.6	213.6	217.9
0.	0.	0.	743.5	421.3	319.5	315.8
0.	0.	0.	0.	0.	245.5	249.6
0.	0.	0.	0.	0.	0.	261.7

BEDLOAD G/M2/DAY Typical dry season conditions

7	6	5	4	3	2	1
0.3659E-01	0.1453	0.4721	0.4534	0.3666	0.2526	0.2521
0.7497E-01	0.1834	0.4810	0.4793	0.4719	0.4459	0.4377
0.1114	0.2204	0.4834	0.4809	0.4702	0.5005	0.4921
0.1633	0.2573	0.4902	0.4903	0.4768	0.5237	0.5238
0.2087	0.2778	0.4801	0.4854	0.4897	0.5435	0.5552
0.	0.	0.4802	0.4852	0.4904	0.5673	0.5821
0.	0.	0.4782	0.4839	0.5036	0.6003	0.6535
0.	0.	0.	0.	0.5515	0.6477	0.6544
0.	0.	0.	0.	0.	0.	0.6610

BED DETRITUS MGS Typical dry season conditions

7	6	5	4	3	2	1
0.1702E+07	0.4364E+08	0.4303E+09	0.4564E+09	0.4296E+09	0.3727E+09	0.2470E+09
0.4530E+07	0.6079E+08	0.4883E+09	0.5365E+09	0.6286E+09	0.6957E+09	0.4521E+09
0.7275E+07	0.7443E+08	0.4992E+09	0.5499E+09	0.6518E+09	0.8161E+09	0.5279E+09
0.1109E+08	0.8753E+08	0.5046E+09	0.5624E+09	0.6664E+09	0.8639E+09	0.5652E+09
0.1194E+09	0.5062E+09	0.5116E+09	0.5709E+09	0.6978E+09	0.9126E+09	0.6079E+09
0.	0.	0.4546E+09	0.4650E+09	0.8621E+09	0.9262E+09	0.1035E+10
0.	0.	0.9452E+09	0.1852E+10	0.1328E+10	0.1473E+10	0.1747E+10
0.	0.	0.	0.	0.2102E+10	0.1557E+10	0.1383E+10
0.	0.	0.	0.	0.	0.	0.1466E+10

FAST DIS.BOD PPM Typical dry season conditions

7	6	5	4	3	2	1
2.191	1.887	1.129	0.6272	0.4086	0.2470	0.2395
2.115	1.729	1.068	0.5448	0.3305	0.2142	0.2042
1.982	1.598	0.9309	0.4398	0.2404	0.1723	0.1730
1.922	1.543	0.9910	0.4104	0.1793	0.1449	0.1533
1.266	0.8240	0.2275	0.6795E-01	0.3855E-01	0.8329E-01	0.1132
0.	0.	0.2272	0.6951E-01	0.3877E-01	0.7989E-01	0.1164
0.	0.	0.4474E-01	0.4237E-01	0.3822E-01	0.7696E-01	0.1302
0.	0.	0.	0.	0.3915E-01	0.7616E-01	0.1301
0.	0.	0.	0.	0.	0.	0.1285

SLOW DIS.BOD PPM Typical dry season conditions

7	6	5	4	3	2	1
2.232	2.161	1.868	1.573	1.404	1.107	1.047
2.229	2.130	1.860	1.485	1.291	1.072	1.012
2.177	2.071	1.741	1.320	1.098	0.9742	0.9436
2.203	2.099	1.928	1.259	0.9339	0.9348	0.9263
1.914	1.623	0.8488	0.5583	0.5115	0.6764	0.7326
0.	0.	0.8484	0.5615	0.5122	0.6554	0.7308
0.	0.	0.5081	0.5075	0.5156	0.6431	0.7553
0.	0.	0.	0.	0.5406	0.6440	0.7552
0.	0.	0.	0.	0.	0.	0.7534

TYPICAL DRY SEASON CONDITIONS IN MUTONGA RESERVOIR

AMMONIA PPM Typical dry season conditions

7	6	5	4	3	2	1
0.1625E-05	0.2945E-05	0.4039E-04	0.9362E-04	0.1235E-03	0.1766E-03	0.1924E-03
-.2434E-05	0.1081E-05	0.4227E-04	0.1296E-03	0.1750E-03	0.2082E-03	0.2220E-03
0.4431E-05	0.9991E-05	0.7049E-04	0.1742E-03	0.2295E-03	0.2418E-03	0.2468E-03
-.7025E-05	-.3091E-05	0.1346E-04	0.1966E-03	0.2853E-03	0.2584E-03	0.2553E-03
0.3285E-04	0.9228E-04	0.3181E-03	0.4067E-03	0.4190E-03	0.3508E-03	0.3257E-03
0.	0.	0.3182E-03	0.4057E-03	0.4188E-03	0.3586E-03	0.3259E-03
0.	0.	0.4240E-03	0.4237E-03	0.4192E-03	0.3648E-03	0.3158E-03
0.	0.	0.	0.	0.4182E-03	0.3687E-03	0.3159E-03
0.	0.	0.	0.	0.	0.	0.3166E-03

NITRATE PPM Typical dry season conditions

7	6	5	4	3	2	1
0.3981	0.3873	0.3134	0.2838	0.2673	0.2275	0.2253
0.3982	0.3977	0.3897	0.3839	0.3595	0.2756	0.2642
0.3965	0.3967	0.3873	0.3631	0.3441	0.2859	0.2758
0.3994	0.3998	0.4061	0.3552	0.3250	0.3004	0.2890
0.3914	0.3771	0.3112	0.2773	0.2621	0.2610	0.2558
0.	0.	0.3111	0.2776	0.2622	0.2571	0.2531
0.	0.	0.2731	0.2708	0.2610	0.2532	0.2474
0.	0.	0.	0.	0.2490	0.2485	0.2474
0.	0.	0.	0.	0.	0.	0.2474

DIS.OXYGEN %SAT Typical dry season conditions

7	6	5	4	3	2	1
96.89	95.69	98.72	96.87	97.16	97.10	93.75
96.34	90.57	79.83	66.68	65.59	77.58	77.29
93.88	87.87	75.67	66.37	63.58	72.03	73.07
94.02	88.11	78.29	64.91	60.83	67.54	69.72
80.63	70.50	58.16	55.95	58.47	65.45	68.76
0.	0.	58.16	56.01	58.48	65.41	69.17
0.	0.	54.60	55.28	58.65	65.37	70.85
0.	0.	0.	0.	62.02	66.18	70.84
0.	0.	0.	0.	0.	0.	70.67

DO CONC PPM Typical dry season conditions

7	6	5	4	3	2	1
8.365	8.260	8.524	8.369	8.400	8.462	8.192
8.316	7.818	6.893	5.764	5.676	6.756	6.746
8.105	7.586	6.538	5.748	5.516	6.280	6.381
8.115	7.605	6.752	5.628	5.290	5.885	6.084
6.965	6.099	5.065	4.890	5.118	5.731	6.024
0.	0.	5.065	4.895	5.119	5.729	6.063
0.	0.	4.773	4.834	5.134	5.729	6.213
0.	0.	0.	0.	5.438	5.803	6.213
0.	0.	0.	0.	0.	0.	6.198

TEMPERATURE DEGC Typical dry season conditions

7	6	5	4	3	2	1
25.00	25.00	24.99	24.95	24.90	24.42	24.26
25.00	25.00	24.99	24.91	24.85	24.47	24.33
25.00	24.99	24.94	24.80	24.69	24.40	24.29
25.01	25.01	25.05	24.73	24.55	24.43	24.34
24.96	24.87	24.47	24.25	24.15	24.14	24.10
0.	0.	24.47	24.26	24.15	24.11	24.08
0.	0.	24.23	24.21	24.14	24.08	24.04
0.	0.	0.	0.	24.06	24.05	24.04
0.	0.	0.	0.	0.	0.	24.04

TYPICAL DRY SEASON CONDITIONS IN MUTONGA RESERVOIR

INERT S.SOL. PPM Typical dry season conditions

7	6	5	4	3	2	1
40.41	35.35	23.79	16.80	12.36	10.76	12.86
38.15	38.59	34.22	30.75	24.94	18.30	19.08
40.22	40.89	40.06	38.59	32.78	22.41	22.15
36.66	38.38	40.41	40.78	35.58	25.67	24.37
51.44	60.99	48.73	41.57	35.20	27.56	25.72
0.	0.	48.73	41.55	35.20	27.97	25.72
0.	0.	43.08	40.44	34.98	28.03	24.87
0.	0.	0.	0.	33.55	27.73	24.87
0.	0.	0.	0.	0.	0.	24.87

CHLOROPHYLL PPB Typical dry season conditions

7	6	5	4	3	2	1
1.108	1.936	5.412	4.790	3.698	2.630	2.427
1.146	0.9556	1.133	0.8827	1.596	2.534	2.202
1.107	0.8060	0.5028	0.1835	0.2149	1.057	0.9050
1.004	0.7458	0.4435	0.1878	0.1335	0.5019	0.5812
0.6138	0.3857	0.1129	0.5881E-01	0.8821E-01	0.2965	0.4484
0.	0.	0.1128	0.5939E-01	0.8842E-01	0.2845	0.4664
0.	0.	0.4227E-01	0.4915E-01	0.8924E-01	0.2726	0.5300
0.	0.	0.	0.	0.1187	0.2742	0.5295
0.	0.	0.	0.	0.	0.	0.5196

ALGAL CARBON PPB Typical dry season conditions

7	6	5	4	3	2	1
55.38	96.80	270.6	239.5	184.9	131.5	121.3
57.31	47.78	56.63	44.14	79.82	126.7	110.1
55.36	40.30	25.14	9.175	10.74	52.87	45.25
50.18	37.29	22.17	9.392	6.676	25.09	29.06
30.69	19.29	5.647	2.941	4.411	14.82	22.42
0.	0.	5.639	2.969	4.421	14.22	23.32
0.	0.	2.113	2.457	4.462	13.63	26.50
0.	0.	0.	0.	5.935	13.71	26.48
0.	0.	0.	0.	0.	0.	25.98

DETRITAL CAR PPB Typical dry season conditions

7	6	5	4	3	2	1
1.089	6.024	19.43	18.41	14.66	10.20	10.35
2.886	7.959	21.20	21.12	20.50	19.10	18.86
4.651	9.356	20.92	21.08	20.78	21.94	21.58
6.830	10.80	20.94	21.31	20.93	22.94	22.90
8.785	11.81	20.82	21.28	21.59	23.87	24.30
0.	0.	20.82	21.28	21.64	24.97	25.58
0.	0.	20.92	21.26	22.22	26.54	28.76
0.	0.	0.	0.	24.25	28.60	28.83
0.	0.	0.	0.	0.	0.	29.12

PHOSPHATE PPM Typical dry season conditions

7	6	5	4	3	2	1
0.1975E-01	0.1813E-01	0.7265E-02	0.3366E-02	0.1540E-02	0.1934E-02	0.3713E-02
0.1968E-01	0.1963E-01	0.1869E-01	0.1901E-01	0.1619E-01	0.8580E-02	0.8746E-02
0.1955E-01	0.1962E-01	0.1901E-01	0.1747E-01	0.1613E-01	0.1117E-01	0.1100E-01
0.1976E-01	0.1981E-01	0.2022E-01	0.1727E-01	0.1533E-01	0.1298E-01	0.1236E-01
0.1933E-01	0.1851E-01	0.1465E-01	0.1259E-01	0.1157E-01	0.1119E-01	0.1081E-01
0.	0.	0.1464E-01	0.1260E-01	0.1157E-01	0.1101E-01	0.1067E-01
0.	0.	0.1236E-01	0.1219E-01	0.1150E-01	0.1081E-01	0.1032E-01
0.	0.	0.	0.	0.1067E-01	0.1052E-01	0.1032E-01
0.	0.	0.	0.	0.	0.	0.1032E-01

Table 8.4 Typical dry season conditions Low Grand Falls Reservoir

TYPICAL DRY SEASON CONDITIONS IN LOW GRAND FALLS RESERVOIR   DAY 230

VOLUMES   m3

19	18	17
0.3717E+07	0.4368E+07	0.3184E+07
0.3419E+07	0.4086E+07	0.2641E+07
0.4321E+07	0.5504E+07	0.3205E+07
0.5049E+07	0.7507E+07	0.5635E+07
0.4207E+07	0.7508E+07	0.
0.5031E+06	0.1046E+07	0.
0.	0.	0.
0.	0.	0.

16	15	14	13	12	11	10	9	8	7	6
0.6537E+06	0.2807E+07	0.1030E+08	0.9749E+07	0.1311E+08	0.1682E+08	0.1618E+08	0.1059E+08	0.6437E+07	0.6335E+07	0.2131E+07
0.5383E+06	0.2445E+07	0.9357E+07	0.9035E+07	0.1238E+08	0.1599E+08	0.1559E+08	0.1053E+08	0.6300E+07	0.5762E+07	0.1660E+07
0.5956E+06	0.3168E+07	0.1230E+08	0.1235E+08	0.1720E+08	0.2242E+08	0.2208E+08	0.1558E+08	0.9041E+07	0.7342E+07	0.1922E+07
0.4278E+06	0.3946E+07	0.1589E+08	0.1739E+08	0.2502E+08	0.3317E+08	0.3333E+08	0.2540E+08	0.1398E+08	0.8767E+07	0.1688E+07
0.	0.3311E+07	0.1911E+08	0.2331E+08	0.3606E+08	0.4982E+08	0.5207E+08	0.4573E+08	0.2016E+08	0.7708E+07	0.
0.	0.	0.	0.9349E+07	0.1680E+08	0.2772E+08	0.3091E+08	0.3267E+08	0.8086E+07	0.1119E+07	0.
0.	0.	0.	0.	0.	0.	0.2176E+08	0.1274E+08	0.1724E+07	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.7847E+06	0.	0.	0.

5	4	3
0.9722E+06	0.7237E+07	0.4677E+07
0.7565E+06	0.7141E+07	0.4245E+07
0.8390E+06	0.1039E+08	0.5526E+07
0.6095E+06	0.1647E+08	0.6964E+07
0.1166E+06	0.2789E+08	0.7246E+07
0.	0.1922E+08	0.1775E+07
0.	0.8562E+07	0.
0.	0.1954E+07	0.

2	1	20
0.3181E+07	0.2540E+07	0.3181E+07
0.3103E+07	0.2294E+07	0.3103E+07
0.4514E+07	0.3004E+07	0.4514E+07
0.7147E+07	0.3842E+07	0.7147E+07
0.1247E+08	0.4481E+07	0.1247E+08
0.9314E+07	0.1757E+07	0.9314E+07
0.4557E+07	0.4085E+06	0.4557E+07
0.2110E+07	0.	0.3014E+07

TYPICAL DRY SEASON CONDITIONS IN LOW GRAND FALLS RESERVOIR DAY 230

X-DISCHARGES east-west (cumec)

19	18	17
3.561	21.97	4.912
4.195	20.02	3.158
-3.720	-5.093	-.8913
-6.803	-11.73	-3.182
-9.396	-13.89	0.
-1.029	-2.087	0.
0.	0.	0.
0.	0.	0.

