Chapter 13

SEDIMENT LOAD, WATER QUALITY AND POLLUTION

13. SEDIMENT LOAD, WATER QUALITY AND POLLUTION

13.1 INTRODUCTION

The Tana river transports water and solids from upper catchment areas, in particular the high elevation areas of the Aberdares and Mount Kenya, to the lowlands and the Indian Ocean. While the primary purpose of dams is to impound and store water for controlled release, sediments are also impounded and stored. Over time the trapped sediment reduces reservoir storage capacity. The quantity and composition of sediment entering the reservoir need to be determined so that reservoir design can anticipate the distribution of sediments within the reservoir and hençe the useful life of the reservoir. Immediately below the dam site, the river looses its sediment load with ramifications on downstream physical, chemical and ecological equilibrium. Downstream aspects are dealt with in later sections. This section reviews previous sediment studies in the reservoir area and includes details of specific studies carried out during the flood periods of November December 1994 and 1995 and during one month of the dry season in September 1995.

The sediment load at Grand Falls that is at present released downstream and would potentially be trapped by a reservoir is derived from the following sources:

- Un-gauged incremental catchments on the right and left bank of Tana river
- Kiambere dam releases
- Mutonga river
- Kathita river

The water quality throughout the present river system is also largely defined by the water quality in the upper catchment, derived from natural and man made activities. Water quality varies throughout the river system, according to the processes that are active within the water body. The construction of reservoirs can have a major impact on water quality, both within the reservoir and downstream, largely resulting from the storage time and higher temperatures that are typical of reservoir systems. In general, the longer storage times and the higher temperatures, will create biotic conditions that did not exist in the natural river system and will result in lower discharged water quality.

13.2 SEDIMENT SOURCES

The primary sediment source for the river system is the erosive process taking place in the upper catchment. These erosive processes can be sub-divided into two stages: the displacement of soil materials from the soil profile and then the transport of those displaced materials away from the site in which the primary erosion has occurred.

The major erosive processes are mechanical[1] and are caused by rainfall and wind physically removing materials from the soil profile. In the climatic conditions within the upper catchment, it will be rainfall that is the dominant factor causing erosion, and although the selective removal of fine soil components and soil chemicals through the soil profile will occur in suspension and as a leachate, it will be the mass removal of soil particles from the soil surface that will dominate the process.

The initial composition of the eroded materials will therefore have the same particulate characteristics as the original soil structure. However, once the initial displacement of soil materials has taken place, there is then a gradual breakdown of the soil particles into their component particles which are removed, sorted and then selectively deposited as part of the transport process. The mechanism for sorting and selective removal is very simple: large particles require high energy flows to carry them; fine particles can be carried by lower energy flows which occur throughout a greater part of the season. Course sediments will therefore be transported predominantly during peak flood periods and deposited nearer the sources, while clays and silts will be transported throughout much of the year and will be carried further. However, within a reservoir body, this transport pattern can be slightly modified by the water salinity which encourages the formation of clay flocs which are then large enough to be deposited within the reservoir body.

This transport process is again dominated by rainfall patterns, initially through field run-off and then through the basin drainage characteristics.

The effect of this selective transport of materials can be seen in the overall morphology of the basin, with the creation of the Tana Delta through the deposition of fine particles at the mouth of the river.

However, despite the rapid morphological changes that can occur as a result of natural or man-made modifications in the environment, these processes of selective movement and deposition should be looked at on a geological time-scale. The "average" short term view[2] of the upper catchment can be taken as being a balanced process, with all eroded materials passing into the river system.

13.2.1 Kathita and Mutonga Unregulated Catchment Sediments

The effects of the existing dams upstream of the Mutonga and Grand Falls dam sites has been to heavily modify the sediment composition transported by the river system. The effect of the reservoirs is to create a water body in which river flow energy is dissipated , and as a result the transport capacity for course and fine sediments is reduced. The most obvious indication of this is the change in sediment load flowing

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[1] For the purposes of sediment studies, chemical weathering of base material can be excluded from the immediate erosive process that effect the sediments in the river system, in that it is the mechanism which produces the soils materials that are then displaced and transported.

[2] In this case the short term view could be a number of years or even decades, given the high annual variability of the system.

out of the system, which has virtually no course sediments, and the creation of delta structures within the reservoirs at the points of inflow.

However it is not just the coarse sediments that are trapped. The concentration of dissolved salts in the river water is high enough to cause individual clay particles to come together to form small flocs or mud particles. As a result part of the clay fraction does not pass through Kiambere as a colloidal suspension but is deposited within the reservoir body. As with all settling processes, the proportion of sediment deposited will depend on the particle size and the transport velocity, at high flow rates there is little deposition, at low flow rates there is greater deposition. The observed "mud" trapping efficiency of Kiambere at flow rates of $100m^3/s$ is in the order of 15%, while at a flow rate of $1000m^3/s$, the mud trapping efficiency drops to 1.5%. This pattern of mud deposition is corroborated by the turbidity measurements, which show an increase with depth.

The Mutonga and Grand Falls sites therefore receive heavily modified sediments from the Kiambere outflow, with an overall lower sediment load (with both coarse and fine particles removed) and a relatively higher load of fine particles, but still receive largely unmodified sediments from the Mutonga and Kathita catchments.

From the information available on the soils[1] within the unregulated catchments it is clear that the primary eroded materials will have generally high clay contents. Table 13-1 gives the proportion of major soil texture classes found within the immediate upper catchments of the proposed reservoirs. It can be seen that the majority of soils are classified as being Clays, defined as having a clay content of over 40%, and including "sandy clays" and "silty clays".

As a whole, clay particles form approximately 56% of the soil profiles found within the unregulated upper catchments, with a further 16 % of the profiles formed by silt particles. Only 18% of the profiles are composed of sand particles.

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1 For the purposes of this study a modified version of the soils textural triangle has been used, based on the classification used in Southern Africa by the "Federal Government of Rhodesia and Nyasaland". Sand is classified as being composed of particles between 50 μm to 2 mm, silt particles are classified as being between 2 and 50 μm and clay is classified as being particles of less than 2 μm.

Table 13-1 Major Soil Classes in the Unregulated Upper Catchment

Major Soil Classes	Clay Content	Area in km²				% Area Total
		Kathita	Mutonga	Ena	Unregulated Other	
Clays	> 40%	1670	1740	430	150	75%
Clay Loams	20 - 40%	470	200		380	20%
Sands and Silts	< 20%	50	10	180	30	5%

The rate of erosion is defined by the erosivity of the rainfall and the erodibility of the soils. The erodibility is not only determined by the actual soil characteristics, but very significantly by the environment and the management of the soils.

The most common method of modelling the rate of erosion is to use the "Universal Soil Loss Equation", which is presented in the following form:

$$A = R \times K \times S \times C \times P$$

where A is soil loss in tons per unit area; R is the erosivity of the rainfall, largely a factor of the rainfall intensity; K is the soil erodibility, based on the strength of the soil structure; S is the slope factor, which combined with the length of slope indicates the ease of transport away from the site of displacement; C is the crop/cover factor, effectively defining the ground cover and therefore the protection from the erosive effects of the rainfall; and finally P is the conservation factor indicating any land management practices to counteract erosion.

From this equation it can be seen that within upper catchment the potential erosion will be predominantly defined by the land use practices. In the higher steeper areas with high rainfall, both the natural vegetation and the farming systems support dense ground cover which will mitigate against increased potential erosion through protection of soil surfaces. In the lower areas, with gentler slopes, nearer to the proposed reservoirs lower gross rainfall and farming and grazing regimes will lead to the presence of exposed soils at the start of the rains and result in a high potential for erosion. Overall, erosion throughout the catchment is likely to be similar, both in terms sediment content and in terms of scale of effects.

For the purposes of this study, it can be further assumed that in the short term the gross sediment movement out of the upper catchment will be approximately equal to the level of erosion.

Given the fairly consistent pattern of soils, with the bulk of the Mutonga and Kathita catchments falling in areas in which soils are predominantly clays, and the relatively short transport distances of the sediments to the Tana River, it would be expected that the sediments moving in to the main river system will have a similar overall particle distribution as the original soil materials.

Table 13-2 Composition of Erodible Materials in the Upper Catchment

Soil Component	Particle Size	Proportion of Eroded Materials in the Upper Catchment
Clay	< 2 μm.	56 %
Silt	> 2 and < 50 μm	16 %
Sand	> 50 μm and < 2 mm	28 %

13.3 PREVIOUS SEDIMENT STUDIES

From 1968 - 1981, studies on sedimentation were intensively carried out by TARDA and Hydraulic Research of Wallingford, UK. These studies were mainly concerned with measurement of trapped sediment volumes in the three upstream reservoirs: Kamburu, Gitaru and Kindaruma. Studies were also undertaken of Masinga dam sediment volume in 1988.

The Tana River Morphology Study by DHV Consulting Engineers in 1986 listed for comparison, the various estimates of sediment transport in the Tana river at Kamburu. The list is partially included in Table 13-3 and indicates the considerable disparity that has resulted from the use of different methods and different time periods in determining sediment load. Estimates for reservoir planning will, as far as possible, be based on actual measurements.

Table 13-3 Estimates of Sediment Transport in the Middle Tana River Reservoirs (Kamburu Gauge R.G.S. 4ED3)

Investigator	Period	Mean Annual Sediment Yield (million tons per year)
Acres/ILACO (1956)[A]	1947-1965	0.3
Dunne and Ongweny (1976)[A]	1956-1970	0.6
Ongweny (1978)[A]	1961-1976	7.1
Dunne and Ongweny (1976)[B]	1956-1970	4.8
Ongweny (1978)[B]	1956-1970	5.3
Moorhead and Sims (1982)[C]	1957-1980	3.4
Wooldridge (1983)[C]	1968-1981	5.0
DHL (1985)[D]	1947-1971	0.9
DHL (1985)[D]	1960-1971	1.3
TARDA/Wallingford[E]	1971-1981	7.0

Based on: A - Suspended sediment sampling at the lower gauging stations; B - Summation of sediment yield from upstream tributaries and interpolation for un-gauged areas; C - Reservoir sediment surveys of Kamburu and Kindaruma Reservoirs; D - Sediment transport relations. E - Actual measurements.

The period between 1940 and 1960 is one of relatively low annual flow peaks compared to years after 1960. The 1960's constituted a period of intense land use change in the high rainfall areas of the catchment. There was a major expansion of arable production, including development of tea, coffee and pineapples with a related loss of bush and forest. The result of these changes was an increased sediment load within the system. With increasing land pressure and movement of populations into more marginal areas, the sediment loads are likely to have remained at high levels or even increased.

13.3.1 Sediment Discharge Estimates at Grand Falls

River gauging stations, 4F1 and 4F13 have been operated at Grand Falls since 1948 (Table 13-4). Due to access problems, maintenance of instruments has been poor resulting in long gaps in flow and sediment sampling records. As a result there are no complete sets of figures available. As with the upstream system a number of estimates have been made during different periods. All listed estimates were made using data for the period before the impoundment of the two reservoirs of Masinga and Kiambere upstream of Grand Falls, and in the case of Acres International data prior to any dam construction.

Table 13-4 Historic Estimates of Sediment Discharge at Grand Falls

Investigator	Data period	Sediment Discharge (million tons/year)
Acres International Ltd (1976)	1948 - 1965	12
TARDA (1976) Upper Reservoir Scheme Appraisal Report	1948 - 1972	7
Tippetts-Abbett-McCarthy Stratton (1980) (TAMS) National Master Water Plan	1948 - 1972	16
JICA (1992) National Water Master Plan	1948 -1981	6

In view of the wide variation in the estimates of the sediment discharge of the whole system, and the sediment discharge passing the critical Grand Falls site, limited field studies were carried out during 1994 and 1995.

13.4 SEDIMENT MEASUREMENTS AT GRAND FALLS: NOVEMBER 1994

The initial study of sediment load at the Grand Falls site (4F13) was undertaken during the 1994 November flood period. The Location of the station at the foot of the Grand Falls rapids confined to a single channel results in turbulent flow. At gauge levels greater than 2 m, the turbulence and tortuous flow suggest high mixing of sediment in the river, bed load as well as suspended load, and this should result in maximum sediment readings.

