1 Meteorology / Hydrology

1.1 Objectives

One of the principal objectives of the WQ Components is to find the reasons for the changes observed in the lake water quality and ecosystem, and identify remedial measures. To identify the reasons for the changes requires also a knowledge of the changes in the pollution loadings to the lake, which, in turn, depends on the discharges to the lake from the catchment and the atmosphere.

Accordingly, the objective of the meteorology / hydrology task is to develop an estimate of the total water balance for the lake over the past 50 years, ie. all discharges to and from the lake, preferably on a daily basis:

- Rainfall onto, and evaporation from the lake surface.
- Discharges to the lake from all rivers and catchments around the lake.
- Discharge from the lake into the Victoria Nile.

1.2 Methods

The steps in the process of developing a water balance model for the lake are:

1. Generate continuous **rainfall** records for the period 1950-2000 for selected stations in the catchment and on islands on the basis of measurements, correlations to adjacent stations and insertion of "typical years".

2. Generate continuous **evaporation** records for the period 1950-2000 for selected stations in the catchment and on islands on the basis of measurements, correlations to adjacent stations and insertion of "typical years".

3. Calculate **discharges** in rivers on the basis of rating curves and measured gauge heights.

4. Perform **rainfall-runoff modelling** to extend the river discharge record to the period 1950-2000.

5. Calculate the **final discharges** for each individual river catchment or basin.

6 Calculate the **water mass balance** for the lake as the sum of all inflows and outflows.

Each of the steps is described in more detail in the following sections.

1.2.1 Rainfall

Selection of rainfall stations

In general, there are a large number of rainfall stations in the Lake Victoria catchment, more than is necessary for the present purposes. One of the first important tasks was accordingly the selection of a limited number of representative rainfall stations for each individual river catchment or basin. The stations should be representative in the sense that they should cover the entire geographical area as well as being placed in each sub-area with different rainfall characteristics, eg high altitude areas with high rainfall and low plains with low rainfall. The number of stations per catchment is generally 2 to 6, depending on the area and the rainfall characteristics.

QC of rainfall data

The rainfall measurements are then subjected to various quality control checks to identify erroneous data. The QC methods could be:

- Visual examination of raw and plotted data.
- Calculate statistical properties (means, running means, max, min, standard deviation etc)
- Comparison with data at adjacent stations.
- Calculate accumulated mass curve to identify changes in measurement technique and changes in instrument location.

Gap filling by correlation

For each river catchment, one or more reference stations are chosen. These are normally the stations with the longest, continuous, high quality record in the area. A "double mass" curve is evaluated for the subject station and the reference station, and a trend line fitted to the curve. The equation of the trend line is used to fill as many gaps as possible in the subject station record. The process is illustrated in Figure 1.1.

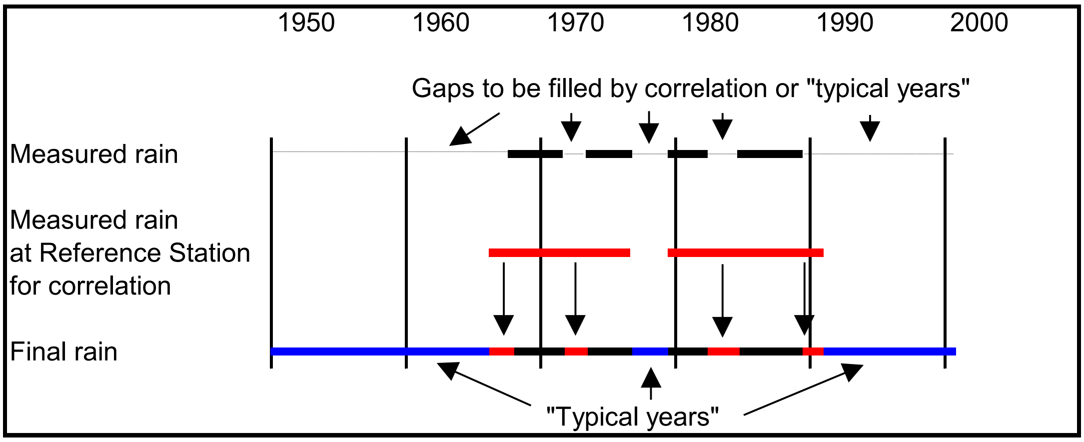

Figure 1.1 Procedure for filling gaps in rainfall records.