16	15	14	13	12	11	10	9	8	7	6
0.	0.	0.	0.	0.	0.	6.869	32.04	-.9578	0.	0.
0.	0.	0.	0.	0.	0.	5.516	30.96	-.2548	0.	0.
0.	0.	0.	0.	0.	0.	1.048	10.83	-1.484	0.	0.
0.	0.	0.	0.	0.	0.	0.1098	13.32	-.6816	0.	0.
0.	0.	0.	0.	0.	0.	-1.258	9.080	-.5387E-01	0.	0.
0.	0.	0.	0.	0.	0.	0.	-8.550	0.3300E-01	0.	0.
0.	0.	0.	0.	0.	0.	0.	-20.42	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	-1.143	0.	0.	0.

5	4	3
0.	9.643	-.9309
0.	9.053	-.5742
0.	9.892	0.9153
0.	14.61	1.499
0.	22.80	2.059
0.	7.896	0.4011
0.	-1.950	0.
0.	-.3225	0.

2	1	20
4.654	0.	0.
4.429	0.	0.
8.032	0.	0.
11.94	0.	0.
16.79	0.	0.
14.67	0.	75.00
12.03	0.	0.
2.456	0.	0.

TYPICAL DRY SEASON CONDITIONS IN LOW GRAND FALLS RESERVOIR DAY 230

Y-DISCHARGES north-south (cumec)

19	18	17
0.	6.229	-2.844
0.	4.703	-3.503
0.	1.641	3.972
0.	0.6355	6.373
0.	-.1721E-01	0.
0.	0.	0.
0.	0.	0.
0.	0.	0.

16	15	14	13	12	11	10	9	8	7	6
0.	22.06	25.73	28.78	34.56	39.57	31.51	20.34	-.2533	22.01	4.713
0.	19.68	22.65	24.83	31.36	35.74	28.79	17.98	-1.535	19.12	2.109
0.	17.63	15.04	8.400	6.674	6.335	6.268	7.324	1.633	-4.402	-6.399
0.	5.636	6.035	5.335	3.402	1.866	5.071	7.762	-1.348	-13.32	-10.42
0.	0.	-4.453	-2.346	-6.284	-11.39	-.7733	6.807	-13.01	-27.57	0.
0.	0.	0.	0.	-4.709	-7.126	-5.869	-3.606	-9.751	-9.840	0.
0.	0.	0.	0.	0.	0.	0.	-3.898	-2.324	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.

5	4	3
0.	-2.136	6.555
0.	-2.588	5.571
0.	4.321	0.1694
0.	4.425	-1.910
0.	8.262	-4.593
0.	0.	0.9746
0.	0.	0.
0.	0.	0.

2	1	20
0.	0.9227E-01	0.
0.	0.6567	0.
0.	-.6452	0.
0.	-1.643	0.
0.	-2.591	0.
0.	-.5047E-01	0.
0.	0.8111	0.
0.	0.	0.

TYPICAL DRY SEASON CONDITIONS IN LOW GRAND FALLS RESERVOIR DAY 230

Z-DISCHARGES down : -ve (cumec)

							19	18	17	
							9.790	12.90	7.757	
							18.69	24.71	14.42	
							16.61	21.95	9.555	
							10.44	15.96	0.	
							1.029	2.087	0.	
							0.	0.	0.	
							0.	0.	0.	
							0.	0.	0.	
16	15	14	13	12	11	10	9	8	7	6
-42.94	3.672	3.056	5.771	5.012	-8.057	-4.298	7.880	-.6614	-22.21	-14.71
-23.26	6.645	5.231	12.31	9.396	-15.01	-9.592	15.13	-.2759	-42.38	-16.82
-5.636	4.054	-1.406	10.58	9.057	-15.08	-7.487	23.99	-2.701	-43.49	-10.42
0.	4.453	-2.107	8.647	7.521	-11.87	-4.686	35.00	-3.631	-37.41	0.
0.	0.	0.	4.709	2.417	-1.257	1.636	33.66	-4.355	-9.840	0.
0.	0.	0.	0.	0.	0.	3.898	19.99	-2.324	0.	0.
0.	0.	0.	0.	0.	0.	0.	1.143	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
						5	4	3		
						-9.005	-13.70	-6.528		
						-17.11	-27.45	-12.42		
						-13.84	-32.55	-10.19		
						-9.521	-37.58	-6.099		
						0.	-36.71	0.6064		
						0.	-19.29	0.		
						0.	-.8208	0.		
						0.	0.	0.		
							2	1	20	
							-4.897	0.8386	-4.654	
							-8.865	0.7561	-9.083	
							-11.37	0.4860	-17.12	
							-15.69	0.6293	-29.05	
							-24.29	1.162	-45.84	
							-17.57	0.8111	14.49	
							-2.778	0.	2.456	
							0.	0.	0.	

TYPICAL DRY SEASON CONDITIONS IN LOW GRAND FALLS RESERVOIR DAY 230

U-VELOCITY east-west (m/s)

19	18	17
0.8130E-03	0.6424E-02	0.4367E-02
0.9710E-03	0.5975E-02	0.3899E-02
-.5947E-03	-.1069E-02	-.1016E-02
-.6924E-03	-.1616E-02	-.2828E-02
-.7733E-03	-.1505E-02	0.
-.3811E-03	-.8697E-03	0.
0.	0.	0.
0.	0.	0.

16	15	14	13	12	11	10	9	8	7	6
0.	0.	0.	0.	0.	0.	0.5157E-02	0.7315E-02	-.3411E-03	0.	0.
0.	0.	0.	0.	0.	0.	0.4839E-02	0.7069E-02	-.9863E-04	0.	0.
0.	0.	0.	0.	0.	0.	0.7059E-03	0.1649E-02	-.4622E-03	0.	0.
0.	0.	0.	0.	0.	0.	0.5857E-04	0.1216E-02	-.1904E-03	0.	0.
0.	0.	0.	0.	0.	0.	-.8390E-03	0.4314E-03	-.2052E-04	0.	0.
0.	0.	0.	0.	0.	0.	0.	-.6275E-03	0.2200E-03	0.	0.
0.	0.	0.	0.	0.	0.	0.	-.2282E-02	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	-.7622E-03	0.	0.	0.

5	4	3
0.	0.2273E-02	-.6230E-03
0.	0.2154E-02	-.4198E-03
0.	0.1595E-02	0.5136E-03
0.	0.1452E-02	0.6663E-03
0.	0.1283E-02	0.8319E-03
0.	0.6086E-03	0.5943E-03
0.	-.1477E-03	0.
0.	-.1536E-03	0.

2	1	20
0.1395E-02	0.	0.
0.1390E-02	0.	0.
0.1797E-02	0.	0.
0.1795E-02	0.	0.
0.1696E-02	0.	0.
0.2240E-02	0.	0.1145E-01
0.1583E-02	0.	0.
0.6775E-03	0.	0.

TYPICAL DRY SEASON CONDITIONS IN LOW GRAND FALLS RESERVOIR DAY 230

V-VELOCITY north-south (m/s)

19	18	17
0.	0.3360E-02	-.1288E-02
0.	0.2878E-02	-.1686E-02
0.	0.8973E-03	0.1417E-02
0.	0.4580E-03	0.8320E-03
0.	-.4918E-04	0.
0.	0.	0.
0.	0.	0.
0.	0.	0.

16	15	14	13	12	11	10	9	8	7	6
0.	0.4509E-01	0.2478E-01	0.8505E-02	0.9810E-02	0.9272E-02	0.4869E-02	0.4160E-02	-.6446E-04	0.7244E-02	0.2857E-02
0.	0.4652E-01	0.2350E-01	0.8037E-02	0.9170E-02	0.8661E-02	0.4540E-02	0.3771E-02	-.4029E-03	0.6471E-02	0.1401E-02
0.	0.3311E-01	0.1147E-01	0.2010E-02	0.1361E-02	0.1066E-02	0.6729E-03	0.1094E-02	0.3036E-03	-.1060E-02	-.3494E-02
0.	0.9127E-02	0.3307E-02	0.9269E-03	0.4491E-03	0.2019E-03	0.3382E-03	0.7805E-03	-.1672E-03	-.2160E-02	-.5450E-02
0.	0.	-.1979E-02	-.2768E-03	-.5942E-03	-.8267E-03	-.3132E-04	0.3938E-03	-.1049E-02	-.3829E-02	0.
0.	0.	0.	0.	-.1029E-02	-.1105E-02	-.4307E-03	-.2989E-03	-.1639E-02	-.5467E-02	0.
0.	0.	0.	0.	0.	0.	0.	-.4916E-03	-.1823E-02	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.

5	4	3
0.	-.8306E-03	0.1986E-02
0.	-.1085E-02	0.1704E-02
0.	0.1358E-02	0.3534E-04
0.	0.1040E-02	-.2484E-03
0.	0.2203E-02	-.3667E-03
0.	0.	0.1688E-03
0.	0.	0.
0.	0.	0.

2	1	20
0.	0.1508E-04	0.
0.	0.2634E-03	0.
0.	-.1830E-03	0.
0.	-.3096E-03	0.
0.	-.2979E-03	0.
0.	-.9613E-05	0.
0.	0.4506E-03	0.

0. 0. 0.

TYPICAL DRY SEASON CONDITIONS IN LOW GRAND FALLS RESERVOIR

DAY 230

VERTICAL VELOCITY down: -ve (m/s)

19	18	17
0.5388E-05	0.6066E-05	0.5456E-05
0.1167E-04	0.1261E-04	0.1182E-04
0.1299E-04	0.1284E-04	0.1042E-04
0.1410E-04	0.1234E-04	0.
0.1022E-04	0.1002E-04	0.
0.	0.	0.
0.	0.	0.
0.	0.	0.

16	15	14	13	12	11	10	9	8	7	6
-.1444E-03	0.2848E-05	0.6225E-06	0.1234E-05	0.7864E-06	-.9817E-06	-.5395E-06	0.1489E-05	-.2064E-06	-.7273E-05	-.1625E-04
-.9658E-04	0.5748E-05	0.1176E-05	0.2824E-05	0.1564E-05	-.1927E-05	-.1259E-05	0.2889E-05	-.8913E-07	-.1565E-04	-.2231E-04
-.3609E-04	0.4240E-05	-.3745E-06	0.2728E-05	0.1658E-05	-.2106E-05	-.1055E-05	0.4658E-05	-.9213E-06	-.1988E-04	-.1978E-04
0.	0.7153E-05	-.8103E-06	0.2809E-05	0.1653E-05	-.1943E-05	-.7518E-06	0.6989E-05	-.1365E-05	-.2834E-04	0.
0.	0.	0.	0.2974E-05	0.9074E-06	-.3261E-06	0.3912E-06	0.8132E-05	-.3173E-05	-.4437E-04	0.
0.	0.	0.	0.	0.	0.	0.1948E-05	0.8345E-05	-.9490E-05	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.7508E-05	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.

5	4	3
-.2156E-04	-.3793E-05	-.2921E-05
-.5050E-04	-.7782E-05	-.6177E-05
-.6275E-04	-.9573E-05	-.6088E-05
-.4083E-03	-.1179E-04	-.5484E-05
0.	-.1535E-04	0.1799E-05
0.	-.1327E-04	0.
0.	-.3172E-05	0.
0.	0.	0.

2	1	20
-.3118E-05	0.6958E-06	-.2963E-05
-.5783E-05	0.6945E-06	-.5925E-05
-.7700E-05	0.5317E-06	-.1159E-04
-.1135E-04	0.1010E-05	-.2102E-04
-.2184E-04	0.4249E-05	-.4122E-04
-.2341E-04	0.1041E-04	0.1930E-04
-.1728E-04	0.	0.1527E-04

TYPICAL DRY SEASON CONDITIONS IN LOW GRAND FALLS RESERVOIR DAY 230

X-1D-DISCHARGES (cumec)

							19	18	17	
							-13.19	9.194	3.998	
16	15	14	13	12	11	10	9	8	7	6
0.	0.	0.	0.	0.	0.	12.29	66.11	-3.399	0.	0.
						5	4	3		
						0.	71.63	3.370		
							2	1	20	
							75.00	0.	75.00	

Y-1D-DISCHARGES (cumec)

							19	18	17	
							0.	13.19	3.998	
16	15	14	13	12	11	10	9	8	7	6
0.	65.00	65.00	65.00	65.00	65.00	65.00	52.71	-26.59	-14.00	-10.00
						5	4	3		
						0.	12.29	6.768		
							2	1	20	
							0.	-3.370	0.	

LATERAL INFLOWS (cumec)

							19	18	17	
							0.	0.	0.	
16	15	14	13	12	11	10	9	8	7	6
65.00	0.	0.	0.	0.	0.	0.	0.	0.	0.	10.00
						5	4	3		
						0.	0.	0.		
							2	1	20	
							0.	0.	0.	

TYPICAL DRY SEASON CONDITIONS IN LOW GRAND FALLS RESERVOIR DAY 230

FB stream conc.s (ppm) Typical dry season conditions

							19	18	17	
							0.	0.	0.	
16	15	14	13	12	11	10	9	8	7	6
0.1300	0.	0.	0.	0.	0.	0.	0.	0.	0.	1.500
						5	4	3		
						0.	0.	0.		
							2	1	20	
							0.	0.	0.	

SB stream conc.s (ppm) Typical dry season conditions

							19	18	17	
							0.	0.	0.	
16	15	14	13	12	11	10	9	8	7	6
0.7500	0.	0.	0.	0.	0.	0.	0.	0.	0.	1.500
						5	4	3		
						0.	0.	0.		
							2	1	20	
							0.	0.	0.	

DO stream conc.s (ppm) Typical dry season conditions

							19	18	17	
							0.	0.	0.	
16	15	14	13	12	11	10	9	8	7	6
6.210	0.	0.	0.	0.	0.	0.	0.	0.	0.	9.200
						5	4	3		
						0.	0.	0.		
							2	1	20	
							0.	0.	0.	

TYPICAL DRY SEASON CONDITIONS IN LOW GRAND FALLS RESERVOIR DAY 230

ON stream conc.s (ppm) Typical dry season conditions

							19	18	17	
							0.	0.	0.	
16	15	14	13	12	11	10	9	8	7	6
0.2500	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.1000
						5	4	3		
						0.	0.	0.		
							2	1	20	
							0.	0.	0.	

MUD stream conc. (ppm) Typical dry season conditions

							19	18	17	
							0.	0.	0.	
16	15	14	13	12	11	10	9	8	7	6
25.00	0.	0.	0.	0.	0.	0.	0.	0.	0.	40.00
						5	4	3		
						0.	0.	0.		
							2	1	20	
							0.	0.	0.	