Samples were collected on alternate days from 5 November to 4 December. The readings on the gauges were recorded at the time of sediment sampling. Discharges corresponding to these level readings were computed from the station rating equations.

Every sample was weighed and filtered to separate un-dissolved solids from the sample solution. The un-dissolved solids were dried and their weights expressed as fractions of the respective original sample weight in parts per million (ppm). All sediment samples obtained from the sampling station and processed as above were mixed to form one compound sample for grain size analysis through sieves of specified mesh width. The weight of each sediment retained in a sieve of a given mesh size was recorded against the mesh size.

The results of sediment load analysis for the samples collected at Tana Grand Falls site are given in Table 13-5. Concentration values range from 7,793 ppm for the discharge of 679.3 m^3/sec occurring on 5/11/94 to 317 ppm for discharge of 543.6 m^3/sec on 3/12/94. The sampled sediment concentrations for instantaneous flow discharges were used to estimate daily sediment discharge. For the days when samples were collected, sediment discharge varied from 537,000 t/day for the highest sampled flow of 1,493 m^3/sec to 15,000 t/day for the second lowest sampled flow of 543.6 m^3/sec.

The average sediment load discharge for the period of measurement was 154,000 tons per day, implying a total sediment load for the 28 day sampling period of 4.3 million tons. This total for the sample period is significantly higher than the estimated average annual discharge of 2.86 million tons, based on previous data, measured and estimated effects of upstream dams. The November 94 wet season sediment discharge was likely to be greater than average since these rains followed a prolonged dry period in which there were two consecutive low rainfall periods in the Grand Falls catchment.

Figure 13-1 shows the relationship between sediment load and river flow at Grand falls during the November 1994 wet season. It is clear from this that a major part of the total sediment discharge occurs during the first few days of rain. It is this sediment which will be deposited in the dam and which at the same time is required for maintenance of downstream productions systems, the floodplain ecology and river morphology.

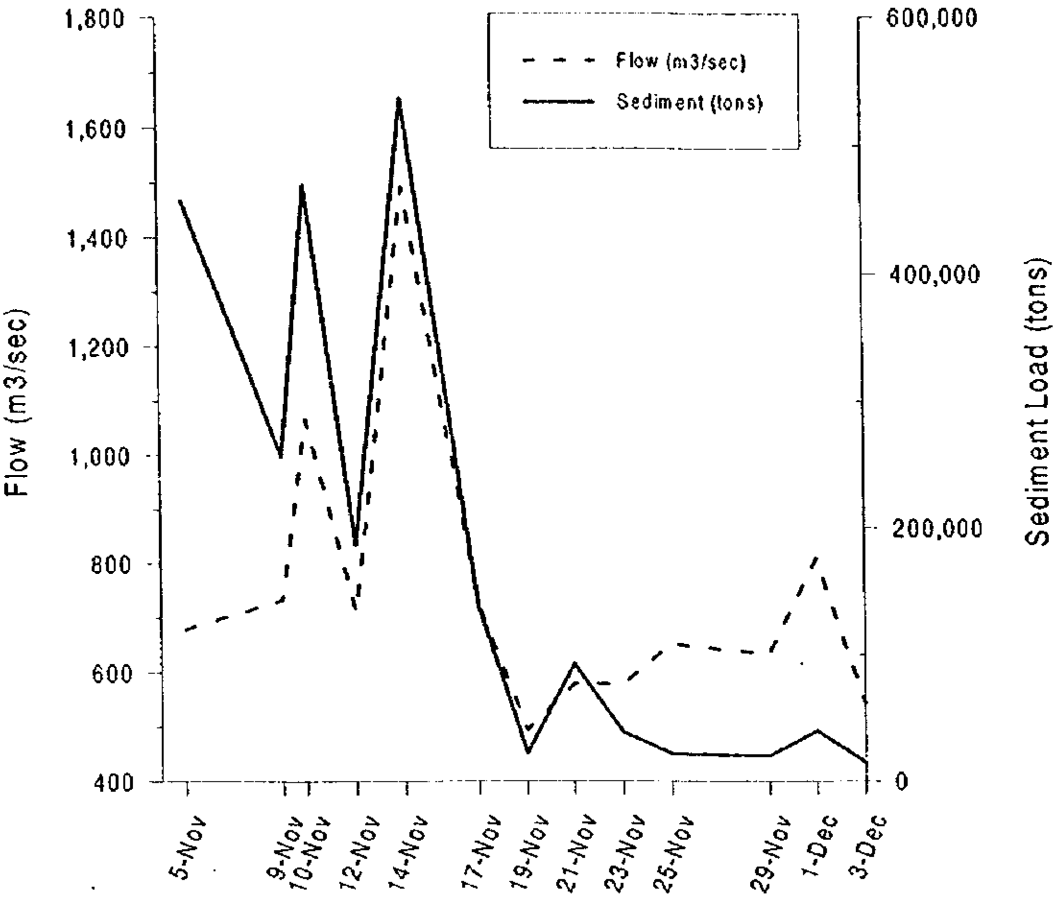
Table 13-5 Sediment Load, November Flood Period, 1994

Date	Discharge m^3/sec.	Sediment Concentration ppm	Gross Daily Sediment Discharge (tons)
5-11-94	679	7,793	457,383
9-11-94	733	4,048	256,190
10-11-94	1,066	5,100	469,898
12-11-94	711	3,031	186,196
14-11-94	1,493	4,165	537,373
17-11-94	724	2,183	136,630
19-11-94	494	522	22,266
21-11-94	579	1,852	92,647
23-11-94	579	771	38,570
25-11-94	653	387	21,848
29-11-94	634	374	20,377
1-12-94	811	571	39,990
3-12-94	544	317	14,889

The discrepancy between the measured loads and the previous average estimates, indicated that more work was required on this topic.[1]. Actual measured sediment discharge and flow data for the Grand Falls site are limited for the period following the commissioning of the five upstream reservoirs. Representative estimates of sediment discharge at Mutonga and Grand Falls sites can only be derived from a sampling programme at all stages of the river flow at Grand Falls (R.G.S 4F13) and Kathita river (R.G.S. 4F19). In order to provide corroborative evaluation data for these sampling sites, Mutonga river (R.G.S.4EA7) and Tana Garissa (4G 1) also need to be sampled at the same intensity.

[1] The concept of average discharge is misleading, unless taken over very long periods. Sediment discharge, relating both to rainfall and preceding rainfall events, is even more variable than the rainfall itself. It is clearly also necessary to look at medium and long term climatic trends in rainfall patterns, and in particular at past and potential future land use changes.

Figure 13-1 Relationship between Sediment Load and River Flow at Grand Falls during the November 1994 Flood.



In order to improve the present analysis of sediment discharge, further studies were therefore commissioned for the 1995 season, covering the sediment discharge through Kiambere and the direct discharge from the Mutonga and Kathita Rivers, as well as the discharge past the Grand Falls site. Given the time constraints, these were however again limited to two further "snap-shots" of the situation, with field studies confined to a one month period during the dry season and a further one month period during the rains.

13.4.1 Particle Size Distribution:

The suspended sediment samples which were dried of the moisture and the organic matter, were mixed into one sample weighed and passed through sieves of various mesh sizes. The particles retained by each sieve were weighed and recorded.

The results indicate that between 30% and 40% of the combined bed and suspended sediment load are silts or finer particles, and a further 20% are fine sands. Results were also analysed using a graph of percentage weights of particles against mesh size[1]. The implication from the curve, corresponding to Table 13-6 is that 36% of suspended sediment plus the wash load that passed through Grand Falls during the sampling time are of silt and clay fraction. Fine sand constituted 52% while particles of sizes greater than 0.2 mm constituted 12% of suspended and wash load.

The particle sizes distribution, implies an increase in coarse silt and sand particles in the sediment load composition downstream of Masinga despite sedimentation in the five reservoirs. The source of these coarse particles must be the intervening un-gauged catchments, and the Mutonga and Kathita rivers as well as river bed erosion.

Table 13-6 Particle Size Distribution November Floods 1994

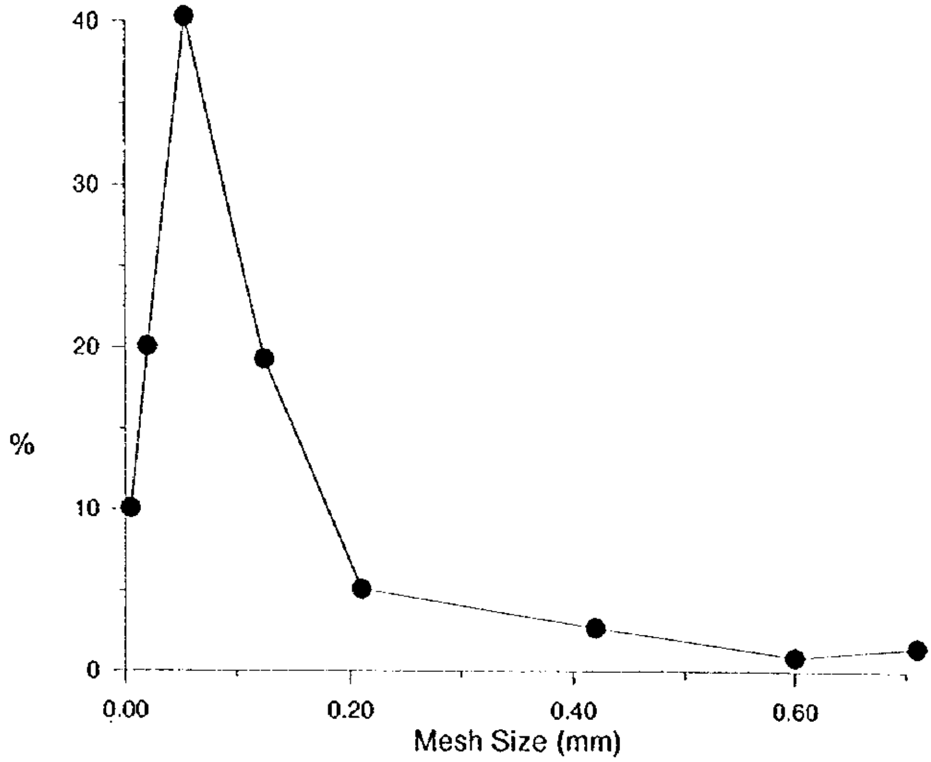
Particle Size Class	Mesh Size mm.	% of Sample	Cumulative %
Coarse Sand to coarser materials	0.71	1.5	1.5
Coarse Sand	0.60	0.9	2.4
Medium Sand (coarser)	0.42	2.7	5.1
Medium Sand (finer)	0.21	5.1	10.2
Fine Sand	0.125	19.3	29.5
Coarse Silt to Fine Sand	0.053	40.3	69.8
Coarse Silts	0.020	20.1	89.9
Medium Silt to finer materials	<0.020	10.1	100.0

It should be noted that the sampled particle size distribution does not correspond to the particle size distribution of the erodible materials in the upper catchment. Given that the upstream reservoirs are expected to trap the majority of course sediments, and despite the effects of floculation and deposition of a proportion of the clay fraction as mud particles, it could be expected that the sediment flow past the Grand Falls site would be characterised by higher proportions of fine sediments, more in line with the particle distribution in the original eroded materials.

However, in the case of the Tana River, although the overall composition of the transported materials throughout the year should be similar or with a greater fine proportion than the original eroded materials, the effects of the highly peaked flows in carrying and temporarily depositing course particles within the river system will change the sediment composition from day to day. This effect would be expected to be particularly noticeable during the highly flashy rainy season flow.

[1] Full data on the samples and details of the analysis are given in a separate report, available from the JICA Study Team, including the particle size distribution curve. This study curve is compared with various previous measurements described by Acres International (1967).

Figure 13-2 Particle Size Distribution November Floods 1994



13.5 SEDIMENT MEASUREMENTS IN THE UPPER CATCHMENT: SEPTEMBER AND NOVEMBER 1995

In recognition of the need to elaborate on the sediment transport mechanisms and the gross and net volumes of sediment passing through the river system, further studies were carried out in 1995 for one month in the late dry season and for a second one month period during the short rains.