Gap filling with "typical years"

The remaining gaps in the rainfall record can only be filled by artificial means. In the present project a very successful method was developed for the choice and use of "typical rainfall years". The basic idea is to fill the gaps with "wet", "average" and "dry" years. The wet, average and dry years were chosen by examining the record of water levels of the lake at Entebbe. In a wet year, the rainfall over the lake and discharges from the rivers will exceed the losses by evaporation and discharge to the Nile, and the lake level will rise. (It could also rise if the outflow to the Nile was reduced, but the outflow is strictly regulated and such a situation does not occur.)

"Wet year":	Lake level rises by more than 0.2 m approx.
"Average year":	Lake level changes by less than ± 0.2 m approx.
"Dry year":	Lake level falls by more than 0.2 m approx.

Note that the hydrological year, 1 October to 30 September is used and not the calendar year. Further, it proved to be necessary to introduce some special cases for extreme rainfall events, both wet and dry. See Table 1.1.

The definition of wet, dry and average years is illustrated in Figure 1.2 and the listed in Table 1.1.

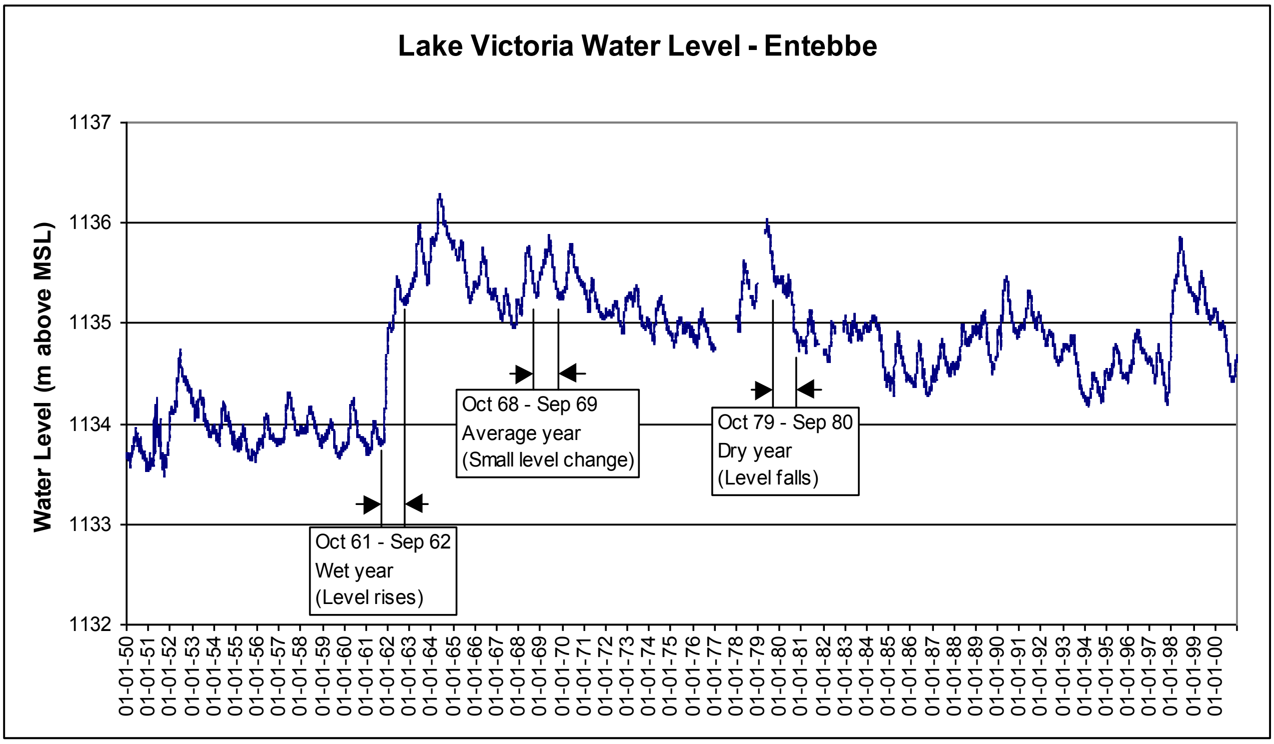

Figure 1.2 Definition of wet, average and dry years.