AC stream conc.s (ppm) Typical dry season conditions

							19	18	17	
							0.	0.	0.	
16	15	14	13	12	11	10	9	8	7	6
0.2650E-01	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.5000E-01
						5	4	3		
						0.	0.	0.		
							2	1	20	
							0.	0.	0.	

TYPICAL DRY SEASON CONDITIONS IN LOW GRAND FALLS RESERVOIR DAY 230

PH stream conc.s (ppm) Typical dry season conditions

							19	18	17	
							0.	0.	0.	
16	15	14	13	12	11	10	9	8	7	6
0.1000E-01	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.2000E-01
						5	4	3		
						0.	0.	0.		
							2	1	20	
							0.	0.	0.	

TP stream conc.s deg. C Typical dry season conditions

							19	18	17	
							0.	0.	0.	
16	15	14	13	12	11	10	9	8	7	6
25.00	0.	0.	0.	0.	0.	0.	0.	0.	0.	20.00
						5	4	3		
						0.	0.	0.		
							2	1	20	
							0.	0.	0.	

TYPICAL DRY SEASON CONDITIONS IN LOW GRAND FALLS RESERVOIR DAY 230

INERT S.SOL. PPM Typical dry season conditions

							19	18	17	
							1.326	1.447	1.658	
							2.831	2.847	2.931	
							4.243	4.195	4.210	
							5.611	5.579	5.577	
							5.625	5.590	0.	
							5.649	5.610	0.	
							0.	0.	0.	
							0.	0.	0.	
16	15	14	13	12	11	10	9	8	7	6
23.54	15.42	6.412	4.597	3.102	1.873	1.469	1.298	1.424	2.180	5.959
23.20	18.22	10.14	7.944	5.999	4.052	3.311	2.804	2.731	3.068	5.266
19.87	14.50	9.079	7.698	6.474	5.188	4.692	4.223	4.097	4.109	5.124
9.308	7.187	6.227	6.000	5.857	5.717	5.667	5.603	5.562	5.481	5.263
0.	6.343	6.053	5.961	5.847	5.726	5.685	5.627	5.593	5.540	0.
0.	0.	0.	5.988	5.843	5.726	5.697	5.653	5.620	5.572	0.
0.	0.	0.	0.	0.	0.	5.756	5.676	5.632	0.	0.
0.	0.	0.	0.	0.	0.	0.	5.667	0.	0.	0.
						5	4	3		
						1.152	1.101	1.172		
						2.495	2.399	2.424		
						3.975	3.891	3.884		
						5.557	5.556	5.542		
						5.624	5.611	5.603		
						0.	5.637	5.632		
						0.	5.648	0.		
						0.	5.648	0.		
							2	1	20	
							1.016	1.046	0.9765	
							2.250	2.278	2.178	
							3.776	3.790	3.712	
							5.540	5.540	5.529	
							5.609	5.601	5.613	
							5.632	5.628	5.627	
							5.643	5.638	5.636	
							5.643	0.	5.642	

TYPICAL DRY SEASON CONDITIONS IN LOW GRAND FALLS RESERVOIR - DAY 230

SETTLED MUD (T) Typical dry season conditions

							19	18	17	
							9.986	15.37	52.65	
							53.98	42.14	53.03	
							120.9	92.43	112.6	
							247.2	190.4	419.2	
							294.5	496.4	0.	
							46.38	95.43	0.	
							0.	0.	0.	
							0.	0.	0.	
16	15	14	13	12	11	10	9	8	7	6
0.	0.	105.1	155.0	94.92	64.64	31.62	0.	3.754	47.08	181.2
0.	0.	204.9	216.0	184.8	142.7	96.36	14.26	26.56	98.31	75.39
0.	0.	573.8	331.9	314.5	286.1	212.5	32.08	59.21	192.5	106.7
0.	139.1	622.4	407.2	446.6	494.3	402.9	65.59	124.2	392.7	243.8
0.	0.	1345.	747.5	914.9	1061.	957.1	400.0	589.4	499.8	0.
0.	0.	0.	0.	1287.	1810.	1016.	804.1	517.4	101.2	0.
0.	0.	0.	0.	0.	0.	0.	1037.	112.4	0.	0.
0.	0.	0.	0.	0.	0.	0.	70.15	0.	0.	0.
						5	4	3		
						0.	1.060	22.23		
						0.	18.12	48.24		
						0.	43.87	115.2		
						0.	96.93	254.5		
						0.	364.6	354.6		
						0.	430.6	154.7		
						0.	549.3	0.		
						0.	118.7	0.		
							2	1	20	
							3.733	12.62	0.	
							7.663	24.05	0.	
							18.89	58.98	0.	
							42.70	132.3	0.	
							123.7	159.8	0.	
							165.9	89.60	0.	
							270.9	35.76	270.5	
							73.62	0.	73.60	

TYPICAL DRY SEASON CONDITIONS IN LOW GRAND FALLS RESERVOIR DAY 230

BED DETRITUS MGS Typical dry season conditions

19	18	17
0.1216E+08	0.1600E+08	0.4498E+08
0.6803E+08	0.4956E+08	0.5781E+08
0.1580E+09	0.1168E+09	0.1379E+09
0.2848E+09	0.2114E+09	0.4623E+09
0.3461E+09	0.5646E+09	0.
0.5479E+08	0.1099E+09	0.
0.	0.	0.
0.	0.	0.

16	15	14	13	12	11	10	9	8	7	6
0.6274E+07	0.1031E+09	0.2244E+09	0.1636E+09	0.1206E+09	0.9501E+08	0.4763E+08	0.	0.3979E+07	0.3192E+08	0.7483E+08
0.1856E+08	0.1023E+09	0.3942E+09	0.2511E+09	0.2412E+09	0.2040E+09	0.1397E+09	0.1871E+08	0.3229E+08	0.9774E+08	0.4987E+08
0.5348E+08	0.1799E+09	0.6504E+09	0.4210E+09	0.4264E+09	0.4017E+09	0.2966E+09	0.4276E+08	0.7656E+08	0.2300E+09	0.8740E+08
0.1214E+09	0.2848E+09	0.9551E+09	0.6113E+09	0.6345E+09	0.6447E+09	0.5017E+09	0.7611E+08	0.1402E+09	0.4346E+09	0.2392E+09
0.	0.4911E+09	0.1958E+10	0.1072E+10	0.1264E+10	0.1362E+10	0.1188E+10	0.4716E+09	0.6784E+09	0.5657E+09	0.
0.	0.	0.	0.1108E+10	0.1748E+10	0.2286E+10	0.1244E+10	0.9522E+09	0.6019E+09	0.1159E+09	0.
0.	0.	0.	0.	0.	0.	0.1114E+10	0.1222E+10	0.1309E+09	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.8235E+08	0.	0.	0.

5	4	3
0.1964E+08	0.1453E+07	0.2718E+08
0.2410E+08	0.2510E+08	0.6350E+08
0.5703E+08	0.6036E+08	0.1549E+09
0.1042E+09	0.1108E+09	0.2875E+09
0.1261E+08	0.4245E+09	0.4107E+09
0.	0.5042E+09	0.1807E+09
0.	0.6424E+09	0.
0.	0.1383E+09	0.

2	1	20
0.5164E+07	0.1646E+08	0.5058E+07
0.1065E+08	0.3221E+08	0.1044E+08
0.2616E+08	0.7958E+08	0.2593E+08
0.4833E+08	0.1480E+09	0.4806E+08
0.1434E+09	0.1842E+09	0.1431E+09
0.1936E+09	0.1042E+09	0.1924E+09
0.3162E+09	0.4165E+08	0.3150E+09
0.8540E+08	0.	0.8530E+08

TYPICAL DRY SEASON CONDITIONS IN LOW GRAND FALLS RESERVOIR DAY 230

BEDLOAD G/M2/DAY Typical dry season conditions

19	18	17
0.2495E-01	0.2349E-01	0.2244E-01
0.5097E-01	0.4790E-01	0.4610E-01
0.7569E-01	0.7231E-01	0.7046E-01
0.7995E-01	0.7671E-01	0.7617E-01
0.8169E-01	0.7863E-01	0.
0.8224E-01	0.7974E-01	0.
0.	0.	0.
0.	0.	0.

16	15	14	13	12	11	10	9	8	7	6
0.2342E-01	0.8078E-01	0.8110E-01	0.7198E-01	0.5777E-01	0.4016E-01	0.3241E-01	0.	0.2365E-01	0.2378E-01	0.3779E-01
0.5864E-01	0.1259	0.1388	0.1273	0.1071	0.7882E-01	0.6532E-01	0.5288E-01	0.4784E-01	0.4540E-01	0.5180E-01
0.1020	0.1395	0.1435	0.1340	0.1192	0.9821E-01	0.8805E-01	0.7720E-01	0.7268E-01	0.6875E-01	0.5993E-01
0.1185	0.1292	0.1249	0.1154	0.1050	0.9282E-01	0.8749E-01	0.8053E-01	0.7781E-01	0.7588E-01	0.6960E-01
0.	0.1191	0.1137	0.1083	0.1013	0.9125E-01	0.8743E-01	0.8197E-01	0.7962E-01	0.7791E-01	0.
0.	0.	0.	0.1056	0.9908E-01	0.8956E-01	0.8622E-01	0.8250E-01	0.8065E-01	0.7901E-01	0.
0.	0.	0.	0.	0.	0.	0.8409E-01	0.8229E-01	0.8072E-01	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.8166E-01	0.	0.	0.

5	4	3
0.2454E-01	0.2337E-01	0.2234E-01
0.4964E-01	0.4769E-01	0.4578E-01
0.7492E-01	0.7332E-01	0.7145E-01
0.7993E-01	0.7856E-01	0.7742E-01
0.8167E-01	0.8061E-01	0.8005E-01
0.	0.8125E-01	0.8097E-01
0.	0.8120E-01	0.
0.	0.8068E-01	0.

2	1	20
0.2225E-01	0.2156E-01	0.2179E-01
0.4586E-01	0.4479E-01	0.4498E-01
0.7212E-01	0.7083E-01	0.7157E-01
0.7771E-01	0.7682E-01	0.7729E-01
0.8018E-01	0.7964E-01	0.7999E-01
0.8085E-01	0.8056E-01	0.8037E-01
0.8096E-01	0.8070E-01	0.8066E-01

TYPICAL DRY SEASON CONDITIONS IN LOW GRAND FALLS RESERVOIR DAY 230

FAST DIS.BOD PPM Typical dry season conditions

19	18	17
0.1414E-01	0.1882E-01	0.2540E-01
0.8761E-02	0.1152E-01	0.1434E-01
0.8775E-02	0.1178E-01	0.1352E-01
0.1617E-02	0.2570E-02	0.2680E-02
0.1569E-02	0.2356E-02	0.
0.1342E-02	0.1930E-02	0.
0.	0.	0.
0.	0.	0.

16	15	14	13	12	11	10	9	8	7	6
0.1205	0.7375E-01	0.2698E-01	0.1863E-01	0.1275E-01	0.9565E-02	0.9793E-02	0.1307E-01	0.1954E-01	0.4172E-01	0.1394
0.1132	0.6550E-01	0.2281E-01	0.1480E-01	0.9811E-02	0.6920E-02	0.6696E-02	0.8419E-02	0.1274E-01	0.2815E-01	0.9488E-01
0.7056E-01	0.3198E-01	0.9959E-02	0.6803E-02	0.5430E-02	0.5442E-02	0.6191E-02	0.8541E-02	0.1287E-01	0.2574E-01	0.7692E-01
0.1047E-01	0.2578E-02	0.9998E-03	0.8663E-03	0.9201E-03	0.1110E-02	0.1255E-02	0.1679E-02	0.2861E-02	0.6842E-02	0.4724E-01
0.	0.9661E-03	0.8618E-03	0.8644E-03	0.9316E-03	0.1112E-02	0.1238E-02	0.1574E-02	0.2370E-02	0.4383E-02	0.
0.	0.	0.	0.8424E-03	0.8945E-03	0.1055E-02	0.1155E-02	0.1327E-02	0.1834E-02	0.3198E-02	0.
0.	0.	0.	0.	0.	0.	0.1088E-02	0.1209E-02	0.1571E-02	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.1122E-02	0.	0.	0.

5	4	3
0.1127E-01	0.1194E-01	0.1462E-01
0.7489E-02	0.7763E-02	0.9401E-02
0.7834E-02	0.8252E-02	0.9614E-02
0.1699E-02	0.1675E-02	0.1883E-02
0.1476E-02	0.1516E-02	0.1574E-02
0.	0.1327E-02	0.1339E-02
0.	0.1243E-02	0.
0.	0.1106E-02	0.

2	1	20
0.1127E-01	0.1219E-01	0.1088E-01
0.7307E-02	0.7792E-02	0.7037E-02
0.7982E-02	0.8322E-02	0.7815E-02
0.1635E-02	0.1629E-02	0.1619E-02
0.1473E-02	0.1481E-02	0.1416E-02
0.1325E-02	0.1321E-02	0.1345E-02
0.1256E-02	0.1236E-02	0.1284E-02
0.1072E-02	0.	0.1064E-02

TYPICAL DRY SEASON CONDITIONS IN LOW GRAND FALLS RESERVOIR DAY 230

SLOW DIS.BOD PPM Typical dry season conditions

19	18	17
0.1769	0.1760	0.1791
0.1464	0.1435	0.1435
0.1110	0.1130	0.1144
0.2376E-01	0.2564E-01	0.2570E-01
0.2420E-01	0.2611E-01	0.
0.2355E-01	0.2513E-01	0.
0.	0.	0.
0.	0.	0.

16	15	14	13	12	11	10	9	8	7	6
0.7182	0.5704	0.3601	0.3101	0.2622	0.2160	0.1960	0.1800	0.1785	0.1931	0.2612
0.7247	0.5431	0.3211	0.2662	0.2232	0.1850	0.1677	0.1511	0.1490	0.1617	0.2119
0.5387	0.3187	0.1648	0.1367	0.1218	0.1157	0.1140	0.1135	0.1191	0.1385	0.1875
0.9740E-01	0.3606E-01	0.2305E-01	0.2136E-01	0.2161E-01	0.2291E-01	0.2339E-01	0.2447E-01	0.2768E-01	0.3874E-01	0.1273
0.	0.2298E-01	0.2179E-01	0.2152E-01	0.2176E-01	0.2267E-01	0.2316E-01	0.2433E-01	0.2643E-01	0.3211E-01	0.
0.	0.	0.	0.2140E-01	0.2162E-01	0.2240E-01	0.2283E-01	0.2353E-01	0.2494E-01	0.2893E-01	0.
0.	0.	0.	0.	0.	0.	0.2260E-01	0.2314E-01	0.2416E-01	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.2283E-01	0.	0.	0.

5	4	3
0.1810	0.1757	0.1747
0.1562	0.1503	0.1484
0.1207	0.1187	0.1190
0.2721E-01	0.2602E-01	0.2648E-01
0.2439E-01	0.2452E-01	0.2474E-01
0.	0.2371E-01	0.2378E-01
0.	0.2341E-01	0.
0.	0.2284E-01	0.