Six sediment sampling and discharge measurement sites were chosen to include the principal river flow, and sediment load and nutrient discharges into and out of the Mutonga and Grand Falls dams sites. At each site as discussed below, measurements and sediment sampling were done on alternate days, 15 times during the dry season and 15 times during the wet season.

13.5.1 Sampling Sites

Kiambere Inflow Site

The site for sediment sampling and discharge determination was situated at Kindaruma power station plunge pool downstream of the generation house. Samples collected here were from a highly turbulent flow which emerges from the turbines. The flow discharge was obtained from the power generation and spill through the gates whenever these were opened at the time of sampling or any other time during the study.

Kiambere Outflow Site

Outflow from Kiambere reservoir was sampled at a site situated on the Tana River immediately after the tailrace confluence with old Tana River channel. Flow at the site is turbulent having emerged from the tunnel. During the dry season, flow was only from the turbines but during wet season, some discharge passed over the spillway subsequently reaching the sampling site via the old Tana River channel. Total flow discharge was obtained from the power generation discharge and any spillway overflow during the wet season was added.

Fluctuation of power generation at Kiambere over the 24 hour period causes fluctuation of river discharge at both Mutonga and Grand Falls dam sites[1].

Mutonga River R.G.S. 4EA7 Site

The Mutonga River has its confluence with the Tana River 3 km upstream of Mutonga dam site. The sediment sampling and discharge measurement site is at the Regular Gauging Station (R.G.S) 4EA7 located 11 km from the confluence with the Tana river. Dry season flow measurements and sediment sampling were done using a boat, current meter, US DH59 sampler and bottom grab sampler. Wet season discharge estimates were made using float velocity and cross-section area. Sampling was done from river bank positions selected relative to alternating incoming and outgoing currents on a turbulent river reach. Choice of method was dictated by lack of gauging cableway on a hazardous rapid river.

Kazita River R.G.S. 4F19 Site

Kazita River is a tributary of the Tana with its confluence 2 km upstream of Tana Grand Falls 4F13 gauging station site. The discharge and sediment sampling site was at the Regular Gauging Station (R.G.S.) 4F19 located 14 km upstream of the confluence with Tana river. Discharge measurements and sediment sampling during the dry season were implemented by wading and using a current meter, US DH59 sampler and bottom grab sampler. Due to the lack of a gauging cableway, wet season discharges were determined using float velocity and cross-section area while sampling was done from river bank at selected incoming and outgoing river flow current positions.

Tana Grand Falls R.G.S. 4F13 Site

Grand Falls 4F13 gauging station is the key station on the Tana River from which the measurements of flow discharge and sediment sampling for Mutonga Grand Falls study have been done. It lacks a gauging cableway and is hazardous for boat gauging even for dry season flow. Discharge determination uses float velocity and cross-

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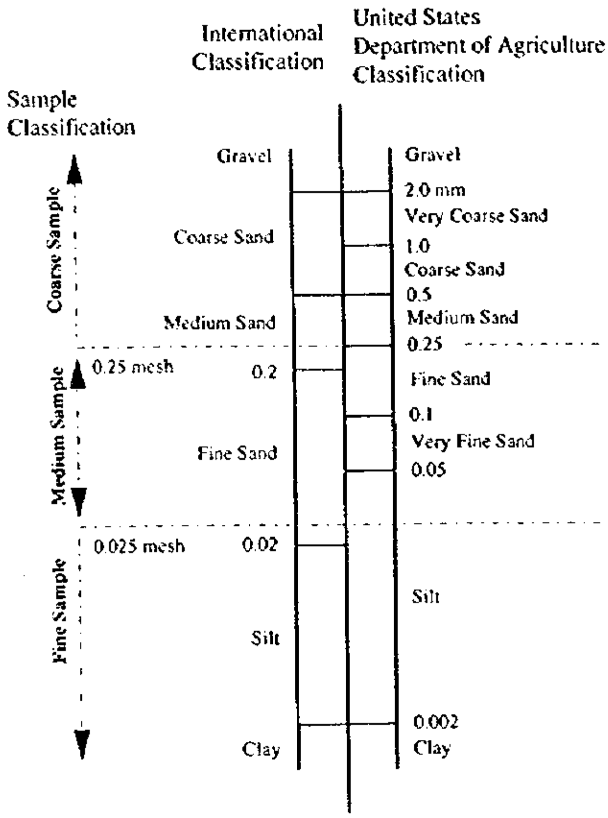
1 Any comparison of flow discharge at the two dam sites with Kiambere discharge has to take into account the time lag between corresponding flows. Kiambere dam is 31 km and 59 km upstream of Mutonga and Grand Falls dam sites respectively.

section area. This is contrasted with the sum of discharges from Kiambere power generation and spillway overflow plus Mutonga 4BA7, Kazita 4F19 and the un-gauged small contribution by Ena stream during the dry season. During the wet season, contribution from the laghas are estimated from the laghas' catchment rainfall. Sediment sampling was conducted from the river bank at the foot of the rapids where flow is turbulent and well mixed. The sampling was carried out on incoming, welling and outgoing flow currents.

Tana Garissa R.G.S 4G1 Site

Tana Garissa Regular Gauging Station (R.G.S) 4G1, is located 220 km downstream of Grand Falls dam site. The site was selected to provide data and information on flow discharge, sediment load and nutrients influx from the Mutonga and Grand Falls dams sites to Lower Tana river. R.G.S. 4G1 is sited at a road bridge. Bridge crane with current meter, sediment samplers US P61 and US DH59 and bottom grab sampler were used both in dry and wet seasons.

Figure 13-3 Particle Size Classification and Sample Ranges



13.5.2 Laboratory Analysis

The laboratory analysis was designed to assess the suspended sediment concentration in samples from the different sampling sites. Sediment proportions with particle sizes greater than or equal to 0.25 mm and proportions of sediment with particles less than

0.025 mm were determined. These sample size classes can be compared to the standard soil particle classification with the smallest particle class corresponding roughly silts and clays, the middle class covering the fine sands and the coarse samples equivalent to the soil classification for medium sands to gravels.

In addition, the nutrient concentrations in the sediment samples were determined by chemical analysis.

Suspended Sediment Concentration

In the laboratory the samples were weighed, filtered, dried and reweighed to determined the dry sediment weight which together with water sample weight are used to determine the sediment concentration in the water in parts per million.

Sediment Grain Sizes

The dry sediment weight was determined. The sample was put on standard 0.25 mm and 0.025 mm stacked sieves. The assemblage is clamped on an electro-mechanical vibrator and by the sieving process, separated sediment particle sizes are obtained. The proportion of particles greater than 0.25 mm which settles in reservoirs or remain on river bed are determined. Proportion of particles which are less than 0.025 mm which neither settle in the reservoirs nor river beds and are carried in flow are also determined. Each proportion is weighed and expressed as a percent of the original sample weight.

13.5.3 1995 Field Results

Field measurements were carried out in a dry and a wet season lasting at least 30 days each between 7th of September and 28th November 1995.

13.5.3.1 Discharge Measurements

The results of discharge measurements for the dry season are shown in Table A13-1 in the Annex to Chapter 13, and for the wet season are shown in A13-2.

At Kindaruma and Kiambere power generation stations, a mean of four 6-hours duration generation discharges have been used to estimate the daily mean generation discharge. During the wet season whenever there were overflows over the spillway or in case of Kindaruma, gates had been opened, this discharge has been added to the generation discharge.

13.5.3.2 Sediment Concentration

The results of sediment sample analysis are presented in Tables A13-3 to A13-8 in the Annex to Chapter 13. These tables show sediment concentration and estimated load discharges, at the flow rates recorded at the time of sampling, at each of the sites for dry and wet seasons.

13.5.3.3 Sediment Particle Size Analysis

The results of sediment particles sizes differentiation by sieving using 0.25mm and 0.025mm sieves are shown in Table A13-9 and A13-10 in the Annex to Chapter 13.

13.5.4 Appraisal of River and Sediment Discharge

The discharge data of the current study was compared with data collected in the past, either published or available in the Ministry of Land Reclamation, Regional and Water Development or the Tana and Athi Rivers Development Authority.

13.5.4.1 River Flow Discharge

The present study discharge data were compared with long term mean monthly data at the flow measuring sites as shown in Table 13-7. Kiambere discharge data is limited to the last seven years after the reservoir was impounded in 1987.

Table 13-7 Comparison of present study with long term mean monthly discharge data (m^3/sec)

Station	Source & Period	Dry Season September/October		Wet Season October/November	
		Data Period Mean	This Study Mean	Data Period Mean	This Study Mean
Kiambere Dam	1988-1994 [2]	73.50	78.09	115.00	117.98
Mutonga 4EA7	1966-1990 [1]	10.30	13.94	61.20	79.55
Kathita 4F19	1966-1990 [1]	2.50	5.81	33.30	28.39
Grand Falls 4F13	1966-1990 [1]	88.30	99.47	223.00	301.13
Garissa 4G1	1966-1993 [1]	91.60	86.83	241.00	265.07

Source: 1) JICA - Mutonga/Grand Falls Hydropower Project Progress Report, February 1995.
2) TARDA - Tana and Athi Rivers Development Authority

It can be seen that the river discharge during the study periods in the 1995 dry and wet seasons are marginally higher than the long term average discharge rates. The variation is not however significant given the high fluctuations of seasonal rainfall and hence discharge[1], and hence the data can be considered as "not un-representative" of the normal flow patterns, and hence sediment transport capacity of the Mutonga, Kathita and Tana Rivers.

The difference between the sum of the discharges at Kiambere, Mutonga and Kathita and the discharge at Grand Falls can be assigned to the input from the intervening un-gauged catchment. The dry season averages indicate an increase of around 1 m^3/sec between the sum of the flows at Kiambere, Mutonga and Kathita and the flow at

[1] Statistically it might be more appropriate to describe "normal" flows using modal flows rather than mean discharges, as mean discharges will include the effects of infrequent major flood events that are not generally considered as normal.

Grand Falls, a difference of approximately 1% which could be assigned to the intervening catchment.

However, the average wet season flows indicate a discrepancy of some 75 m^3/sec between the gauged inputs and the output at Grand Falls. This represents a difference of 25% in the measured daily flows. Part of this discrepancy will be accounted for by the un-gauged catchment, but there must also be errors that have occurred as a result of the sampling strategy and the flashiness of river flow[1]. Again this indicates the critical need to implement a full daily, twice-daily or continuous sampling programme.

> ***In view of these observed discrepancies, all results must be treated as indicative, rather than truly quantitative.***

13.5.4.2 Sediment Load Discharge

Daily sediment load discharge results from the six sampling sites are shown in Tables A13-3 to A13-8 in the Annex to Chapter 13.

The validity of the results, in terms of gross sediment load, must be assessed with reference to the accuracy of the measurements of flow rates at the time of sampling. However, given this limitation, certain indicative conclusions can be drawn.

Table 13-8 Mean Daily Sediment Loads

	Dry Season			Wet Season		
	Mean Daily Load tons/day	Minimum Load ppm	Maximum Load ppm	Mean Daily Load tons/day	Minimum Load ppm	Maximum Load ppm
Kindaruma	312	32	55	402	24	66
Kiambere	220	30	39	342	18	44
Mutonga	39	30	52	70,324	218	41,720
Kathita	14	20	47	16,176	122	28,437
Grand Falls	369	31	98	15,500	113	1,993
Garissa	1,388	110	499	83,674	1,758	8,169

The majority of the flow through Kiambere is a result of the direct discharge from Kindaruma, the input from the intervening catchment is relatively small, both in terms of discharge and sediment load. The gross loss of sediment load between the outflow

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[1] This is particularly critical with the flows in the Mutonga and Kathita rivers, which were observed to vary by over 300% in a twenty four hour period.

of Kindaruma and the outflow of Kiambere can therefore be attributed to the trapping effect of Kiambere reservoir. From the sample data it would appear that Kiambere traps approximately 30% of the incoming sediment load during the dry season and 15% during the wet season.

Although the higher flow rate during the wet season would result in a higher transport capacity, particularly for the coarser particles, the proportion of the total sediment load that would be coarse particles would also be higher.