Hydrological Year (1 Oct - 30 Sept)	"Typical Year"	Hydrological Year (1 Oct - 30 Sept)	"Typical Year"	Hydrological Year (1 Oct - 30 Sept)	"Typical Year"
1949 - 1950	Average	1969 - 1970	Average	1989 - 1990	Wet
1950 - 1951	Average	1970 - 1971	Average	1990 - 1991	Average
1951 - 1952	Wet	1971 - 1972	Average	1991 - 1992	Dry
1952 - 1953	Dry	1972 - 1973	Average	1992 - 1993	Dry
1953 - 1954	Average	1973 - 1974	Average	1993 - 1994	Average
1954 - 1955	Average	1974 - 1975	Average	1994 - 1995	Average
1955 - 1956	Dry	1975 - 1976	Average	1995 - 1996	Average
1956 - 1957	Average	1976 - 1977	Wet	1996 - 1997	Dry
1957 - 1958	Average	1977 - 1978	Wet	1997 - 1998	Wet
1958 - 1959	Dry	1978 - 1979	Wet	1998 - 1999	Dry
1959 - 1960	Average	1979 - 1980	Dry	1999 - 2000	Dry
1960 - 1961	Average	1980 - 1981	Dry	2000 2001	Dry
1961 - 1962	Wet	1981 - 1982	Wet	Special Cases:	
1962 - 1963	Wet	1982 - 1983	Average		
1963 - 1964	Wet	1983 - 1984	Dry	Oct 61-Dec 61:	
1964 - 1965	Dry	1984 - 1985	Average	Use wettest Oct-Dec recorded	
1965 - 1966	Average	1985 - 1986	Average		
1966 - 1967	Dry	1986 - 1987	Average	May 89-Oct 89 & May 97-Oct 97:	
1967 - 1968	Wet	1987 - 1988	Wet	Use driest May-Oct recorded	
1968 - 1969	Average	1988 - 1989	Dry		

Table 1.1 List of wet, average and dry years.

The next step is to examine the measured rainfall record at the subject station and choose the "typical years" for that station:

"Wet year": Hydrological year with maximum total rainfall.
"Average year": Hydrological year with total rainfall closest to annual mean.
"Dry year": Hydrological year with minimum total rainfall.

Finally these typical years are inserted in the remaining gaps to give a complete record for the period 1950 to 2000, inclusive. See Figure 1.1.

1.2.2 Evaporation

The method for the development of a continuous evaporation record is in principle exactly the same as that for the rainfall. In practice there are some differences caused by:

1. There are fewer evaporation stations because it is only recorded at full meteorological stations.

2. The use of correlation to an adjacent station is frequently not relevant because the stations are so far apart.

3. There is no well defined method of choosing evaporation for wet, average and dry years, so the daily (or monthly) mean evaporation is used to fill gaps in the record, ie the mean of all measurements on 1 Jan are used to fill all 1 Jan gaps, etc.

1.2.3 River Discharges

In this step the objective is to generate the measured river discharges on the basis of the rating curve and the measured daily gauge heights (river water levels).

Choice of gauging station

Each river basin in the Lake Victoria catchment has several gauging stations placed at various locations on the main stream, near the confluence of major tributaries and near the river mouth. Since the main interest in the project is the discharge of water to the lake, it is natural to concentrate on the stations nearest the mouth.

In the next phase of LVEMP it would be of interest to compute the discharges from the various sub-catchments of each river to determine the distribution of the water and pollution loads. This could identify specific areas where remedial action is required.

QC of rating curve data

The rating curve data at each gauging station (measurements of level and flow) should be quality controlled to remove outliers and erroneous data. Since the number of data is generally small, visual examination of a flow-level (Q-h) plot is sufficient.

Develop rating curves

The rating curve for each chosen gauging station is developed on the basis of the measurements of level and flow (m^3/s) at the station. The standard power formula is used in all three countries:

$$Q = k\,(h_0 - h)^x$$

where Q = river discharge (m^3/s)
k = coefficient
h_0 = gauge height of zero flow (m)
h = gauge height (m)
x = exponent

The values of k, h_0 and x are chosen to give the rating curve which best fits the measured values of Q and h. The best fit is chosen by minimising the value of

$$\Sigma\,(Q_{\text{rating curve}} - Q_{\text{observed}})^2$$

Compute discharges

The river discharges are computed by application of the rating curve equation to the daily measurements of gauge height. Gaps in the record will be subsequently filled by rainfall-runoff modelling. The procedure is illustrated in Figure 1.3.