2	1	20
0.1728	0.1715	0.1716
0.1485	0.1464	0.1479
0.1196	0.1181	0.1204
0.2628E-01	0.2580E-01	0.2664E-01
0.2449E-01	0.2458E-01	0.2436E-01
0.2378E-01	0.2379E-01	0.2398E-01
0.2350E-01	0.2344E-01	0.2367E-01
0.2272E-01	0.	0.2269E-01

TYPICAL DRY SEASON CONDITIONS IN LOW GRAND FALLS RESERVOIR DAY 230

AMMONIA PPM Typical dry season conditions

19	18	17
0.4075E-04	0.4189E-04	0.4294E-04
0.6746E-04	0.6781E-04	0.6804E-04
0.8250E-04	0.8165E-04	0.8134E-04
0.1026E-03	0.1021E-03	0.1021E-03
0.1025E-03	0.1020E-03	0.
0.1027E-03	0.1022E-03	0.
0.	0.	0.
0.	0.	0.

16	15	14	13	12	11	10	9	8	7	6
0.2918E-05	0.1395E-04	0.3084E-04	0.3440E-04	0.3675E-04	0.3764E-04	0.3827E-04	0.3968E-04	0.4070E-04	0.4330E-04	0.5611E-04
-.2853E-06	0.2484E-04	0.5732E-04	0.6419E-04	0.6744E-04	0.6690E-04	0.6636E-04	0.6610E-04	0.6530E-04	0.6299E-04	0.6302E-04
0.2714E-04	0.6098E-04	0.8436E-04	0.8752E-04	0.8779E-04	0.8538E-04	0.8394E-04	0.8190E-04	0.7990E-04	0.7513E-04	0.6751E-04
0.9402E-04	0.1032E-03	0.1046E-03	0.1045E-03	0.1040E-03	0.1033E-03	0.1030E-03	0.1025E-03	0.1016E-03	0.9911E-04	0.8010E-04
0.	0.1048E-03	0.1046E-03	0.1044E-03	0.1040E-03	0.1033E-03	0.1030E-03	0.1025E-03	0.1019E-03	0.1006E-03	0.
0.	0.	0.	0.1044E-03	0.1040E-03	0.1033E-03	0.1030E-03	0.1027E-03	0.1023E-03	0.1013E-03	0.
0.	0.	0.	0.	0.	0.	0.1029E-03	0.1027E-03	0.1024E-03	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.1027E-03	0.	0.	0.

5	4	3
0.3753E-04	0.3809E-04	0.3896E-04
0.6214E-04	0.6277E-04	0.6324E-04
0.7929E-04	0.7939E-04	0.7921E-04
0.1018E-03	0.1020E-03	0.1019E-03
0.1025E-03	0.1024E-03	0.1023E-03
0.	0.1026E-03	0.1025E-03
0.	0.1026E-03	0.
0.	0.1026E-03	0.

2	1	20
0.3767E-04	0.3833E-04	0.3741E-04
0.6192E-04	0.6267E-04	0.6143E-04
0.7874E-04	0.7911E-04	0.7831E-04
0.1019E-03	0.1020E-03	0.1018E-03
0.1024E-03	0.1023E-03	0.1024E-03
0.1025E-03	0.1025E-03	0.1025E-03
0.1026E-03	0.1026E-03	0.1025E-03
0.1026E-03	0.	0.1026E-03

TYPICAL DRY SEASON CONDITIONS IN LOW GRAND FALLS RESERVOIR DAY 230

NITRATE PPM Typical dry season conditions

							19	18	17	
							0.1672	0.1657	0.1644	
							0.1611	0.1599	0.1591	
							0.1632	0.1621	0.1616	
							0.1239	0.1240	0.1239	
							0.1242	0.1244	0.	
							0.1241	0.1243	0.	
							0.	0.	0.	
							0.	0.	0.	
16	15	14	13	12	11	10	9	8	7	6
0.2461	0.2228	0.1931	0.1867	0.1807	0.1748	0.1717	0.1682	0.1662	0.1629	0.1521
0.2449	0.2218	0.1891	0.1810	0.1745	0.1682	0.1651	0.1618	0.1601	0.1579	0.1522
0.2274	0.1988	0.1769	0.1720	0.1690	0.1670	0.1658	0.1641	0.1632	0.1619	0.1515
0.1384	0.1258	0.1234	0.1231	0.1233	0.1239	0.1240	0.1242	0.1248	0.1273	0.1418
0.	0.1234	0.1232	0.1232	0.1234	0.1238	0.1239	0.1242	0.1246	0.1259	0.
0.	0.	0.	0.1232	0.1234	0.1237	0.1238	0.1241	0.1243	0.1252	0.
0.	0.	0.	0.	0.	0.	0.1238	0.1240	0.1242	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.1239	0.	0.	0.
						5	4	3		
						0.1692	0.1681	0.1671		
						0.1620	0.1611	0.1604		
						0.1663	0.1656	0.1649		
						0.1255	0.1250	0.1250		
						0.1243	0.1244	0.1244		
						0.	0.1242	0.1242		
						0.	0.1241	0.		
						0.	0.1239	0.		
							2	1	20	
							0.1679	0.1673	0.1679	
							0.1608	0.1605	0.1607	
							0.1661	0.1654	0.1665	
							0.1252	0.1249	0.1253	
							0.1244	0.1244	0.1244	
							0.1242	0.1242	0.1243	
							0.1241	0.1241	0.1242	
							0.1239	0.	0.1239	

TYPICAL DRY SEASON CONDITIONS IN LOW GRAND FALLS RESERVOIR DAY 230

DIS.OXYGEN %SAT Typical dry season conditions

19	18	17
99.05	98.72	98.45
83.16	83.50	83.76
86.27	86.58	86.76
80.86	80.94	80.93
80.89	80.98	0.
80.84	80.91	0.
0.	0.	0.
0.	0.	0.

16	15	14	13	12	11	10	9	8	7	6
75.68	87.21	96.39	97.73	98.73	99.64	99.78	99.47	99.27	98.52	92.61
74.66	75.48	77.91	78.76	79.87	81.60	82.45	83.32	84.10	85.87	90.06
77.34	80.49	83.35	84.07	84.67	85.34	85.70	86.22	86.60	87.29	89.00
79.78	80.23	80.48	80.56	80.65	80.78	80.83	80.91	81.07	81.64	86.02
0.	80.40	80.51	80.57	80.65	80.77	80.82	80.90	81.00	81.29	0.
0.	0.	0.	80.56	80.62	80.74	80.79	80.85	80.91	81.11	0.
0.	0.	0.	0.	0.	0.	80.78	80.81	80.86	0.	0.
0.	0.	0.	0.	0.	0.	0.	80.78	0.	0.	0.

5	4	3
100.5	100.3	99.96
84.17	84.19	84.31
86.25	86.38	86.47
81.07	81.01	81.03
80.91	80.92	80.93
0.	80.87	80.87
0.	80.84	0.
0.	80.80	0.

2	1	20
100.5	100.1	100.6
84.43	84.31	84.55
86.45	86.45	86.50
81.04	81.00	81.06
80.92	80.93	80.92
80.88	80.88	80.89
80.85	80.84	80.87
80.81	0.	80.82

TYPICAL DRY SEASON CONDITIONS IN LOW GRAND FALLS RESERVOIR DAY 230

DO CONC PPM Typical dry season conditions

							19	18	17	
							8.618	8.595	8.576	
							7.228	7.261	7.286	
							7.518	7.547	7.564	
							7.039	7.045	7.045	
							7.041	7.049	0.	
							7.037	7.043	0.	
							0.	0.	0.	
							0.	0.	0.	
16	15	14	13	12	11	10	9	8	7	6
6.535	7.539	8.348	8.470	8.564	8.653	8.671	8.653	8.642	8.591	8.120
6.443	6.524	6.749	6.827	6.927	7.082	7.158	7.240	7.312	7.476	7.879
6.692	6.985	7.251	7.317	7.372	7.432	7.465	7.512	7.548	7.613	7.779
6.937	6.981	7.004	7.011	7.019	7.031	7.036	7.043	7.057	7.109	7.507
0.	6.998	7.007	7.012	7.020	7.030	7.034	7.042	7.051	7.077	0.
0.	0.	0.	7.011	7.017	7.027	7.032	7.037	7.043	7.061	0.
0.	0.	0.	0.	0.	0.	7.031	7.034	7.038	0.	0.
0.	0.	0.	0.	0.	0.	0.	7.031	0.	0.	0.
						5	4	3		
						8.745	8.725	8.700		
						7.311	7.315	7.327		
						7.513	7.526	7.534		
						7.057	7.052	7.054		
						7.042	7.044	7.045		
						0.	7.039	7.039		
						0.	7.037	0.		
						0.	7.033	0.		
							2	1	20	
							8.741	8.714	8.751	
							7.335	7.326	7.345	
							7.532	7.532	7.536	
							7.054	7.051	7.056	
							7.044	7.044	7.043	
							7.040	7.040	7.041	
							7.037	7.036	7.039	
							7.034	0.	7.034	

TYPICAL DRY SEASON CONDITIONS IN LOW GRAND FALLS RESERVOIR DAY 230

TEMPERATURE DEGC Typical dry season conditions

							19	18	17	
							24.52	24.48	24.45	
							24.59	24.56	24.53	
							24.42	24.41	24.40	
							24.49	24.49	24.49	
							24.49	24.49	0.	
							24.50	24.49	0.	
							0.	0.	0.	
							0.	0.	0.	
16	15	14	13	12	11	10	9	8	7	6
24.98	24.91	24.80	24.76	24.71	24.64	24.59	24.53	24.48	24.38	24.05
25.01	24.92	24.79	24.75	24.72	24.68	24.65	24.60	24.56	24.48	24.19
24.86	24.67	24.53	24.50	24.48	24.46	24.45	24.43	24.41	24.38	24.24
24.56	24.51	24.50	24.50	24.50	24.50	24.50	24.49	24.49	24.47	24.33
0.	24.50	24.50	24.50	24.50	24.50	24.50	24.49	24.49	24.48	0.
0.	0.	0.	24.50	24.50	24.50	24.50	24.50	24.49	24.49	0.
0.	0.	0.	0.	0.	0.	24.50	24.50	24.49	0.	0.
0.	0.	0.	0.	0.	0.	0.	24.50	0.	0.	0.
						5	4	3		
						24.54	24.52	24.50		
						24.62	24.61	24.59		
						24.45	24.44	24.43		
						24.49	24.49	24.49		
						24.49	24.49	24.49		
						0.	24.50	24.49		
						0.	24.50	0.		
						0.	24.50	0.		
							2	1	20	
							24.52	24.51	24.52	
							24.61	24.60	24.61	
							24.44	24.44	24.44	
							24.49	24.49	24.49	
							24.49	24.49	24.49	
							24.50	24.50	24.49	
							24.50	24.50	24.50	
							24.50	0.	24.50	

TYPICAL DRY SEASON CONDITIONS IN LOW GRAND FALLS RESERVOIR DAY 230

CHLOROPHYLL PPB Typical dry season conditions

19	18	17
0.2396	0.2276	0.2249
0.2744	0.2569	0.2503
0.1851	0.1856	0.1858
0.1010E-01	0.1205E-01	0.1202E-01
0.1051E-01	0.1280E-01	0.
0.8907E-02	0.1085E-01	0.
0.	0.	0.
0.	0.	0.

16	15	14	13	12	11	10	9	8	7	6
0.5737	0.9791	0.8609	0.7417	0.5790	0.3968	0.3167	0.2502	0.2297	0.2330	0.2799
0.7070	0.7006	0.7399	0.6733	0.5721	0.4330	0.3608	0.2878	0.2636	0.2581	0.2502
0.4536	0.2295	0.1505	0.1448	0.1580	0.1833	0.1886	0.1902	0.1963	0.2149	0.2285
0.6885E-01	0.1826E-01	0.8159E-02	0.6718E-02	0.7322E-02	0.9756E-02	0.1038E-01	0.1151E-01	0.1583E-01	0.3176E-01	0.1478
0.	0.6991E-02	0.6489E-02	0.6528E-02	0.7150E-02	0.8471E-02	0.9142E-02	0.1069E-01	0.1348E-01	0.2160E-01	0.
0.	0.	0.	0.6200E-02	0.6463E-02	0.7420E-02	0.7957E-02	0.8861E-02	0.1074E-01	0.1612E-01	0.
0.	0.	0.	0.	0.	0.	0.7140E-02	0.8033E-02	0.9112E-02	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.7329E-02	0.	0.	0.

5	4	3
0.2493	0.2294	0.2213
0.2928	0.2711	0.2609
0.2069	0.2033	0.2021
0.1763E-01	0.1496E-01	0.1563E-01
0.1104E-01	0.1116E-01	0.1155E-01
0.	0.9230E-02	0.9344E-02
0.	0.8546E-02	0.
0.	0.7324E-02	0.