13.5.4.3 Sediment Particle Sizes

The sediment samples were sieved to separate the particles equal to or greater than 0.25mm and those that are less than 0.025mm. As indicated in the section above, describing the analytical procedures, the sample classes correspond to silts and clays, fine sands, and coarse sands to gravels.

The results of sieving are presented in Tables A13-9 and A13-10 in the Annex to Chapter 13.

As would be expected, all sampling sites indicated a higher proportion of course sediments during the wet season, corresponding to the higher transport capacity of the river system and the higher expected input of coarse materials into the primary drainage system. The only exception to this is the outflow from Kindaruma, which only contains fine particles during both sampling periods, indicating the trapping of all coarse materials in the upstream dam systems.

Table 13-9 Suspended Sediment Particle Size Distribution

	Dry Season			Wet Season		
	% Coarse	% Medium	% Fine	% Coarse	% Medium	% Fine
Kindaruma	Trace	Trace	97	Trace	Trace	97
Kiambere	Trace	Trace	97	Trace	Trace	90
Mutonga			100	24	71	5
Kathita			100	82	17	1
Grand Falls	4	Trace	95	33	66	1
Garissa	2	15	82	21	77	1

Dry Season Sediment Size Distribution

The dry season coarse suspended sediment particles greater than or equal to 0.25 mm were detected only from the samples collected at Tana Grand Falls 4F13 and Garissa 4G01 in small proportions of 4.4% and 2.42% respectively. The fine particles with sizes less than 0.025 mm dominated the sediment load discharges ranging from 100% in Mutonga and Kazita rivers to 97% in reservoir discharges from Kindaruma and Kiambere.

Wet Season Sediment Sizes Distribution

Coarse suspended sediment particles greater than or equal to 0.25mm were detected in all rivers sampling sites. Kazita River showed a proportion of 82% followed by Grand Falls 33%, Mutonga River 24% and Garissa 21%. Kindaruma and Kiambere dam discharges had only trace amounts. Proportions of the fine sediment particle sizes less than 0.025mm appear in the reverse order so that Kazita River, Grand Falls and Garissa had less than 1%, while Mutonga River had less than 5%.

13.6 SEDIMENT TRANSPORT CONCLUSIONS

The results of the limited field work carried out in 1994 and 1995, clearly demonstrate the inadequacy of short "snap-shot" sample periods as a means of quantitatively assessing sediment discharge. The transport mechanisms need to be modelled for a full season, covering the two rainy periods and the two dry periods, and extrapolated to give average values. However, given the variability of the system, the average values need to be reviewed within the context of both "normal" flows and the irregular flood and drought events. In addition to averages, modal values need to be looked at, as well as the extremes of climatic variations.

Clearly the volume of sediment transported depends on the erodibility of the source material, as well as the erosivity of the rainfall. A similar rainfall event late in the season will have a totally different effect to the same type of event at the beginning of the season when there is typically less vegetative cover. Indeed the effects of the preceding rains will also have major impacts, in that rain following drought periods will cause greater erosion than rain following seasons which had good rainfall.

Given these limitations, it can be seen that the results of the sample periods must be treated with great caution and only taken as indicative in terms of the scale of impacts.

The results of the study show that the volume of sediment derived from the upper catchment and transported by the Kathita and Mutonga rivers in both wet and dry seasons, was similar to the volume discharged at Garissa, and that the extrapolation of this data to cover the whole annual cycle also provided roughly balanced results. The discharge/transport system would therefore appear to be in balance over the sample period.

The total measured mass of materials that would have been transported within the river system within the projected sample one year period has been estimated as around 5.5 million tons. This is both the amount derived from the catchments of the Mutonga and Kathita rivers, and discharged through Kiambere dam, and the amount discharged through Garissa.

Approximately 90% of the transported load was carried during the wet seasons, indicating the critical importance of the transport capacity of the wet season flood discharge.

A review of the particle composition of the eroded source material and the discharged sediment indicates that the there is an apparent loss of fine material.

It is possible that some of this apparent loss may be a result of the particle size analysis methodology, which could include the largest clay flocs/mud particles within the "medium" particle size fraction. However, dry season and wet season measurements of transport within Kiambere show a mud trapping efficiency ranging from 1.5% at 100 m^3/s to 15% at 1000 m^3/s. Floculation and deposition of clay particles can not account for the apparent loss of the fine particle component.

In addition, given that the erosion/transport system appears to be roughly in balance for coarse particles, this indicates that the sampling techniques, or more specifically the sampling periods, are likely to be missing the important fine component, and that therefore the value of 5.5 million tons is likely to be a significant underestimate of the actual amount transported.

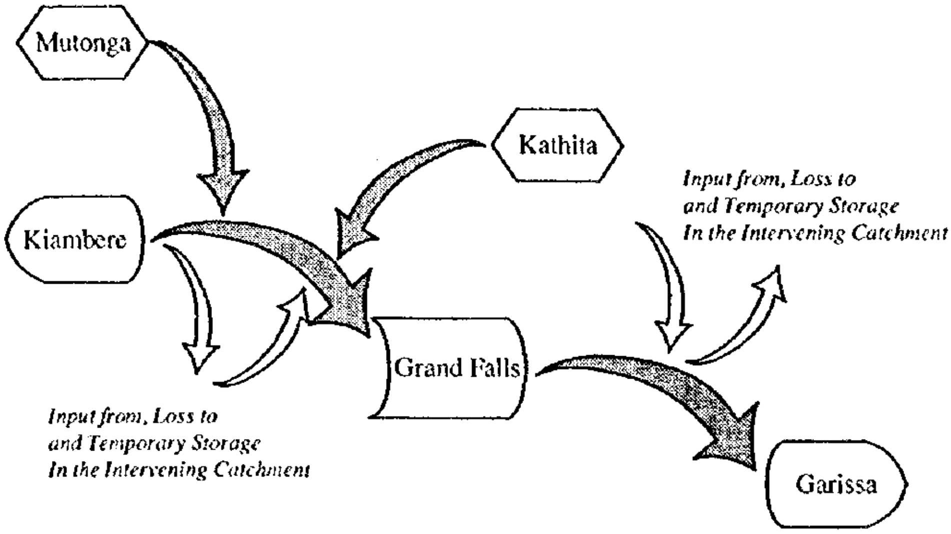
> ***The least reliable data appears to be that taken at Grand Falls during the wet season, which should therefore be treated with extreme caution. The flow discharges are clearly high, while the sediment load is clearly too low.***

These discrepancies are likely to be a result of lack of facilities and maintenance of structures at the Grand Falls site, and the resulting difficulties in conducting an adequate sampling programme.

13.7 INPUT-OUTPUT MODEL

The basic principle underlying the analysis of all flows through the river system is the input-output model. This type of model has been used to predict the impact of the proposed reservoirs on the flow regime, indicating the likely discharge to the downstream floodplain systems. A number of models have now been run with differing levels of complexity, based on the measured flow rates within the river system over a number of years, and the results of the latest models are described Chapter 16.

Figure 13-4 Basic Input Output Model For Grand Falls



Although these models have so far been primarily used to look at discharges, they are equally applicable to the transport of sediments and pollutants, and again a modified version of the model following movements through a 3 dimensional simulation of the proposed reservoirs has now been used to evaluate impacts on water quality. This is described in Chapter 14.

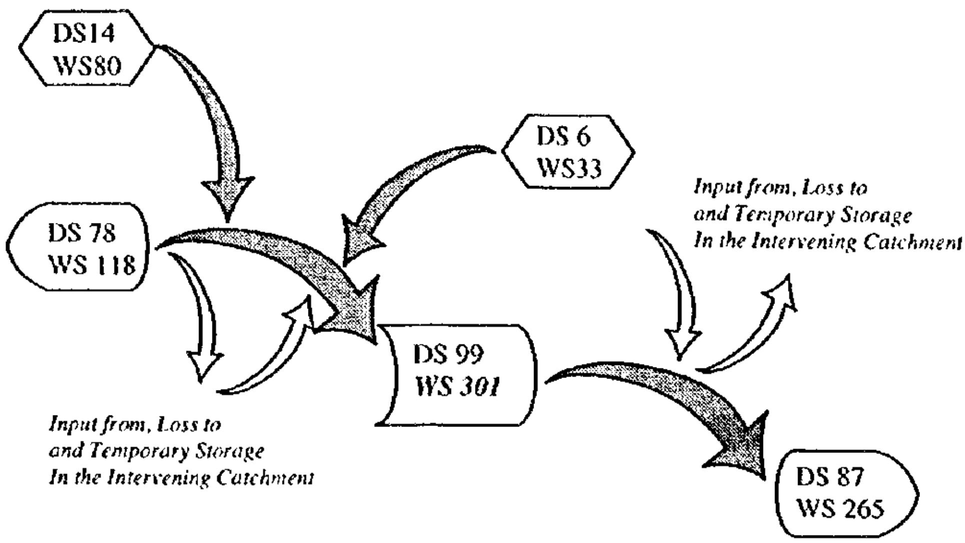
An additional use of the input-output model is to validate field data, indicating areas of uncertainty. The basic model for the Tana River Grand Falls site includes inputs from Kiambere, Mutonga and Kathita, transport through Grand Falls, and output at Garissa. Additional changes occur with additions from un-gauged catchments and unquantified losses from the system.

Although theoretically the model could be used to predict the movements at any one point in time, this would require detailed knowledge of the transport times between different points in the system. In practice, the longer the period for which data is averaged, the better the model will indicate actual discrepancies rather than the effects of "background" noise of unquantified environmental variables.

13.7.1 Seasonal Discharge Values

The average measured dry season flows are not significantly different from the quoted long term average means. The average gross input from Kiambere, Mutonga and Kathita is virtually identical with the amount flowing through Grand Falls. The drop in volume between Grand Falls and Garissa is not unexpected, and could be accounted for by evaporation and groundwater recharge.

Figure 13-5 Dry and Wet Season Sample Discharge Balance (Average Flow m³/sec)



The wet season results are less clear, in that the recorded average flow rate at Grand Falls considerable exceeds the combined flow rates of the upstream inputs. The balance of approximately 70 m^3/sec, or over 20% of the total flow is unlikely to have been contributed by the intervening un-gauged catchment. However, the flow at Garissa, which is far closer to the combined inputs up-stream does appear to be consistent. The higher flow at Garissa will be the result of the inputs from the intervening catchments, which clearly exceed any losses from the system during the rains.

The implication of this that the measurements taken during this season at Grand Falls are an overestimate of the actual flow; this is possibly a result of inaccuracies in the high flow gauging equipment which requires re-calibration[1]. However, this means that inaccuracies in all results derived from this measurement at Grand Falls will be compounded by the poor flow data.

13.7.2 Seasonal Sediment Load Values

The seasonal balance in sediment load is expected to vary considerably more than the discharge. This is the result of intra-seasonal storage of sediments within the river system itself. This also explains why the daily input-output data varies so considerably from station to station, as high velocity/high transport capacity flows from the Mutonga and Kathita rivers deposit considerable quantities of sediment as they reach the larger but slower moving Tana river, forming major temporary deposits within the Tana bed, that are gradually dispersed later in the season.

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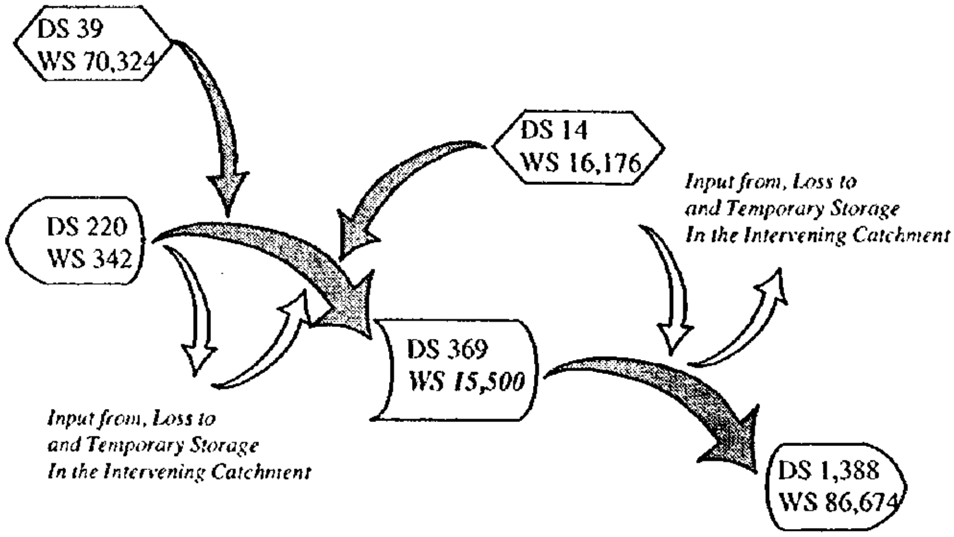
1 The consultant was required to record flow data at the sample sites, and at Grand Falls relied on the existing flow measurement systems maintained by TARDA.