2	1	20
0.2182	0.2136	0.2140
0.2608	0.2544	0.2568
0.2059	0.2027	0.2081
0.1570E-01	0.1477E-01	0.1654E-01
0.1112E-01	0.1135E-01	0.1081E-01
0.9386E-02	0.9398E-02	0.9872E-02
0.8741E-02	0.8555E-02	0.9132E-02
0.7091E-02	0.	0.7029E-02

TYPICAL DRY SEASON CONDITIONS IN LOW GRAND FALLS RESERVOIR DAY 230

ALGAL CARBON PPB Typical dry season conditions

							19	18	17	
							11.98	11.38	11.25	
							13.72	12.84	12.51	
							9.255	9.280	9.291	
							0.5050	0.6025	0.6009	
							0.5254	0.6400	0.	
							0.4453	0.5423	0.	
							0.	0.	0.	
							0.	0.	0.	
16	15	14	13	12	11	10	9	8	7	6
28.68	48.95	43.04	37.08	28.95	19.84	15.84	12.51	11.48	11.65	13.99
35.35	35.03	36.99	33.66	28.60	21.65	18.04	14.39	13.18	12.91	12.51
22.68	11.47	7.527	7.241	7.900	9.163	9.429	9.511	9.814	10.75	11.42
3.442	0.9132	0.4079	0.3359	0.3661	0.4878	0.5189	0.5753	0.7917	1.588	7.389
0.	0.3495	0.3244	0.3264	0.3575	0.4236	0.4571	0.5347	0.6739	1.080	0.
0.	0.	0.	0.3100	0.3231	0.3710	0.3979	0.4430	0.5369	0.8062	0.
0.	0.	0.	0.	0.	0.	0.3570	0.4016	0.4556	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.3664	0.	0.	0.
						5	4	3		
						12.46	11.47	11.06		
						14.64	13.55	13.05		
						10.34	10.16	10.10		
						0.8815	0.7482	0.7813		
						0.5521	0.5580	0.5774		
						0.	0.4615	0.4672		
						0.	0.4273	0.		
						0.	0.3662	0.		
							2	1	20	
							10.91	10.68	10.70	
							13.04	12.72	12.84	
							10.30	10.14	10.40	
							0.7852	0.7386	0.8271	
							0.5559	0.5676	0.5404	
							0.4693	0.4699	0.4936	
							0.4371	0.4278	0.4566	
							0.3545	0.	0.3515	

TYPICAL DRY SEASON CONDITIONS IN LOW GRAND FALLS RESERVOIR DAY 230

DETRITAL CAR PPB Typical dry season conditions

							19	18	17	
							0.9916	0.9335	0.8885	
							2.120	1.993	1.916	
							3.223	3.077	2.996	
							3.475	3.320	3.297	
							3.540	3.415	0.	
							3.569	3.462	0.	
							0.	0.	0.	
							0.	0.	0.	
16	15	14	13	12	11	10	9	8	7	6
0.7498	3.304	3.274	2.888	2.305	1.596	1.287	1.033	0.9403	0.9473	1.528
2.375	5.356	5.883	5.378	4.499	3.288	2.719	2.199	1.990	1.893	2.176
4.299	5.945	6.227	5.810	5.150	4.212	3.764	3.288	3.091	2.921	2.545
5.070	5.536	5.388	4.967	4.536	4.030	3.798	3.495	3.373	3.286	2.989
0.	5.159	4.963	4.730	4.416	3.964	3.796	3.556	3.454	3.376	0.
0.	0.	0.	4.620	4.308	3.891	3.745	3.581	3.500	3.425	0.
0.	0.	0.	0.	0.	0.	3.653	3.573	3.504	0.	0.
0.	0.	0.	0.	0.	0.	0.	3.547	0.	0.	0.
						5	4	3		
						0.9689	0.9276	0.8851		
						2.059	1.981	1.900		
						3.184	3.115	3.033		
						3.465	3.407	3.357		
						3.544	3.497	3.472		
						0.	3.527	3.514		
						0.	3.525	0.		
						0.	3.503	0.		
							2	1	20	
							0.8818	0.8528	0.8653	
							1.902	1.856	1.870	
							3.060	3.003	3.039	
							3.369	3.331	3.351	
							3.478	3.454	3.470	
							3.509	3.496	3.488	
							3.514	3.503	3.501	
							3.483	0.	3.478	

TYPICAL DRY SEASON CONDITIONS IN LOW GRAND FALLS RESERVOIR DAY 230

PHOSPHATE PPM Typical dry season conditions

19	18	17
0.2011E-02	0.2082E-02	0.2185E-02
0.1653E-02	0.1704E-02	0.1764E-02
0.2150E-02	0.2181E-02	0.2209E-02
0.2889E-02	0.2897E-02	0.2900E-02
0.2883E-02	0.2885E-02	0.
0.2884E-02	0.2884E-02	0.
0.	0.	0.
0.	0.	0.

16	15	14	13	12	11	10	9	8	7	6
0.9516E-02	0.6682E-02	0.3395E-02	0.2791E-02	0.2348E-02	0.2062E-02	0.1994E-02	0.2006E-02	0.2102E-02	0.2441E-02	0.3755E-02
0.9358E-02	0.6959E-02	0.3571E-02	0.2823E-02	0.2264E-02	0.1820E-02	0.1687E-02	0.1643E-02	0.1707E-02	0.1995E-02	0.3223E-02
0.7545E-02	0.5323E-02	0.3477E-02	0.3058E-02	0.2700E-02	0.2337E-02	0.2215E-02	0.2129E-02	0.2142E-02	0.2261E-02	0.3056E-02
0.3632E-02	0.3076E-02	0.2937E-02	0.2915E-02	0.2903E-02	0.2890E-02	0.2886E-02	0.2883E-02	0.2882E-02	0.2870E-02	0.2977E-02
0.	0.2938E-02	0.2920E-02	0.2911E-02	0.2902E-02	0.2891E-02	0.2888E-02	0.2882E-02	0.2882E-02	0.2876E-02	0.
0.	0.	0.	0.2909E-02	0.2901E-02	0.2891E-02	0.2888E-02	0.2883E-02	0.2883E-02	0.2879E-02	0.
0.	0.	0.	0.	0.	0.	0.2886E-02	0.2883E-02	0.2884E-02	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.2883E-02	0.	0.	0.

5	4	3
0.2000E-02	0.1996E-02	0.2032E-02
0.1595E-02	0.1583E-02	0.1613E-02
0.2019E-02	0.2011E-02	0.2031E-02
0.2853E-02	0.2865E-02	0.2865E-02
0.2878E-02	0.2877E-02	0.2876E-02
0.	0.2881E-02	0.2880E-02
0.	0.2881E-02	0.
0.	0.2882E-02	0.

2	1	20
0.1984E-02	0.1991E-02	0.1978E-02
0.1556E-02	0.1565E-02	0.1542E-02
0.1970E-02	0.1987E-02	0.1945E-02
0.2860E-02	0.2865E-02	0.2855E-02
0.2876E-02	0.2875E-02	0.2876E-02
0.2880E-02	0.2879E-02	0.2878E-02
0.2880E-02	0.2880E-02	0.2879E-02

0.2882E-02 0. 0.2882E-02

Figures

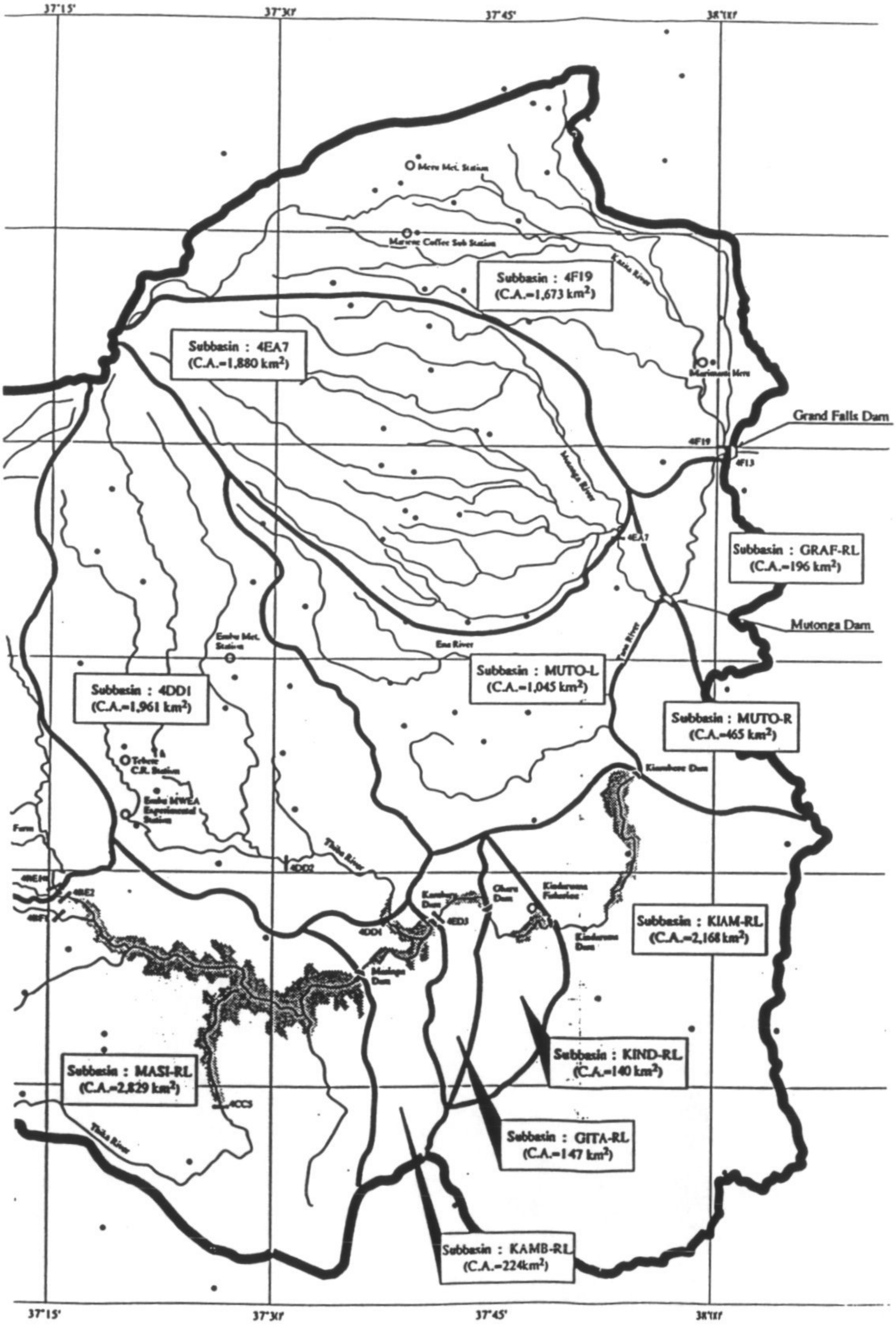


Figure 1.1 Regional Location Plan of Upper Tana catchment

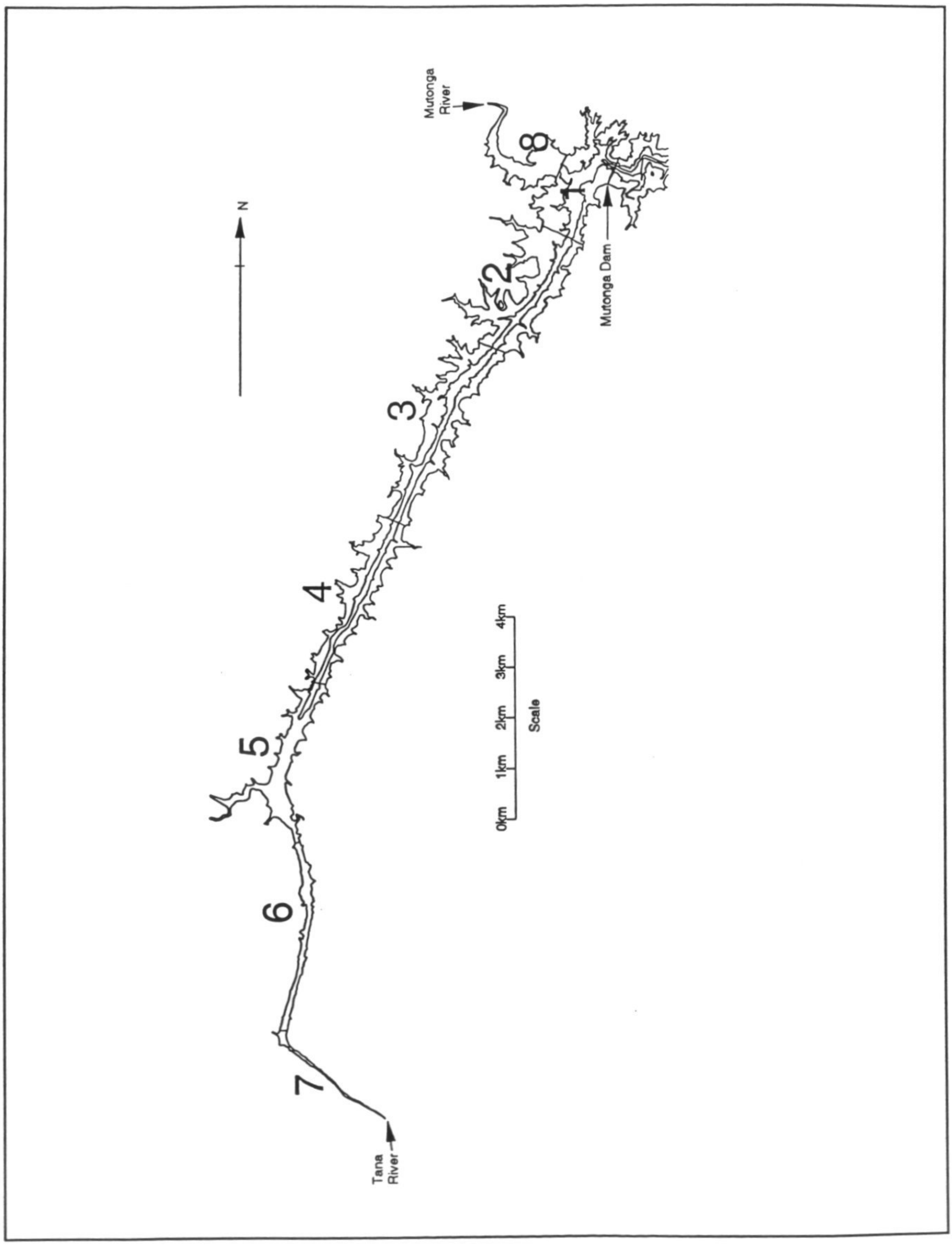


Figure 3.1 Mutonga Reservoir location plan

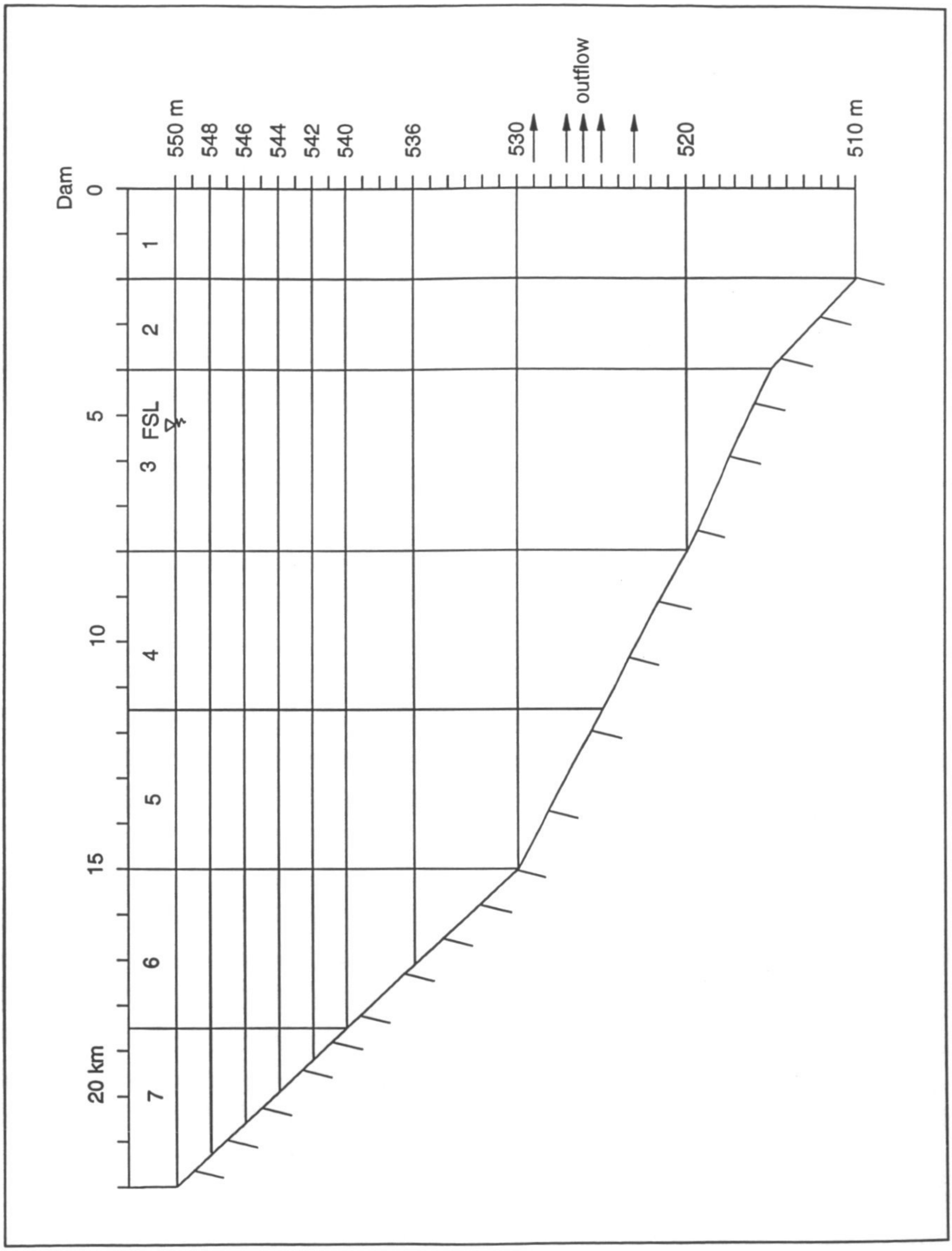
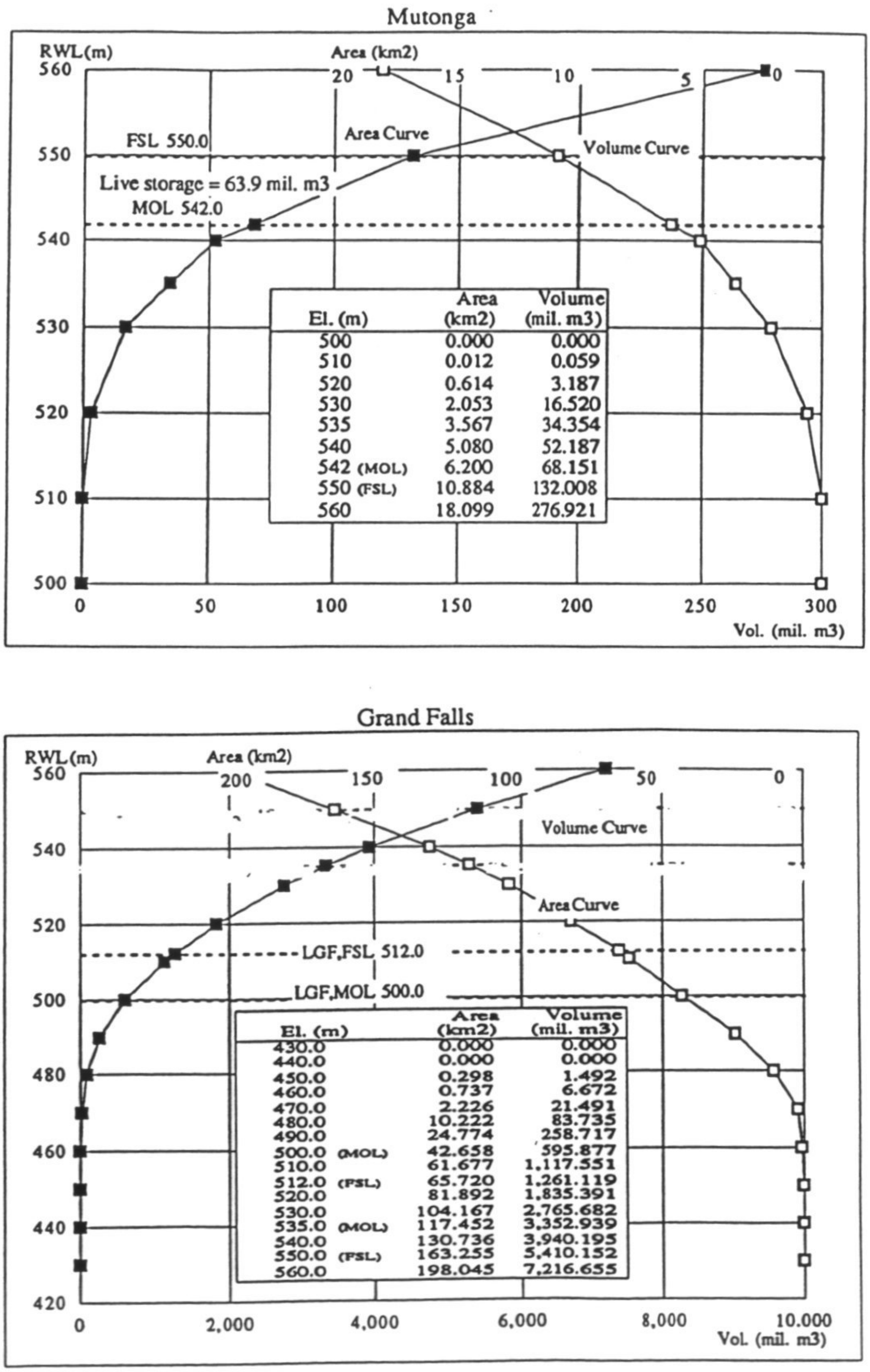


Figure 3.2 Schematic section along Mutonga Reservoir



Mutonga

El. (m)	Area (km2)	Volume (mil. m3)
500	0.000	0.000
510	0.012	0.059
520	0.614	3.187
530	2.053	16.520
535	3.567	34.354
540	5.080	52.187
542 (MOL)	6.200	68.151
550 (FSL)	10.884	132.008
560	18.099	276.921

Grand Falls

El. (m)	Area (km2)	Volume (mil. m3)
430.0	0.000	0.000
440.0	0.000	0.000
450.0	0.298	1.492
460.0	0.737	6.672
470.0	2.226	21.491
480.0	10.222	83.735
490.0	24.774	258.717
500.0 (MOL)	42.658	595.877
510.0	61.677	1,117.551
512.0 (FSL)	65.720	1,261.119
520.0	81.892	1,835.391
530.0	104.167	2,765.682
535.0 (MOL)	117.452	3,352.939
540.0	130.736	3,940.195
550.0 (FSL)	163.255	5,410.152
560.0	198.045	7,216.655

Figure 3.3 Reservoir geometry characteristics

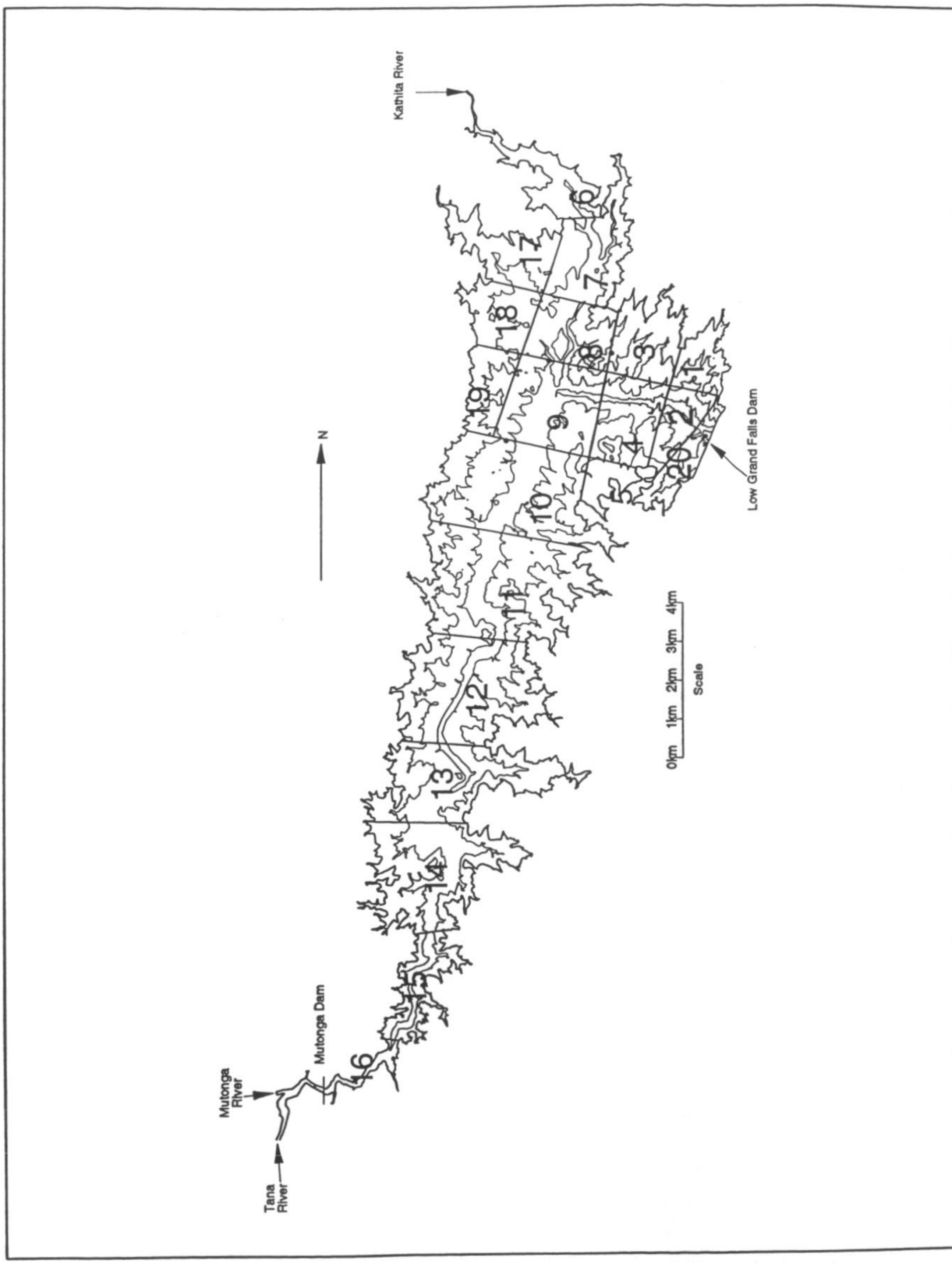


Figure 3.4 Low Grand Falls Reservoir location plan

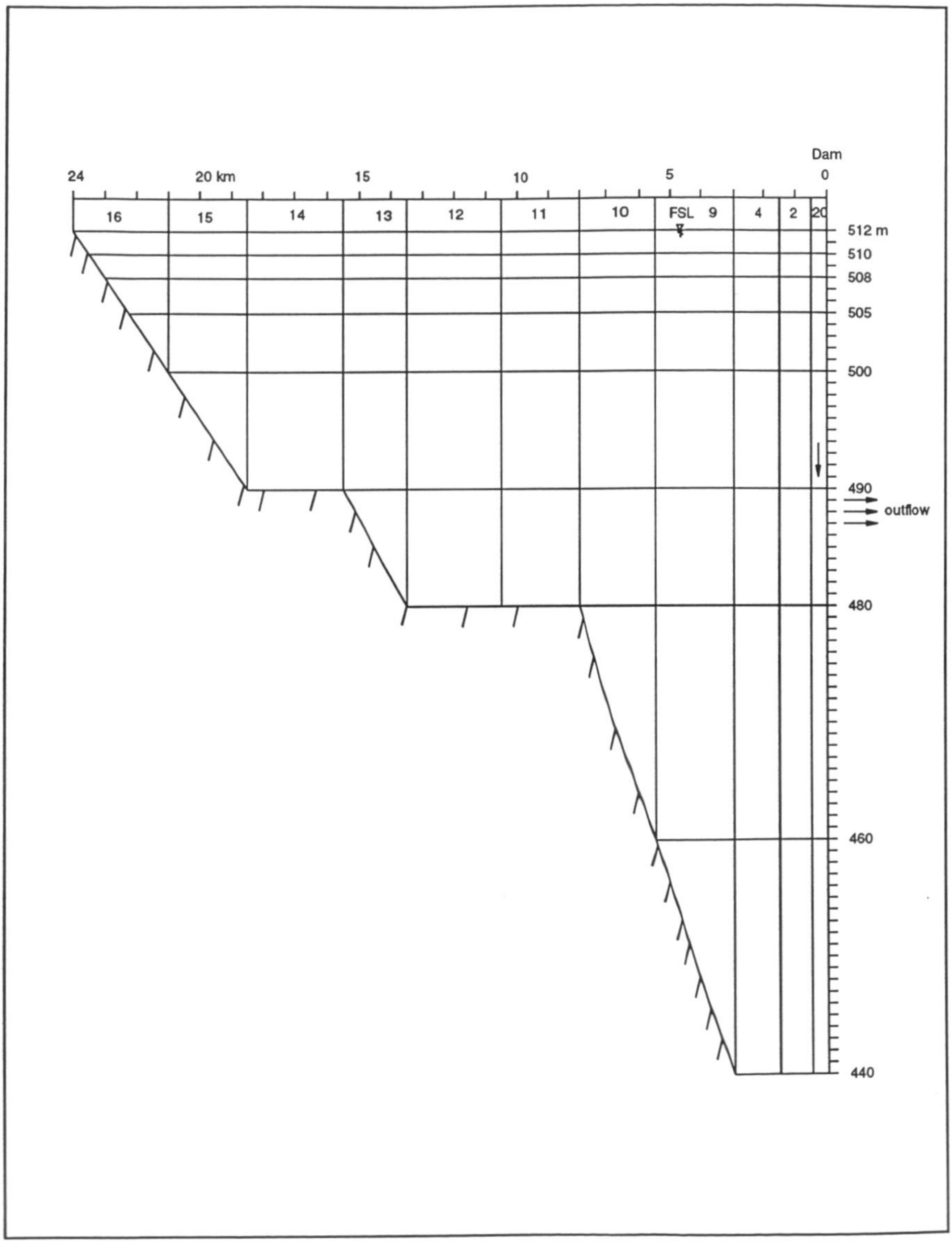
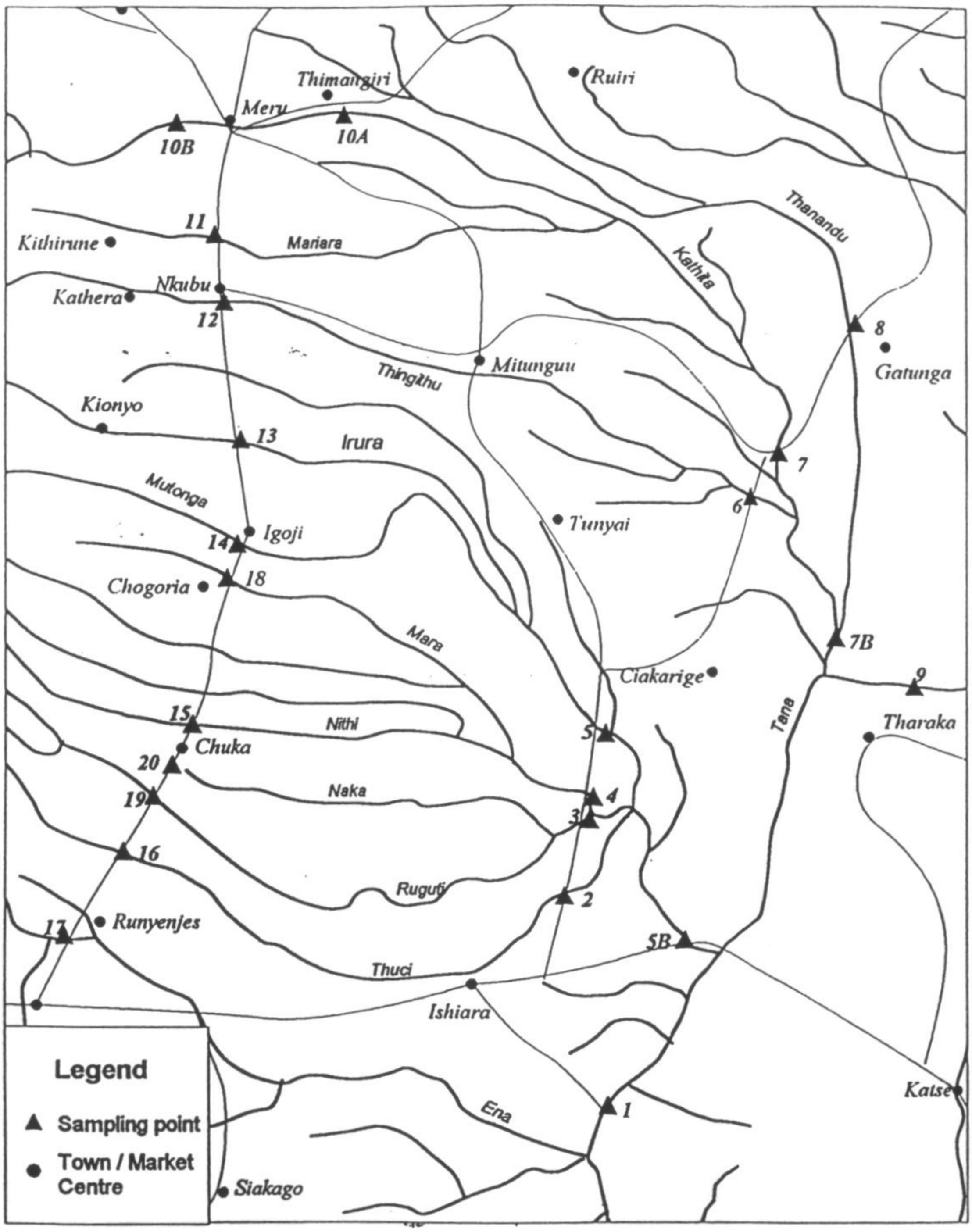