Figure 13-6 Dry and Wet Season Sample Sediment Load Balance (Average Load in tons/sec)



This effect can also be seen further downstream where the deposits from laga flows in the main channel are eroded throughout the dry season adding sediment to the dry season discharge.

This expected increase in sediment load is supported by the data obtained during the dry season sampling period, with an increase in sediment load found at both Grand Falls and at a significantly higher level at Garissa.

The analysis of the wet season sediment load, based on a short sample period, is likely to be considerably less consistent. The peakiness of the sediment load in the primary drainage systems of the Mutonga and Kathita rivers, with values changing by up to a factor of 20 during a twenty-four hour period, means that it is statistically far more likely to collect a random but still un-representative sample over a short period.

Despite this risk, the sample analysis indicates that the sediment balance throughout the system as a whole appears to be giving a consistent pattern. The average combined wet season daily load from Kiambere, Mutonga and Kathita is around 86,800 tons per day, while the discharge at Garissa is around 86,700 tons per day[1]. In this case, probably more as a result of co-incidence, the deposition within the river system upstream of Garissa appears to be compensated for by input from the intervening catchment.

However, it is again the results from Grand Falls are not consistent with this overall picture, giving average daily sediment loads that are far lower than would be

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[1] Given that these results are derived from a series of measurements, each of which has inherent inaccuracies, this consistency should not be taken as clear "proof" of the data accuracy.

expected[1]. Again this is likely to be a result of the problems associated with sample collection at the Grand Falls site, which are particularly bad during the wet season. As described previously in Section 13.5, the samples had to be taken at points along the river bank where turbulent flow was assumed to provide adequate mixing of the sediment laden current.

Again this indicates that, although the overall picture provided by the field work in the two seasons is likely to represent a true picture of the sediment and discharge situation, the results for Grand Falls should be treated with caution, and should probably not be included for the wet season analysis.

13.7.3 Total Annual Sediment Load

The extrapolation from the two one-month periods sampled, a dry season month and a wet season month, to give a total annual load requires further assumptions to be made as to the representativeness of the two sampled flows and the length of the wet and dry seasons. It is also clear that different season lengths should be used for different components of the river system, depending on their specific catchment characteristics including rainfall, and very significantly land use patterns.

However, despite these limitations it is still possible to make some estimates based on the data collected, that can be compared with previous estimates. In order to do this, an assumption has to be made as to the length of the wet season that the sample period represents. Clearly, as the concentration of sediment transport occurs in the wet season, as does the distribution of sediments to the flood plain, the gross movement of sediment through the system will be largely affected by the length of the wet season selected as typical.

It must be emphasised that this analysis has been carried out to assess whether the sample data collected is within the same range of data as previous estimates, and therefore a valid sample. The data collected over one season, no matter how "normal" a season, can not be considered as indicating the long term water and sediment discharge of the river system.

If the wet season river discharge is taken as being two months[2] of the annual cycle, in two one-month periods, and the sampled data is accepted as being representative of the two month peak wet season flow, then a simple multiplication of sediment load by number of days will give the total wet season load transported through the system. A similar analysis then gives the dry season load, and the total annual load can be calculated.

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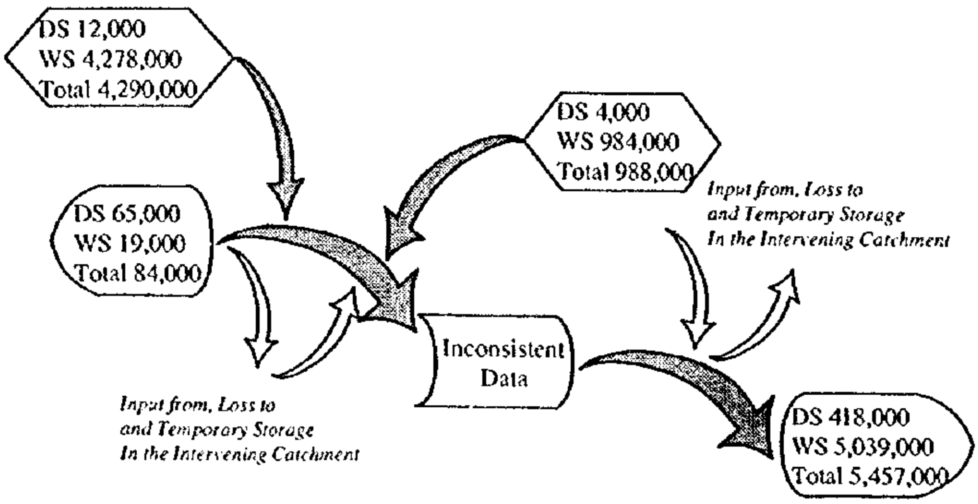
1 It is worth noting that the overestimates of discharge should have resulted in an overestimate of sediment load, given that the sediment concentrations were measured.

2 The sampled average flow for the wet season for the Mutonga river was around 80 m^3/sec, based on the flow characteristics for the 30 year flow cycle, this flow rate represents 15% of the daily discharge events, or approximately 2 months of the year.

Figure 13-7 Estimated Dry Season, Wet Season and Annual Sediment Discharge (Based on a two month wet season; values in Tons)



The total annual sediment load, based on the limited sample period, is projected to be around 5.5 million tons at Garissa, of which some 90% is transported in the wet season. The only input that is maintained at high values all year round is the sediments from Kiambere, which indicates the impact on discharge and sediment load of a regulated river flow regime. Clearly there are additional inputs from the un-gauged catchments, which will be compensated for to some extent by losses from the main river flow through discharge to flood plains areas above Garissa, but these seem to be relatively balanced for the sample period, as the increased sediment load at Garissa is only equivalent to 2% of the combined inputs of Kiambere, Mutonga and Kathita.

13.7.4 Particle Size Distribution of Sediment Discharge

It is clear that the vast majority of sediments discharged through the system must come from the un-regulated catchments of Mutonga and Kathita, and as a result would be expected to have a similar overall composition to the eroded source material from these catchments. In addition, despite the estimated mud trapping efficiency of Kiambere as a result of the floculation of clay particles and deposition as muds within the reservoir, the impact of the outflow of Kiambere would be to increase the proportion of fine particles in the overall sediment particle balance.

The soils within the Kathita and Mutonga catchments are classified as predominantly clay soils, which have clay contents of up to 70% and in a few cases are pure, massive clays. The overall proportion of clay, silt and sand particles forming the soils of the Mutonga and Kathita catchments (described in Section 13.2) are Clays 56%, Silts 16% and Sand 28%. The sample classes required for the field work effectively combined the clays and silts into a single class of fine particles.

The balance of particles transported by the system at any one time will depend on the previous erosion, deposition pattems of rainfall and discharge. There will be selective movement of particles within the system according to the transport capacity of the stream flow. The high stream flow during the wet season, following the initial high sediment inputs at the start of the rains, should increase the proportion of course particles transported. Sediment transported during the wet season should have a higher proportion of course particles, which should be compensated for by higher proportions of fine particles carried during the dry season.

However, if we assume that, up to the point at which there is selective deposition of sediments in the flood plain, the overall (annual) sediment input is balanced by the sediment transport, then the composition of the transported sediment should be similar to the eroded source material.

From this assessment, it would appear that the sampled sediments at all points through the system are under-represented in fine particles, apart from at Kiambere; and specifically that the samples do not contain an adequate proportion of clays and silts, if they are composed of the eroded soil materials of the upper catchment. The sample data indicates that the fine particles passing through Garissa form around 10% of the total load, as opposed to the expected 70% component of the original materials.

The conclusion must therefore be that the sampling regime has missed the fine particle component of the gross sediment discharge. This may be a result of sampling at the start of the rains when there are indications that the course sediments will be dominant in the transport mechanism. Conversely, the samples collected at the end of the dry season will have the lowest flow discharge and the lowest concentration of coarse sediments, assuming that these have been selectively deposited throughout the dry season.

Table 13-10 Sediment and Soil Particle Composition

Sediment Composition	% Course Particles > 0.25 mm	% Medium Particles 0.025 to 0.25 mm	% Fine Particles < 0.025 mm
Kiambere	0	0	100
Mutonga	24	71	5
Kathita	82	17	1
Garissa	20	73	7
Soil Composition	**% Sand > 0.05 mm**		**% Silt and Clay < 0.05 mm**
Mutonga and Kathita Catchments	28		72

It is therefore likely that the total discharge estimated from the measured sediment load is an underestimate of the actual sediment transported through the system, and that the 5.5 million tons derived for the annual period may be showing a ten percent fine particle composition, but missing the other 60% that passed through.

13.8 WATER QUALITY AND POLLUTION

As with sediment load, the critical factor determining the water quality and pollution levels in the river system is the discharge into the upper catchment. The water quality of the discharge from Kiambere reservoir has already been through a number of changes as a result of processes within the upstream river systems, and more significantly as a result of processes within the upstream reservoirs.

The water quality of the Mutonga and Kathita rivers will directly reflect the discharge of pollutants in the immediate upper catchment to the east of the Tana river.

The effects of the Kiambere reservoir on water quality can be used to indicate the likely processes that will occur in the proposed reservoirs, although clearly there will be a difference of scale which has implications on average storage time.

13.8.1 Land Use in the Upper Catchment

For the purposes of this section, the Upper Catchment of the Mutonga/Tana River covers Northern Embu District and large parts of Meru and Nyambene Districts on the eastern slopes of Mt. Kenya. The Mid and Lower Catchment above the Grand Falls also encompass the lower slopes of Mt. Kenya in the Tharaka-Nithi District. This catchment is amongst the most productive regions in the Country, much of it at high altitude between 1500 - 3000 m. asl. Rainfall intensity is high, reducing towards the proposed reservoirs where rainfall can be considered to be low.

The catchment is truncated by many perennial rivers which flow from Mt. Kenya and the slopes of the Nyambene hills. The north-western catchment is drained by the Kathita (Kazita) River flowing from the northern slopes of Mt. Kenya through Meru Town. The Thanandu drains the Nyambene hills. In addition to these rivers, the Tana at Grand Falls receives water from the five existing dams. In addition many Laghas, or seasonal rivers, from Mwingi District contribute substantial and seasonal flash flood waters at various points between Kiambere dam and Grand Falls on the east banks of the Tana River. Although little is known about the discharges of the laghas their contributions are considered to be of significance.

Due to the relatively high population in upper catchment areas, urban trading centres have developed. Some of the larger ones are Chuka (administrative centre) for Tharaka-Nithi District; Nkubu, Chogoria, Kiriaini, and Meru town. Such centres are very important for trade as they provide the economic infrastructure supporting the fast growing populations.

Agricultural	The high rainfall and fertile soils are contributory factors to intensive cultivation. Various cash crops particularly coffee, tea and pyrethrum are grown. Other crops grown for subsistence farming include maize, bananas, potatoes, tomatoes, cabbages, yams. Along with these crops unknown amounts of fertilisers and pesticides are used. Because of population pressure on the land livestock is kept on a zero grazing scale in much of the Upper Catchment. On the semi-arid lower catchment in Tharaka-Nithi livestock, particularly cattle and goats are kept on more open and extensive fields.
Industrial	The industries in this area are directly related to agricultural output. The majority of industries are agro-based and are mainly primary processing factories for coffee pulping, tea processing and fruit juice processing. These factories discharge their effluents into the rivers and have a definite impact on the water quality of these rivers.
Urban Land	Due to the high population and intense agricultural activities, one very important land use includes urban centres. These have inevitably developed to render services e.g. trading in agricultural products and provision of other attendant services essential to high population densities, including utilities such as butcheries, hotels, retail shops, hospitals, schools.