Figure 3.5 Schematic section along Low Grand Falls Reservoir



Lower Catchment Basins

1. Irira bridge
2. Thuci river
3. Ruguti river
4. Mara river
5. Mutonga
6. Thingithu river
7. Kathita river
8. Thanandu river
9. Grand Falls (Tana)

Upper Catchment Stations

10. Kathita river
11. Mariara river
12. Thingithu river
13. Irura river
14. Mutonga river
15. Nithi river
16. Thuci river
17. Ena river
18. Mara river
19. Ruguti river
20. Naka river

Figure 4.1 River sampling sites

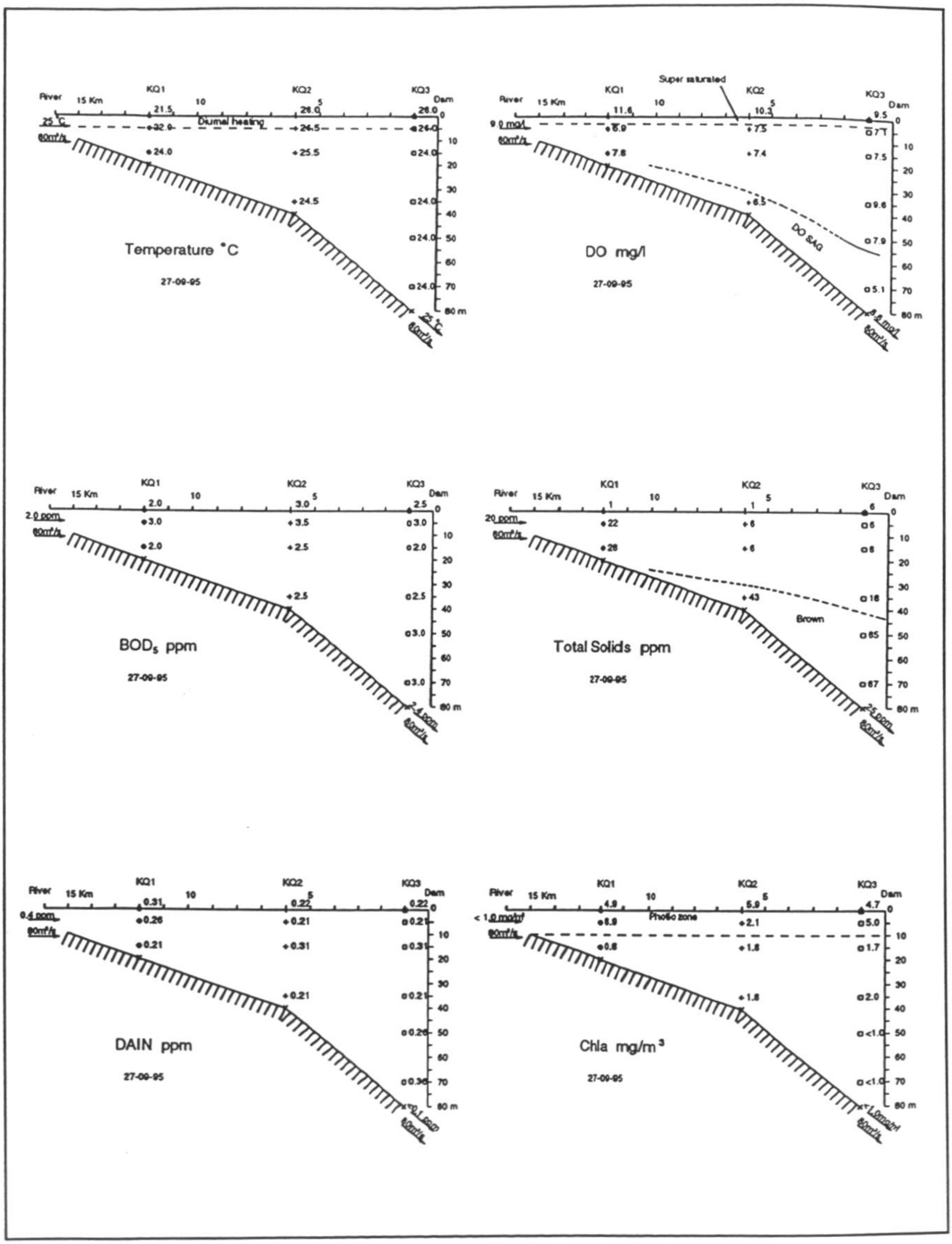


Figure 5.1 Late dry season survey of Kiambere Reservoir - 27 September 1995

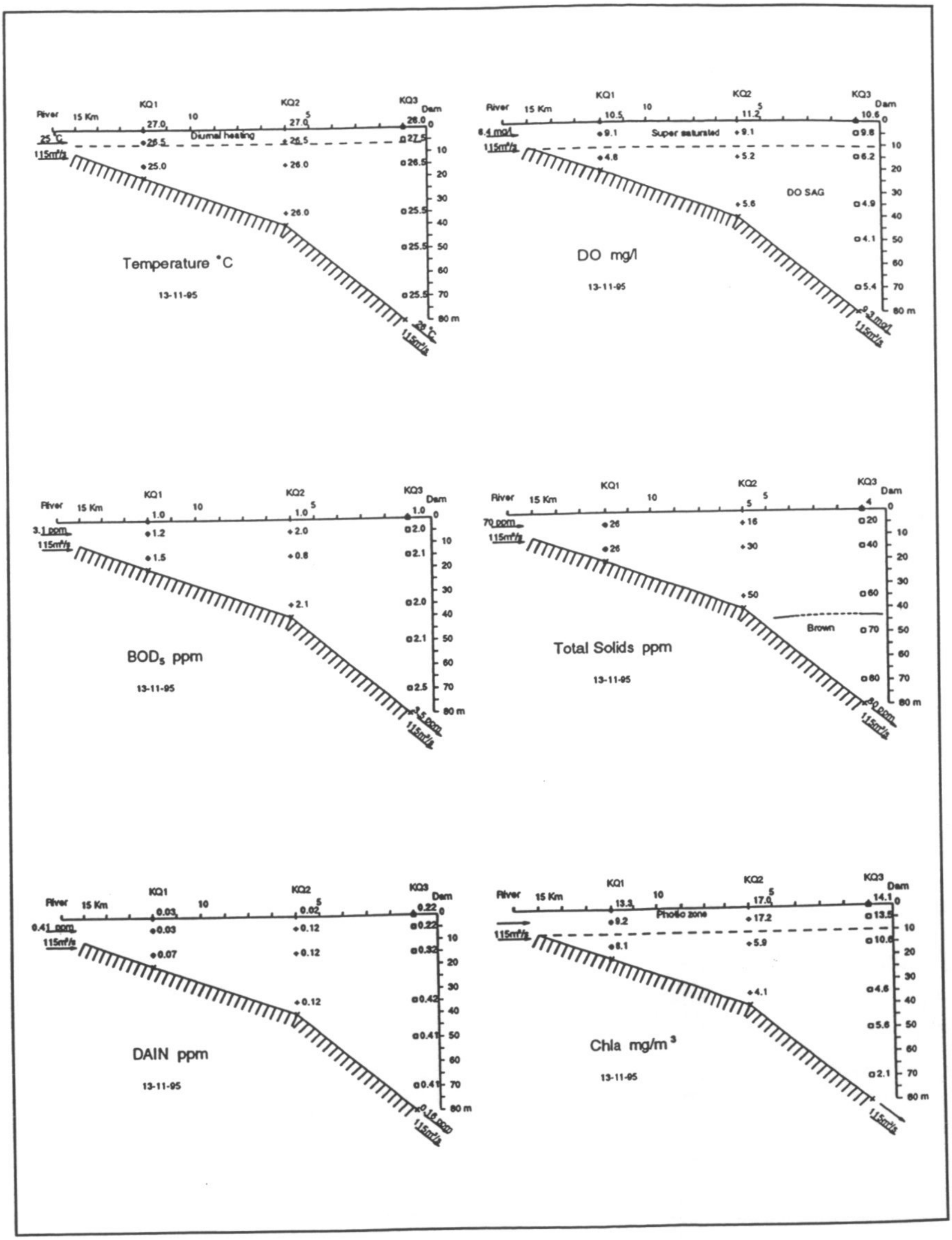


Figure 5.2 Early wet season survey of Kiambere Reservoir - 13 November 1995

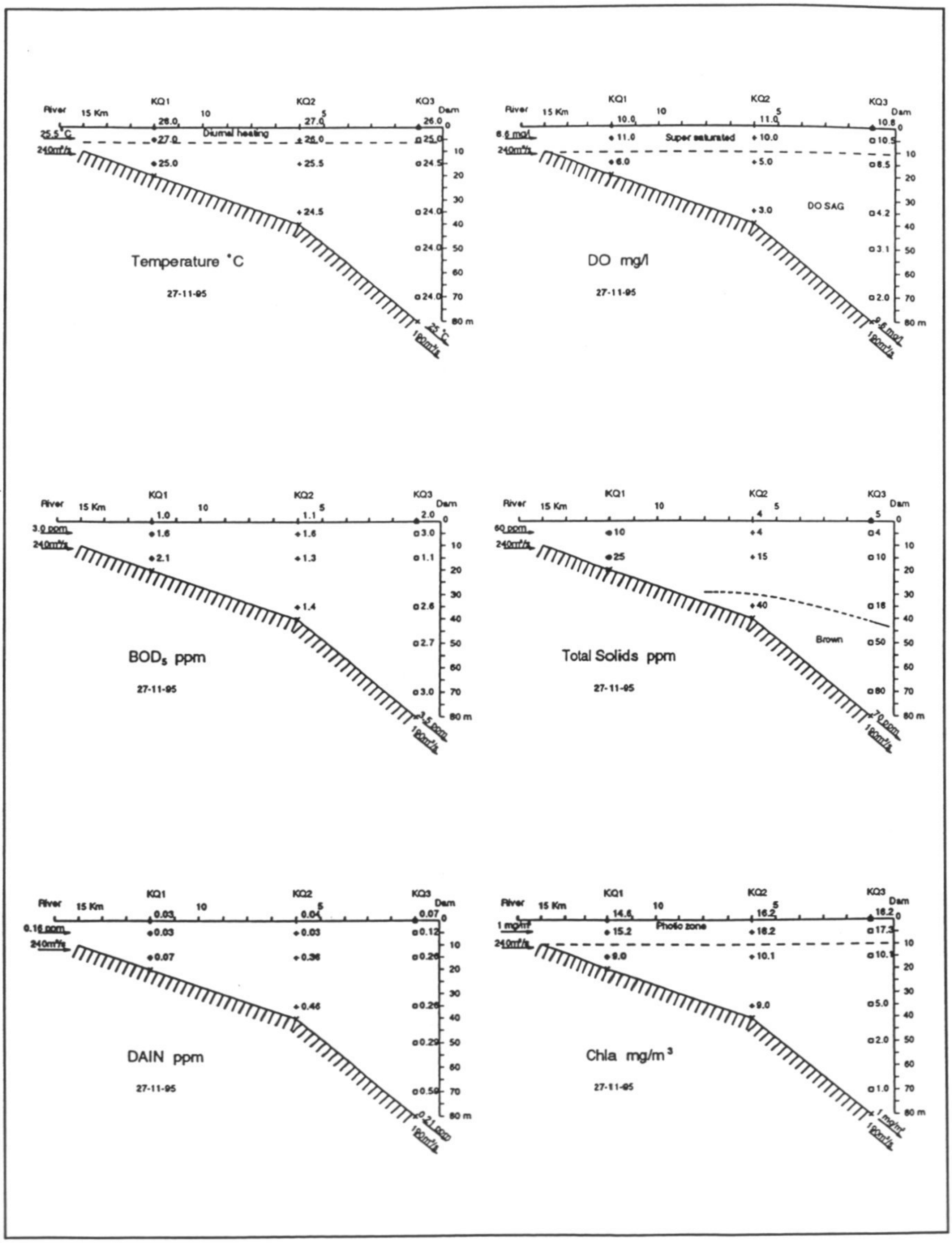


Figure 5.3 Mid wet season survey of Kiambere Reservoir - 27 November 1995

Appendices

Appendix 1

Water Quality theory used in 3DSL

Appendix 1 Water Quality theory used in 3DSL

Mathematical model theory

In order to model the water quality of a reservoir many inter-dependent processes need to be simulated. These may be conveniently separated into three main groups; transport and mixing processes, biochemical interaction of water quality variables and the utilisation and re-cycling of nutrients by living matter.