The area is heavily afforested in the upper reaches of the mountainous zone where the soils are lateritic and good for agricultural activities. Farming is intensive with crops such as coffee, tea, bananas, maize, yams etc. The human population of the area is also high with some areas estimated at over 5,000 people per km^2.

Further details of the upper catchment are given in Chapter 7, including some projections of future population growth and agricultural and industrial expansion.

13.8.2 Pollutant Studies

In recognition of the significance of the pollutants inputs and transport through the system, a limited field study was carried out during the 1994 rainy season, followed by further studies during the end of the dry season and the start of the rains in September and November 1995.

During the 1994 study, water samples were taken from the Mutonga Rivers, Kathita Rivers, Kiambere outflow, and at Grand Falls and Garissa. In addition in the down stream areas, samples of recent alluvium were taken from the banks for nutrient analysis. A number of laboratory tests were carried out to determine whether the water contained impurities and whether it is fit for domestic water supply, for plants and wild life and especially for irrigation in the downstream areas.

The following characteristics were reviewed:

- **Colour:** In the project area, the colour source is mainly generated by soil erosion in the upper zone. When water with heavy colour collects in large dams, it can have a substantial impact, making water treatment an expensive undertaking and impeding biomass production as photosynthesis is reduced significantly due to decreased sunlight penetration.
- **Turbidity:** High turbidity again results in poor water quality for domestic purposes, and hence greater treatment costs. It also has a similar impact on photosynthesis as high colour.
- **Temperature:** Water temperature values in the upper zone of Tana tributaries are low, however the increased temperatures in the lower Tana results in increased nutrient solubility and would increase biomass productivity in the reservoir. Evaporation in the Grand Falls site would result in an increase in water salinity.
- **Total Dissolved Solids (TDS):**TDS are low in the upper zone due to the dilution effect of high rainfall and low temperatures. At the Grand Falls site, TDS are still relatively low at 69-87 mg/1. This level of TDS is classified as soft water good for domestic use as well as for irrigation.

The chemical characteristics of water are quantified in terms of the inorganic and organic constituents present.

- **Dissolved Oxygen:** Dissolved oxygen levels in the upper catchment were found to be relatively high, 8-15 mg O_2/l; the result of mixing of air and water in fast flowing and turbulent streams in relatively low temperatures. However, as the organic matter level in the river increases it causes dissolved oxygen levels to decrease. At the Grand Falls Dam site, dissolved oxygen concentration is likely to be low, and may pose problems for fish particularly during the filling phase.

- **Iron:** The bulk of iron and manganese emanate from eroded soils in the upper catchment zone where in some cases there are high concentrations in the rivers (e.g. Mariara Fe^{++} 8.74 mg/l, Mutonga Fe^{++} 4.4 mg/l, Ena Fe^{++} 4.7 mg/l and Thanantu Fe^{++} 12.0 mg/l). Manganese levels are relatively low in all rivers with Thingithu recording 0.18 mg/l, and the rest with less than 0.4 mg/l.

- **Flourides:** In some of the upper zone tributaries fluoride levels are high, but still below maximum potable levels.

- **Nitrates:** Analysis has shown moderate to heavy nitrate concentrations in the upper catchment. The main sources are organic matter, domestic wastes, humus, coffee pulp, decaying agricultural crop residues and organic fertilisers. Nitrates are quite soluble in water and would be transported to Grand Falls.

- **Phosphates**Phosphates were found in moderate concentrations in the upper catchment river waters. These are found in decomposing organic matter as well as in solution and absorbed in sediment particles. Phosphates originate from the following sources: domestic wastes; coffee effluent; agricultural waste; fertilisers; and industrial effluents.

Both phosphates and nitrates can create similar problems of eutrophication; the process in which algal blooms and in particular the decay of algal blooms reduces oxygen supply, with potentially damaging effects on the system.

The results of bacterial examination in the upper catchment indicate major bacterial contamination. Samples taken from the Thuci river at the Meru road, from the Mara above the bridge, and from the Thingithu, Mariara, Mutonga Thanantu and Ena rivers all gave *E. Coli* results of over 2,400 count per 100 ml and over 1,100 count per 100 ml for *Faecal Coliform*. Similar levels were found down stream at Garissa, Hola, Garsen and Ngau. These levels are not in themselves serious, but do indicate the requirement for treatment of domestic water.

13.8.3 Sources of Pollution

A more detailed field study was then carried out during a one month period during the dry season and a one month period during the wet season, in September and November 1995. This study, concentrating in the upper catchment, included sampling all major streams flowing into the Mutonga and Kathita rivers, both above and below the main Embu Meru road to try to identify the influence of the peri-urban ribbon developments on water quality.

The pollution sources and trends are closely linked to the broad land use categories already defined above. Agriculture contributes to pollution mainly in the form of effluents from coffee pulping waste water and milk processing. Domestic effluent, waste water and of course human and animal wastes from trade centres are significant.

The quality of pollutants plus its quality are closely linked to the particular source. For example, the coffee water effluent is very serious because of the composition in terms of chemical oxygen demand (COD). Coffee effluent is known to have a COD of up to 30,000 mg/l. Studies (Thitai 1978) showed that the equivalent of 1 tonne of coffee will produce waste effluent equivalent to 2,000 head of population. With well over 150 coffee factories within the upper catchment area, the pollution load, mainly organic but including pesticide residue is known to find its way into the rivers shown in the catchment area.

High sediment and silt levels are further evidence of the quantity of pollution. Other pollutants include high levels of Nitrates and Phosphates which would also have a direct bearing on water quality in the proposed dam.

It is known from earlier studies that dissolved oxygen in river water diminishes with increased pollution loads. The measured BOD5 of the river waters on all the sampling stations did not give significant values which may indicate elevated organic pollution. However increased farming, pesticide and fertiliser use as well as urban and agro-factories based effluent is also likely to aggravate the pollution impact into the Tana River system. Non-point sources of pollution from storm water floods are also expected to increase as agricultural output and rural population increase.

Tables A13-11 to A13-15 in the Annex to Chapter 13 show the results for full chemical analysis and microbiological assay.

13.8.3.1 Dry Season Water Quality

Chemical analysis

The salient feature of the dry weather samples show relatively low level parameter values notably of turbidity and colour. This is expected because there are low levels of sediment load carried from the area. The upper catchment of the Tana contains significant forest cover and the river reaches are deep into the bedrock with little sediment. It will also be recalled that non-point source contamination of these rivers is least because no flash floods had at that time taken place. Land is least utilised and therefore little soil erosion takes place. Parameters such as Nitrates levels are also low because there is little influx of organic matter from the land. This information is confirmed by the BOD5 levels which are good indicators of organic pollution. Other parameters that contribute significantly include Iron, responsible for heavy red colour on account of the oxides.

The general water quality in all the rivers was found to be good in as far as the chemical side of it is concerned. Fairly low Total Dissolved Salts were recorded here (the highest TDS of 58 mg/l in upstream Kathita.

Microbiological Assay

Due to increased human activity in the area including developing urban centres there was increased waste water generation. This arises from activities such as trading and manufacturing that support the growing economy. These rapidly developing urban centres have also multiplied the complexity of industrial waste flows. It is no wonder then that the general trend of water quality in this aspect shows heavy contamination (in excess) of 2400 coliform colonies per 100 ml of water.

13.8.3.2 Wet Season Water Qualitys

Rains in the wet season in the Upper Tana Catchment started on or about the 20th October 1995 and the first heavy and continuous downpour occurred on 27/28 October, 1995 - whilst the field survey teams were on-site. A second wet season sampling was conducted on 28th November 1995 for the lower and upper catchment stations including Grand Falls. Samples were taken for both chemical and microbial analysis.

Chemical Analysis

The results of chemical analysis of water samples from the various stations done during the rains showed a very significant departure from those collected during the dry season in the following manner.

The physical characteristics of colour and turbidity were at their highest levels. This was expected because of high wash off, discharge rate and sediment load. The overall water quality changed completely to present a different scenario i.e. one of maximum pollution, both physical and chemical, and more seriously bacteriological. For example turbidities are the highest recorded (greater than 50 N.T.U). Other parameters that show an upward trend are overall Electrical Conductance (Thingithu 200 uS/cm of dry weather E.C. level of 82 uS/cm).

It is evident from Tables A13-16 & A13-18, in the Annex to Chapter 13, that a number of parameter levels increase significantly during the rains. This has important implications for the overall impact on water quality expected at the dam.

Nutrient Chemistry

The most important parameters in this category are the Nitrates and Phosphates carried downstream by the rivers. During wet periods there is increased wash-off of organic matter both through waste waters and also from decaying forest foliage. Phosphates are in particulate form. Samples taken and analysed showed that there would be a constant flow of nutrients into the River Tana. The phosphates appear to be substrate sediment based as the levels in the water samples indicate.

Influx of nutrients will mean their build up in the proposed dam, supporting microfauna and microflora - in turn supporting high plant and animal life and, with time high algal blooms causing high primary production which would encourage fish production in the dam. However, excessive algal blooms are likely to result in eutrophication.

13.8.3.3 Pollution Control

Principal waste water management alternatives will need to be put in place. In the case of coffee effluent, this will mean that low-cost waste-water treatment plants will have to be planned and installed for all coffee factories throughout the catchment area. Basic engineering approaches with scientific and logical considerations will have to be put in place. Management will have to be considered on the following.

- Industrial waste water - e.g. Municipal waste water treatment
- Industrial sludge (a good example is slaughter houses in trading centres)
- Agro-Industrial wastes - e.g. coffee factory effluent.

The issue of sludge handling is important as location of new industry may depend on the method of sludge disposal. Adequate handling of urban effluents will have to be planned early during the development of urban centres.

13.8.3.4 Water Supplies/Treatment

With poor water quality there will be a necessity to plan fairly elaborate water treatment works in order to cope with treatment of poor quality water for domestic and other purposes. This will certainly affect the general economy of the country and area in particular. Full chemical treatment works design is quite expensive but this would be the only way to cope with this problem, unless the sources of pollution can be prevented from discharging polluted water into the Tana River system.

It has already been established that the proposed dam area has expansive large trees and other heavy plant growth riverine plant communities. Clearance of these will be very necessary to reduce future high COD from on the plants inundated dam waters which may cause oxygen depletion and hence fish kills.

Table 13-11 Typical Chemical Constituents and their Effects

Constituent	Effect	Critical Contamination mg/l
Inorganic Ammonia	Toxic to fish. Can be converted to Nitrates	Any amount
Nitrates	Stimulates algal growth and aquatic growth. Can cause methaemoglobinaemia in infants (blue babies).	0.3mg/l
Phosphates	Stimulates algal growth and aquatic growth. Interferes with coagulation in water treatment	0.2-0.4mg/l

Chapter 14

WATER QUALITY & NUTRIENT AND PARTICULATE MATTER FLUSHING

14. WATER QUALITY AND NUTRIENT AND PARTICULATE MATTER FLUSHING

14.1 SUMMARY

As part of the Phase 3 study, field work was carried out in 1995 during the dry season in September and during the November rains, to establish water quality parameters in Kiambere reservoir and in the Mutonga and Kathita rivers, as well as the main Tana channel. In addition a deterministic three-dimensional segmented and layered model 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 to 20% of the wash load of clay particles, which are weakly flocculated by the presence of natural salts in solution (75 ppm) and settle at a rate estimated to be about 5×10^{-6}m/sec.

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 rapidly through the Grand 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 affected by recycling of dissolved available inorganic nitrogen into the lower layers of the reservoir, unless strong winds 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 50% and 80% of the relatively small incoming loads of dissolved available phosphorous in wet and dry season respectively and that the algal blooms in the surface layers would be limited by lack of phosphorous.

The model predicted a 2-4 m deep photic zone with variable and an acceptable range of chlorophyll-a concentrations (i.e. 5-15 mg/m^3) depending on light penetration, and 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 sensitive to the factors affecting the growth of the specific algae species in the Tana River reservoirs which are not available; this informationwould have to be obtained from further research. 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.

Table 14-1 Reservoir operating characteristics used in this study

	Mutonga	Grand Falls (LGF)	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/secec)	171	191	137
Max (m^3/secec)	823	861	
Min (m^3/secec)	93	93	
Power Outflow:			
Average (m^3/secec)	136	147	
Max (m^3/secec)	200	210	122
Min (m^3/secec)	65	75	
Monthly Spill-out:			
Average (m^3/secec)	34	39	
Max (m^3/secec)	643	662	
Min (m^3/secec)	0	0	0
Average monthly evaporation (m^3/secec)	0.78	4.74	

14.2 RESERVOIR WATER QUALITY

The Phase 2 report 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 the 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.

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

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

14.2.1 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 previous studies (Roggeri 1985) indicated that the characteristics of all the waters of the Tana River reservoirs were similar, in particular:

- 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 Masinga, Kamburu, Kindaruma reservoirs were unfit for human consumption,
- the use of the water for domestic purposes was judged to be risky and this risk was being increased by the lack of adequate sanitary installation.

14.2.2 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 pollutants from 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, strict 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.

14.2.3 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 more intensive settlement is likely to lead to increased erosion. Impacts can be reduced through active management of the buffer zone and direct and indirect interventions through extension services to promote conservation oriented farming systems.

More general management of sediment load may be possible through sediment release or diversion structures, although the critical factor still remains as control of land use in the upper catchment. Further sampling of dry season and rainy season sediment loads over a longer time period 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 be necessary.

14.3 METHODOLOGY

A forecast was made of the likely trophic state of the proposed reservoirs by analysing limited available data and data obtained from the field studies, 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, a water sampling survey of the Kiambere Hydropower Reservoir upstream in the Tana River was commissioned at the same time as the river survey.

The following data were also included as part of the model::-

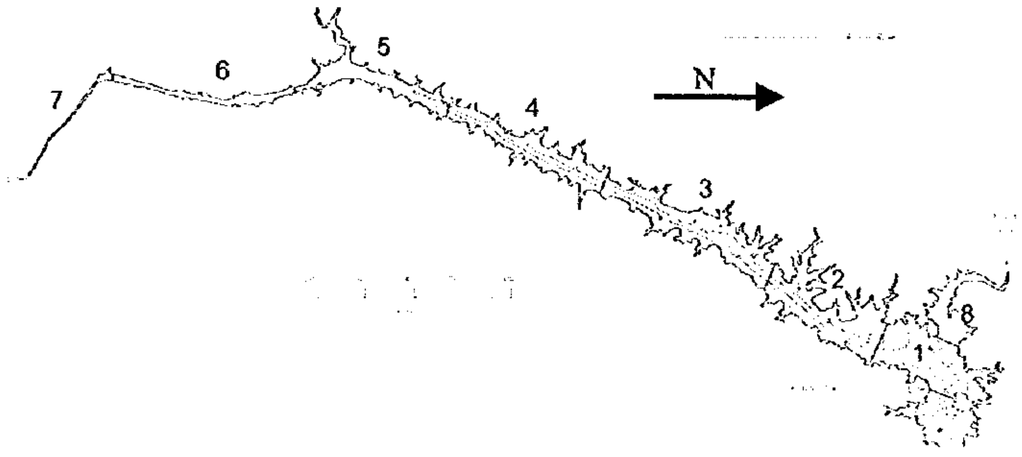
- A digital ground level data set of the proposed reservoirs based on contours at 10 metre intervals and paper copies of 44, 1:5,000 scale plans based on contours at 2m intervals.

- Forecast daily flows with proposed hydropower plants and reservoir working in an optimised mode.

The small amount of existing water quality data collected in Phase 2 was assessed and a water quality survey of Kiambere Reservoir was specified at the same time as 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. The surveys of Kiambere Reservoir were used to evaluate various processes described in section 14.6 and to design the models.

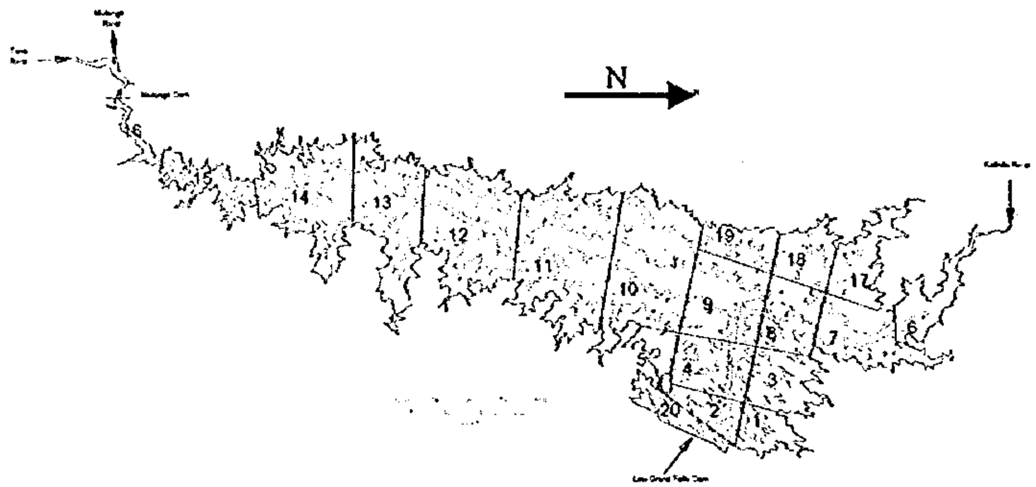
The topographical maps and information on the design of the dams and the observed pattern of water quality in Kiambere Reservoir were used to set up separate schematic 3D models of the Mutonga and Low Grand Falls Reservoirs in terms of a series of in-plan segments and horizontal layers of variable thickness. The Mutonga Reservoir was divided into eight segments, seven of which represented the submerged Tana River Valley (Figure A14-2 in the Annex to Chapter 14). The Mutonga model had 9 layers. The base of the top layer was set at 548 m, two meters below the FSL spilling level. The lower layers were 2, 2, 2, 2, 4, 4, 10 and 30 metres thick (Figure A14-3).

Figure 14-1 Mutonga Reservoir showing division into segments for modelling (see also Fig A14-2).



The flow to the turbines was extracted from between 520 and 530 m (layer 8). The segment boundaries were orthogonal to the existing river channel and spaced at intervals of between 2 to 3 km as shown in (Figure 14.1). The FSL was 550 m. 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 contained in the Phase 2 reports (Figure 14.3).

Figure 14-2 Low Grand Falls Reservoir showing division into segments for modelling (see also Figure A14-5).



The Low Grand Falls Reservoir was schematised into 19 segments and 8 layers (Figure 14-2 and Figure A14-5). The top base of the layer was set at 510 m, 2 m below the FSL. 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 490 m in layer 6 (Figure A14-6). The theory behind the models and the particular assumptions made for this study are given in the Annex to Chapter 14. The main assumptions are defined in section 14.7

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/sec and 220 m^3/sec 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 section 14.8.

The exercise was repeated on the dry season assuming discharges of 65 m^3/sec and 75 m^3/sec through the turbines on the Mutonga and Low Grand Falls Dams, representing an 80 percentile flow condition. The results are described in section 14.9.

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

14.4 SOURCES OF WATER, MUD AND POLLUTANTS TO THE PROPOSED RESERVOIRS

14.4.1 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 the Low Grand Falls Reservoir which accepts flow from the Kathita River, another perennial stream fed from the slopes of Mount Kenya.

The Mutonga and Kathita Rivers are considerably 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.

14.4.2 Mud (clay) inflows

The clay and silt (mud) volumes used in this analysis are based on the figures reported from the field work carried out during the 1995 dry and wet seasons. The values obtained for the clay and silt component as part of the sampling programme appear to be underestimates, although they are consistent with the values obtained during the peak November 1994 floods. The clay and silt fractions of the source materials in the upper catchment form 70% of the eroded soil materials (further details are given in Chapter 13). The mechanism for clay transport may therefore be one of seasonal storage within the catchment and river system, with proportionally higher release later in the wet season or during the early part of the dry season.

The flow characteristics used in the model are given in the following table. These would appear to indicate a total annual mud load of 180,000 tons, or about 3% of the estimated annual load at Garissa for the periods during which the data was collected..

Table 14-2 Flow and mud transport statistics

Catchment	Tana at Kiambere Tailrace	Mutonga at 4EA7	Kathita at 4FI9
Average flow (m^3/sec)	111	29	16
5% percentile (m^3/sec)	330	160	100
90% percentile (m^3/sec)	35	10	5
Average daily mud load (t/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]

An analysis of data from the 1995 river sampling exercise at the outflow from the Kiambere Dam showed only mud (fine clay particles) and no sand or silt. Furthermore, the mud concentrations only varied from 30-40 ppm for a three fold change in discharge for 65 to 210 m^3/sec, i.e. 170-730 tonnes/day.

Based on the sample data, 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 14-3).

Table 14-3 Mud transport through Kiambere Reservoir

	Kindaruma Tailrace		Kiambere Tailrace		
	Mean daily outflow m^3/sec	Mean daily suspended load t/d	Mean daily outflow m^3/sec	Mean daily suspended 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)

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/sec 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%.

The Mutonga and Kathita rivers flow into the Mutonga and 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/sec which is greater than the 5 percentile 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 the 1995 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 to 20% of the incoming fine sediment is trapped in Kiambere Reservoir.

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.

The concentrations shown in Table 14-4 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 1,000 m^3/sec are as follows. The estimated trapping efficiency refers to clay particles travelling the full length of the reservoir.

The observations of turbidity in 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 35 m and the time of travel of 68 days at 100 m^3/sec. So the settling velocity of the clay particles is of the order of 5×10^{-6} m/sec. A typical value for fully flocculated mud is 10^{-3} m/sec.

Table 14-4 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/sec)	89	83	10	330
Total dissolved salts	73	74	89	77
Conductivity (s/cm)	100	100	115	110

Table 14-5 Estimated mud trapping efficiency of the reservoirs: observations from Kiambere and extrapolations for Mutonga and Grand Falls (LGF)

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

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-percentile flow to

3% at the 5-percentile flow. However mud settling in the deeper water near the dam can subsequently be re-eroded by turbulence caused by the flow into the turbine.

14.5 WATER QUALITY OF THE RIVER WATER

Water quality sampling surveys of the Tana were carried out, 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).

Table 14-6 A: Dry Season River Survey 26-27 September 1995

Dry Season 1995	Discharge m^3/sec	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
B: Early Wet Season Survey 28 October-13 November 1995							
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
C: Wet Season River Survey 25-27 November 1995							
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

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.

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.

14.6 ANALYSIS OF CONDITIONS IN KIAMBERE RESERVOIR

Surveys in Kiambere Reservoir were carried out simultaneously with the river water quality surveys in September, October and November 1995. The results as longitudinal sections of the temperature, DO, total Solids, nitrate, Chlorophyll a and BOD_5 are illustrated in A14-8, 9 & 10 in the Annex to Chapter 14.

14.6.1 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/sec close to the 40 percentile 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 2 m surface layer. The Secchi disc depth was less than 2 m. 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 40 m below the water surface. However, the observations reported a whirling undercurrent at a depth of 75°m, 1 km from the dam. This suggests that the turbines could draw in water from all layers below 40 m at higher discharges. The Secchi disc depth of 1.8 m 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 2 ppm 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/m²/day assuming a plan area of 20 km².

The suspended clay flocs in the water column settle by about 30 m over the 60 day retention time which is equivalent to a settling velocity of about 5×10^{-6} m/sec in the absence of vertical turbulent exchange. The month long sediment survey indicated a trapping efficiency of 15-20% with a discharge of about 80-100 m³/sec 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/m³ (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 14-6a). The chlorophyll-a values hardly exceeded 5 mg/m³ 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/m³.

14.6.2 Early wet season survey-13 November 1995

The Tana River discharges were slightly higher at about 115 m³/sec during the survey on 13 November 1995, the 50 percentile 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 mglm³) 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.

14.6.3 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 200m³/sec.

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/m³.

14.7 MODEL ASSUMPTIONS

The sections indicate the major assumptions that were made in applying the 3D model.

14.7.1 Solar radiation

The solar radiation was assumed to average 1.4 m Joules/m²/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/cm²/day, an average transmission coefficient of 0.8 and an average of 8 hours sunshine per day. This is equivalent to 33.5 cal/m²/hr, which is twice the optimum of 17 cal/m²/hr for maximum algal growth used in the model.