In order to minimise computation the calculation of flows, salt transport and gravitational circulation is performed in the flow model and the results used to drive the water quality and algal growth model. In this way the effects of several different pollution control measures can be predicted by running the flow model for one prescribed yearly cycle and then using the results to drive several runs of the water quality model simulating the effect of a different measure.

Equations of transport

The model applies mass balance equations for each of the substances under consideration in each of a series of inter-connected elements.

In each element the mass balance equation for an arbitrary substance can be written as:

$$\frac{\partial C}{\partial t} + \frac{\partial}{\partial x}(uC) + \frac{\partial}{\partial y}(vC) + \frac{\partial}{\partial z}(wC) = K_x \frac{\partial^2 C}{\partial x^2} + K_y \frac{\partial^2 C}{\partial y^2} + K_z \frac{\partial^2 C}{\partial z^2} + \omega C + \Sigma S \qquad (1)$$

where

C	is the concentration of substance
u,v,w	are the components of velocity
K_x, K_y, K_z	are the components of the coefficient of eddy diffusivity
ω	is the settling velocity for particulate substances
Σ	is the net effect of all the source and sink terms simulated in the water quality and ecosystem interactions for the substance.

The numerical solution of this equation for the many water quality variables is described in Appendix A.

Water Quality

3DSL models the interactions between the following 12 water quality parameters:

Slow dissolved carbonaceous biochemical oxygen demand (CSB)
Fast dissolved carbonaceous biochemical oxygen demand (CFB)
Slow organic nitrogen (CSN)
Fast organic nitrogen (CFN)
Ammoniacal nitrogen (CAM)
Nitrate nitrogen (CON)

Dissolved oxygen (CDO)
Salinity (CS)
Temperature (TM)
Suspended solids (inert particulate) (CMUD)
Fast particulate biochemical oxygen demand (CFBMUD)
Slow particulate biochemical oxygen demand (CSBMUD)

The temperature is not modelled directly but is passed from the flow model.

The temperature in each element is used to determine the rates of reactions, and temperature and salinity to determine the saturation concentration of dissolved oxygen using Fox's equation. The suspended solids concentration is used to predict light extinction in the ecosystem part of the model.

The interactions between the water quality variables are as follows. Organic nitrogen hydrolyses to ammoniacal nitrogen. If there is an oxygen concentration of at least 5% of saturation ammoniacal nitrogen is oxidised to nitrate. Carbonaceous material (BOD) is oxidised using dissolved oxygen, however if the dissolved oxygen concentration is less than 5% of saturation then nitrate is utilised to provide the necessary oxygen. If there is no nitrate (or insufficient to satisfy all the demand) oxygen is obtained by the reduction of sulphates producing the malodorous gas hydrogen sulphide (the model keeps a log of oxygen obtained in this way as an indicator of anaerobic conditions). The particulate organic matter on the bed continues to oxidise exerting an oxygen demand on the water in the element above.

The use of two components of organic nitrogen and carbon is based on studies which have shown that the rate of oxidation of organic matter, in fresh and saline water, is best represented by a composite exponential. It is assumed that the organic matter being oxidised consists of several components which are oxidised independently at different rates. Studies by the Water Research Centre (WRc) have shown that the oxidation of a wide range of organic wastes can be adequately represented by the use of two rate constants, one being one fifth the value of the other, so that

$$y = E_c [1 - ((1 - \rho)e^{-kt} + \rho e^{-kt/5})] \qquad (2)$$

where

- y is the uptake of oxygen in time t
- k is the standard (fast) rate constant
- ρ is the proportion of organic material considered to be oxidised at the slower rate
- E_c is the ultimate oxygen uptake, that is the amount of oxygen consumed during the total oxidation of the substance.

The usual BOD determination is over a period of five days so that the value obtained needs to be adjusted to give the ultimate demand. If B is the 5 day BOD at 20°C then E_c is defined as

$$E_c = \lambda B \qquad (3)$$

where

λ is a constant

The fast rate constant for carbonaceous material at 20°C is usually taken to be 0.23 per day.

Substituting y = B, t = 5 and k = 0.23 d^{-1} in equation (2) gives

$$\lambda = \frac{1}{0.69 - 0.48\rho} \tag{4}$$

In the case of untreated settled sewage ρ = 0 so that the appropriate value of λ is 1.45.
The rate constants for the reactions in the water quality part of the model are functions of water temperature and are prescribed by equations of the form

$$K_t = K_{20}(1 + \frac{\alpha}{100})^{T-20} \tag{5}$$

where

K_t is the value of the constant at T°C
K_{20} is the value of the constant at 20°C
α is the temperature coefficient

The source-sink term associated with each reaction is of the form K.V.C.

where

K is the first order decay rate (s^{-1})
V is the element volume
C is the concentration of substance

The reaction coefficients used in the study are given in Table 2. Nitrification of ammonia can only occur when the dissolved oxygen concentration is greater than 5% of the saturated value so the source-sink term has the form

$$\Sigma S = K_{FN} \cdot V \cdot C_{FN} + K_{SN} \cdot V \cdot C_{SN} - H_1(DO) \cdot K_{AM} \cdot V \cdot C_{AM} \tag{6}$$

where

H_1 (DO) = 1 if DO ≥ 5%
H_1 (DO) = 0 if DO ≤ 5%

If there is insufficient dissolved oxygen to satisfy the carbonaceous oxygen demand then sufficient nitrate is reduced to satisfy the demand. The source-sink term for nitrate is of the form

$$\Sigma S = H_1(DO) \cdot K_{AM} \cdot V \cdot C_{AM} - D_H \tag{7}$$

where

D_H is the reduction of nitrates needed to satisfy the oxygen demand when dissolved oxygen levels are less than 5% saturation.

Dissolved oxygen is used in the oxidation of carbonaceous material and in the nitrification of ammonia and is added to the system through reaeration at the water surface.

The reaeration rate is

$$K_A = f \frac{A}{V}(1.016)^{T-20} \quad (8)$$

where

A   is the plan area of the surface of the element
V   is the element volume
f   is the exchange coefficient for oxygen which has a value of the order of 0.05m/hr although this does vary with the wind speed.

A value of f is prescribed for each segment so that sheltered and exposed segments can be differentiated.

The source-sink term for dissolved oxygen is of the form

$$\Sigma S = K_A \cdot V \cdot DOD - H_2(DO) \cdot V \cdot (K_{FB} \cdot C_{FB} + K_{SB} \cdot C_{SB} + BD) - 4.57 \cdot H_1(DO) \cdot V \cdot K_{AM} \cdot C_{AM} \quad (9)$$

where

$H_2(DO)$ controls the consumption of dissolved oxygen in the oxidation of carbonaceous material.
BD   is the benthal demand calculated as described in section 2.4
4.57   is the mass of oxygen consumed in the oxidation of a unit mass of ammonia
DOD   is the deficit of dissolved oxygen, the amount of oxygen needed to fully saturate a unit mass of water

DOD = DOS - DO

DOS   is the saturation concentration of oxygen (kg/m^3) as calculated from Fox's equation.

$$DOS = 0.00143\,[(10.291 - 0.2809T + 0.006009\,T^2 - 0.0000632T^3) - 0.607\,(0.1161 - 0.003922T + 0.0000631T^2)\,S] \quad (10)$$

where

T   is the water temperature in °C
S   is the salinity (kg/m^3)

Ecosystem

A simple algal growth model is used which includes the effect of 7 substances, these are:

Algal carbon (AC)
Detrital carbon (DC)
Slow organic nitrogen (CSN)
Nitrate (CON)
Orthophosphate (CPH)
Silica (CSI)
Dissolved oxygen (CDO)

Nitrate, organic nitrogen and dissolved oxygen are the 'link substances' between the water quality and algal growth parts of the model. Concentrations of these substances ($C^{'}$) are calculated from water quality considerations and amended according to the algal growth to give C^{*}.

Primary production

Productivity is calculated from the temperature dependant maximum productivity for the species of phytoplankton considered. The maximum productivity is then modified to take account of the limiting effects of nutrient concentrations using Michaelis-Menten relationships.

$$PROD = P_{MAX}(T) \cdot \mu_1 \cdot \min(\mu_2, \mu_3, \mu_4) \qquad (11)$$

where

$P_{MAX}(T)$ is maximum productivity for species

$$P_{MAX}(T) = \exp(2.30259mT + c) \qquad (12)$$

(where m and c are constants)

μ_1 is limitation due to light intensity (I)

$$\mu_1 = \frac{e}{k_3(b_2 - b_1)} \left[\exp\left(-\frac{I}{I_m} e^{-k_3 b_2}\right) - \exp\left(-\frac{I}{I_m} e^{k_3 b_1}\right)\right] \qquad (13)$$

b_2 is the depth of bottom face of element from water surface (m)
b_1 is depth of top face of element from the water surface (m)
I_m is light intensity required for maximum productivity
k_3 is an equivalent extinction coefficient which takes account of turbidity in the overlying water
μ_2 is limitation due to nitrate concentration

$$\mu_2 = \frac{CON}{CON + MON} \qquad (14)$$

μ_3 is limitation due to phosphate concentration

$$\mu_3 = \frac{CPH}{CPH + MPH} \qquad (15)$$

μ_4 is limitation due to silica concentration

$$\mu_4 = \frac{CSI}{CSI + MSI} \qquad (16)$$

MON, MPH, MSI are the nutrient concentrations which would permit 50% of maximum productivity.

Respiration

Losses due to respiration are calculated as a function of temperature as

$$RESP = RP_{10} \cdot Q_{10}^{\frac{T-10}{10}} \times AC \qquad (17)$$

RP_{10} is the respiration rate at 10°C
Q_{10} is the rate of increase of respiration for a 10°C rise in temperature.

11.0.1 Mortality of algae

In the algal growth model mortality includes the losses due to grazing by zooplankton which is modelled explicitly by

$$INAK = Mp \bullet AC \qquad (18)$$

Mp is the mortality of algae (day^{-1})

Decomposition

Detritus is considered to decay in a similar manner to BOD

$$DECC = KR \bullet DC \qquad (19)$$

where

$$KR = K_{DC} \bullet (1 + \alpha_{DC})^{(T-20)} \qquad (20)$$

K_{DC} and α_{DC} are constants

Settling of algae and detritus
As algae and detritus are particulate the model allows for settlement in the settling procedure. Particles either settle into a lower element and are then incorporated into the equations for that element or are deposited on the bed where a log is kept of the masses deposited. This calculation is performed before the ecosystem reactions are calculated.

Effect of ecosystem on water quality

From the processes described above, the resultant concentrations of algal growth parameters are:

$$AC_k^{*} = AC_k^{'} + (PROD - INAK - RESP) \times VOLRAT \qquad (21)$$
$$DC_k^{*} = DC_k^{'} + (INAK - DECC) \times VOLRAT \qquad (22)$$
$$CON_k^{*} = CON_k^{'} + JNPN \bullet PROD \bullet VOLRAT \qquad (23)$$
$$CSN_k^{*} = CSN_k^{'} + JNPN \bullet DECC \bullet VOLRAT \qquad (24)$$
$$CPH_k^{*} = CPH_k^{'} + JNPP\ (DECC - PROD) \times VOLRAT \qquad (25)$$
$$CSI_k^{*} = CSI_k^{'} + JNPS\ (DECC - PROD) \times VOLRAT \qquad (26)$$
$$CDO_k^{*} = CDO_k^{'} + 2.67\ (PRODD\text{-}DECC\text{-}RESP) \times VOLRAT \qquad (27)$$

where JNPN, JNPP, JNPS are the nutrient to carbon ratios in the algae for the relevant nutrient and 2.67 is the carbon to oxygen conversion factor.

$$VOLRAT = \frac{V_k^-}{V_k^+}$$

Coliforms

It is possible to include an indication of coliform distribution in the system. A more accurate assessment is impossible because the elements are large, the advective and dispersive discharges relatively small and the mortality rate of coliforms high. As with other substances the concentration of coliforms due to advection/dispersion is calculated and this concentration CF* amended to allow for mortality.

$$CF_k^+ = CF_k^* - MORT \times VOLRAT \qquad (28)$$

$$MORT = M_{CF} \times CF_k^*$$

M_{CF} is mortality of coliforms (day $^{-1}$)

Benthal demand

Both particulate BOD and detrital material settling onto the bed exhibit an oxygen demand. The rate of decay of material on the bed is taken to be similar to its rate in suspension, thus the total benthal demand is:

$$BD = 2.67 \bullet KR \bullet (SETDC+SETAC) + K_{FB}\ SETFBOD + K_{SB}\ SETSBOD \qquad (29)$$

where

SETDC, SETAC, SETFBOD, SETSBOD are the total amounts of settled detrital carbon, algal carbon, fast BOD and slow BOD respectively.

The amount of material on the bed is then decayed so:

$$SETDC^+ = (1 - KR)\ SETDC \qquad (30)$$
$$SETAC^+ = (1 - KR)\ SETAC \qquad (31)$$
$$SETFBOD^+ = (1 - K_{FB})\ SETFBOD \qquad (32)$$
$$SETSBOD^+ = (1 - K_{SB})\ SETSBOD \qquad (33)$$

Light penetration

The calculated concentrations of particulate are used to calculate the penetration of light into the water column. This is done by calculating the extinction coefficient, k_3, within each element of the model as a function of the concentrations of suspended mud and algae.

$$k_3 = 1.7\,(0.025(CMUD + CFBMUD + CSBMUD) + 0.04) + 0.85\,(AC + DC) \qquad (33)$$

where CMUD, CFBMUD, CSBMUD are the concentrations of mud, fast particulate BOD and slow particulate BOD (mg/l).

AC, DC are the concentrations of algal and detrital carbon (mg/l).

The constant of proportionality relating the light extinction coefficient to the suspended solids was based on empirical relationships derived by IMER for the Bristol Channel.

Effluent loadings

In addition to the transport processes modelled by the transport equations it is necessary to take account of the initial vertical mixing. In stratified conditions, where vertical mixing is inhibited, an effluent loading discharging near the bed will tend to remain in the lower layers. The level at which an outfall loading is exerted is determined using a simple model of the initial spreading of a buoyant plume. This is described in Appendix B.

Solution procedure

The equations described above are solved using the following procedure.

(i) Solve transport equations taking account of loading of dissolved substances
(ii) Calculate the settling of particulate substances and the resultant benthal demand
(iii) Amend concentrations to take account of particulate loadings
(iv) Calculate the reactions and amend concentrations.

The above steps are repeated for each model timestep.

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