There was insufficient data on local meteorological conditions to predict diurnal fluctuations in temperature in the surface layer. The buoyancy effect was simulated by assuming negligible vertical turbulence exchange across the thermocline at about 2 m. 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 at the top of Mt Kenya and rainfall in the high, cool upper catchment. 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 diluted form. However, the process of selective withdrawal would still result in the outflow having the same temperature.

14.7.2 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 37 mm/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 theoretical values, details of which are presented in the Annex to Chapter 14. The rivers were seeded with a chlorophyll a concentration of 1.0 mg/m^3.

14.7.3 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.

14.7.4 Settling velocity of mud flocs

The mud particles (clay flocs) were assumed to settle at 5×10^{-6} m/sec 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/sec, based on the low trapping efficiency expected in the Mutonga Reservoir (See Table 14-5). By comparison, the values for much larger and stronger fully flocculated marine mud are 10^{-3} m/sec and 0.3 m/sec respectively.

14.8 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/sec from the Tana River and 70 m^3/sec from the Mutonga River and an outflow of 200 m^3/sec via the turbines. The Low Grand Falls Reservoir, which has an addition inflow of 20 m^3/sec from the Kathita River, discharged 220 m^3/sec via the turbines. The water quality of the incoming flows was based on the observations as follows:-

Table 14-7 River flows and loads for typical wet season conditions

	Tana	Mutonga	Kathita
Discharge (m^3/sec)	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.

14.8.1 Mutonga Reservoir

The results at midnight, when DO levels would be expected to be low, are shown in Table A14-1 in the Annex to Chapter 14, in the form of a section along the reservoir. The outflow of 200 m^3/sec was withdrawn from between 520-530 m which is the 8th layer in segment 1. The water quality of the outflow and the trapping efficiency of the reservoir was as indicated in Table 14-8.

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 2 m 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.

Table 14-8 The water quality of the outflow and the predicted 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%
NO3 (mg/l)	0.64 [0.64]	(0.69)	10% [8]
NH4 (mg/l)		neg	-
PO4 (mg/l)	0.028	(0.036)	22%

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

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 22% 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 2 m 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 (8 m) 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.

14.8.2 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 25°C-the natural water temperature in the Tana Valley locally.

The results are shown in Table A14-2, in the Annex to Chapter 14, in the form of parallel sections northward along the reservoir. The outflow of 220 m^3/sec 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 14-9 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)	0.49	(0.66)	26%
NH_4 (mg/l)	neg		-
PO_5 (mg/l)	0.0155	(0.0264)	41%

(Bracketed figures based on incoming loads)

The model predicted that 46% of the influx of suspended clay particles (1,418 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 10 ppm 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 0.014 mg/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/m²/d.

The model predicted a 26% loss in nitrate and a 41% loss of dissolved phosphorus, both bound into detrital matter settling on the bed.

14.9 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 m³/sec from the Tana River and 18 m³/sec from the Mutonga River and an outflow of 65 m³/sec via the turbines. The Low Grand Falls Reservoir gained an additional flow of 10 m³/sec from the Kathita River and discharged 75 m³/sec 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 14-10 River flows and load for typical dry season conditions

	Tana	Mutonga	Kathita
Discharge (m^3/sec)	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.

14.9.1 Mutonga Reservoir

The 3D steady state velocities and concentrations are shown in Table A14-3, in the Annex to Chapter 14, in the form a section along the reservoir. The quality of the outflow and the trapping efficiency are listed below (Table 14-11).

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.

Table 14-11 The water quality of the outflow and the trapping efficiency of Mutonga Reservoir-dry season

	Outflow	Inflow	Loss
Temperature (^oC)	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	(0.02)	50%

(Bracketed figures based on incoming loads)

{unrestricted recycling of nitrogen from the bed]

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 50% 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.

14.9.2 Low Grand Falls 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 A14-4 in the Annex to Chapter 14. 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 14-12 **Water quality of the outflow and trapping efficiency of the Low Grand Falls Reservoir-dry season**

	Outflow	Inflow	Loss
Temperature (oC)	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%
NO3 (mg/l)	0.12 [0.16]	(0.23)	32%
NH4 (mg/l)	neg		-
PO4 (mg/l)	0.003	0.011	73%

Org N (mg/l)

(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 from 75 days to about 225 days, the length of the test.

The model predicted that 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 5 ppm throughout the reservoir allowing for considerable light penetration and a deeper and weaker diurnal thermocline-not modelled expect by suppression of vertical mixing.

Predicted surface chlorophyl a concentrations were low, averaging only about 0.4 mg/l in the 7 m deep surface layer. Dissolved nitrate and phosphate concentrations averaged 0.13 mg/l and 0.003 mg/l, respectively. The latter 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% of 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.

14.10 DISCUSSION

14.10.1 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 proposed 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.

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 14.6 a, b & c). These were used to estimate typical equivalent steady dry and wet season inflows (Tables 14-7 and 14-10). The models of the Mutonga and Low Grand Falls reservoirs 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.

14.10.2 Fluvial Mud (Clay) Loads

The magnitude of the load of clay particles and 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 trap nutrients in the bed. They also contain slowly oxidising organic detritus which, over time, adds to the benthal oxygen demand. 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 by the sediment load field studies. However, the percentage composition of the parent materials is significantly different and it likely that these field studies underestimated the proportion of fine particles during the wet season (see Chapter 13).

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.

14.10.3 Large episodic fluvial floods

Large (>200 m^3/sec) 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 530 m. The volume of the dead zone, below the out-take, is 16×10^6 m^3.

This volume is equivalent to 1 day at 200 m^3/sec. Mutonga floods of a lesser volume will be trapped in this dead zone (Figure A14-3). 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 was 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 490 m in the Grand Falls Reservoir, is about 260 × 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 Kathita 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. 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 chapter do not show the effect of episodic floods on the water quality of the reservoirs, mainly because of the current lack of data to estimate the clay and nutrient loads during floods.

14.10.4 Settling velocity of mud flocs

An analysis of the fluxes and distribution of relatively dilute suspension of mud in Kiambere Reservoir indicate that there were sufficient salts in solution 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/sec. 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 in typical dry and wet season conditions by consideration of their relative residence times.

Table 14-13 Predicted mud trapping efficiencies of the reservoirs

		Mutonga	L.G Falls	Combined
Wet Season	Trapping efficiency	8%	54%	60%
	Influx (t/d)	1,400	1,496	1,728
	Outflow (t/d)	1,290	690	690
Dry season	Trapping efficiency	38%	79%	86%
	Influx (t/d)	224	174	258
	Outflow (t/d)	140	36	36

The critical velocity to allow deposition was found by trial and error to be about 20 mm/sec. In other words, it was adjusted to give the Mutonga reservoir a realistic trapping efficiency compared to that observed in the Kiambere reservoir.

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.

14.10.5 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 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 14-14. [The sinking algae detritus and recycled nutrients may be the cause of the discoloured water at depth in Kiambere Reservoir]. After 230 days, starting from a clear reservoir, 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 14-14 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%	17%	29%
Influx (t/d)	11.9		
Outflow (t/d)	10.9		
DRY SEASON	100 days	230 days	
No benthal recycling			
Trapping efficiency	22%	48%	55%
Influx (t/d)	1.8	1.5	1.8
Outflow (t/d)	1.4	0.8	0.8
With benthal recycling			
Trapping efficiency	17%	32%	42%
Influx (t/d)	1.8	1.6*	1.9
Outflow (t/d)	1.5	1.1*	1.1

*Adjusted to allow for recycling in Mutonga Reservoir

14.10.6 Phosphorous

The model was run using estimated loads of dissolved available inorganic phosphorous. The concentrations of dissolved phosphorous in the rivers varied from 0.01-0.05 mg/l. Observations in the November 1995 wet season at Station 4EA7 on the Mutonga River indicated concentrations of particulate phosphorous averaged about 2 ppm of the average dry weight of all suspended solids of 12,000 ppm. This is equivalent to a concentration of phosphorous of 0.024 mg/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.

Table 14-15 **Predicted dissolved phosphate trapping efficiency of the reservoirs (without benthal cycling)**

	Mutonga	Grand Falls (LGF)	Combined
Wet Season			
Trapping efficiency	22%	41%	53%
Influx (t/d)	0.62	0.50	0.62
Outflow (t/d)	0.48	0.29	0.29
Dry Season			
Trapping efficiency	50%	73%	82%
Influx (t/d)	0.11	0.07	0.11
Outflow (t/d)	0.06	0.02	0.02

14.10.7 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.

14.10.8 Primary production

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 the Annex to Chapter 14. The reaction coefficients are given in Table 14-15. The half saturation nutrient concentrations permitting 50% of maximum productivity were as follows:-

Nitrate	0.1 mg/l
Phosphorous	0.014 mg/l

The light intensity for maximum productivity was 17 cal/cm^2/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.

Table 14-16 Reaction constants

BOD: rate const., t coeff., rate of decay	0.23	4.7	0.2
Fast Org N: rate const., t coeff., rate of decay	0.23	4.7	0.2
Nitrification AM: rate const., t coeff	0.26	4.7	
De-nitr. Of ox.nitrogen: rate const., t coeff	0.0	4.7	
Oxygen exchange coeff (m/hr)	0.037		
Reaeration coeff. and rate	1.6	0.5	
Nitrate: Half-sat.n constant, N-Carbon phytopl. ratio	0.1	0.16	
Phosphate: Half-sat.n constant, P-Carbon ratio	0.014	0.024	
Silica: Half-sat.n constant, SI-Carbon ratio	0.00	0.00	
Gradient & Intercept parameters for max production	0.037	-1.564	
Light intensity for max productivity (cal/cm^2/hr)	17.0		
Max respiration rate (gC/day), respirat.n param	0.02	2.2	
Light extinction coeffs : phytopl. & detritus	1.7	0.85	
Mortality of phytoplankton	0.35		
Detritus: Decay rate, temp. Coeff of decay	0.046	4.7	
Settling velocity of phytoplankton & detritus (mm/sec)	0.001	0.1	

14.10.9 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 were insufficient data to do a complete thermal balance, which also 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.

14.10.10 Wind effects

The observed wind speeds at the Kindaruma Fisheries Station average 65 miles/day through the year, which is only 1.2 m/sec, and would hardly effect the reservoir. However, values in excess of about 5 m/sec 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.

14.10.11 Local pollution

The reported problems of high bacterial counts preventing the local population from using the Tana reservoirs for drinking purposes is most likely to be related to local (i.e. upstream) urban pollution settling in poorly flushed bays within the reservoirs.

14.10.12 Comparison with phase 2 predictions

Following these more detailed studies, it is useful to examine the conclusions of the present modelling study and compare these with predictions made by Phase 2 studies.

Phase 2 Conclusions	Phase 3 Conclusions
These studies expected the nitrate and phosphate concentrations to be medium to high, and the chlorophyl-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 0.3-1.5 m.	The conclusions of the present modelling study are 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- 4 m deep photoc zone are likely to be below 0.01 ppm and will limit the algal biomass (chlorophyl-a) in much of the downstream parts of the reservoirs in calm conditions to between 5-15 mg/m^3. Suspended solids concentrations will be considerably lower in the surface than in the bed layers. The dissolved oxygen (DO) sag at depth is likely to deepen with time but to remain aerobic.

14.11 FURTHER INFORMATION REQUIREMENTS

The predictions of the model are sensitive to the factors affecting the growth of the specific species of algae in the Tana River reservoirs. These data are not currently available but could be obtained through new research commissioned to examine environmental and physical parameters controlling growth and population dynamics of algae in the existing Tana River reservoirs. There is also a lack of knowledge of the rates of recycling of nitrogen from silted mud and detrital matter. The coefficients used should be treated and verified by simulating conditions in the existing reservoirs, especially Kiambere.

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 to 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. These studies will need to be coupled to detailed measurements of discharge and sediment loads, concentrating especially on the fine sediments within the Mutonga and Kathita Rivers, and a land use based analysis within these catchments facilitating the application of the universal soil loss equation (or similar approach). Finally, 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 3-D model.