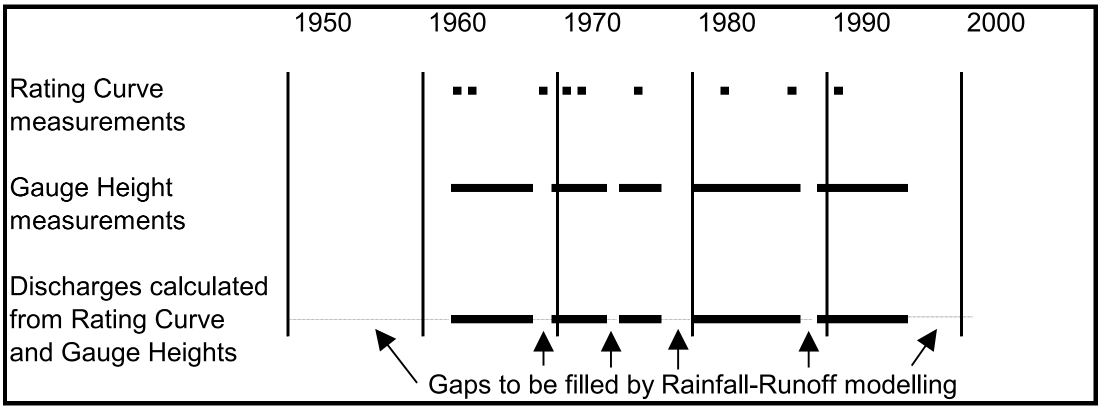

Figure 1.3 Procedure for computation of river discharges

1.2.4 Rainfall-Runoff Modelling

Rainfall-runoff modelling is applied to fill the gaps in the river discharge measurements. It is also used to estimate the runoff from ungauged catchments. Three different models were considered for use in the study and are described below.

Rainfall-runoff models

Sacremento Model

The Sacremento Model is used in the Lake Victoria Decision Support System (Georgagakakos et al, 2000), and is further described in Singh, 1995. Initially it seemed logical to use the model for the all the rainfall-runoff modelling, particularly because two LVEMP staff from each country had been trained for 6 months in the use of the system. However, after setting it up for one catchment (Katonga), its further use was abandoned due to a number of difficulties:

- The Kenyan staff who were trained in the use of the model were not available.
- The Tanzanian rainfall data was monthly whereas the Sacremento requires daily data.
- It proved to be difficult and time consuming to reformat the enormous quantities of data for use as input to the model.
- It was not user friendly.
- The NAM model is more user friendly, easier to input data, easier to calibrate, and, even although theoretically simpler, gave equally good results.

NAM Model

The NAM model originates from the Danish Technical University and was made available to the project by the Consultant. NAM is an abbreviation of the Danish name, "Nedboer-Afstroemning Model", which, translated, simply means Rainfall-Runoff Model.

NAM is, like the Sacremento model, classified as a Conceptual Model with the following characteristics:

- Lumped (the entire catchment is considered as a single unit with uniform properties).
- The flow of water through the system is conceptualised into a number of reservoirs.
- The parameters partly reflect the physical properties of the catchment.

Although some users claim that Conceptual Models can be used to simulate changes in the catchment properties (eg deforestation) the clear recommendation is not to use them for this purpose. Deterministic, distributed models should be used for such studies.

The structure of NAM is illustrated in Figure 1.4.

A Users Guide was provided with the model.

SMAP Model
The SMAP model is also a Conceptual Model, but simpler in structure than Sacremento and NAM because it has fewer reservoirs. It is best suited to use with monthly rainfall data and was therefore chosen for use on the Tanzanian catchments. The model and the Users Guide were provided by the Consultant for use in the project.

In the next phase of LVEMP it would be advisable to obtain the daily rainfall data in Tanzania and to calibrate and apply NAM models for all the catchments.

The structure of SMAP is illustrated in Figure 1.5.

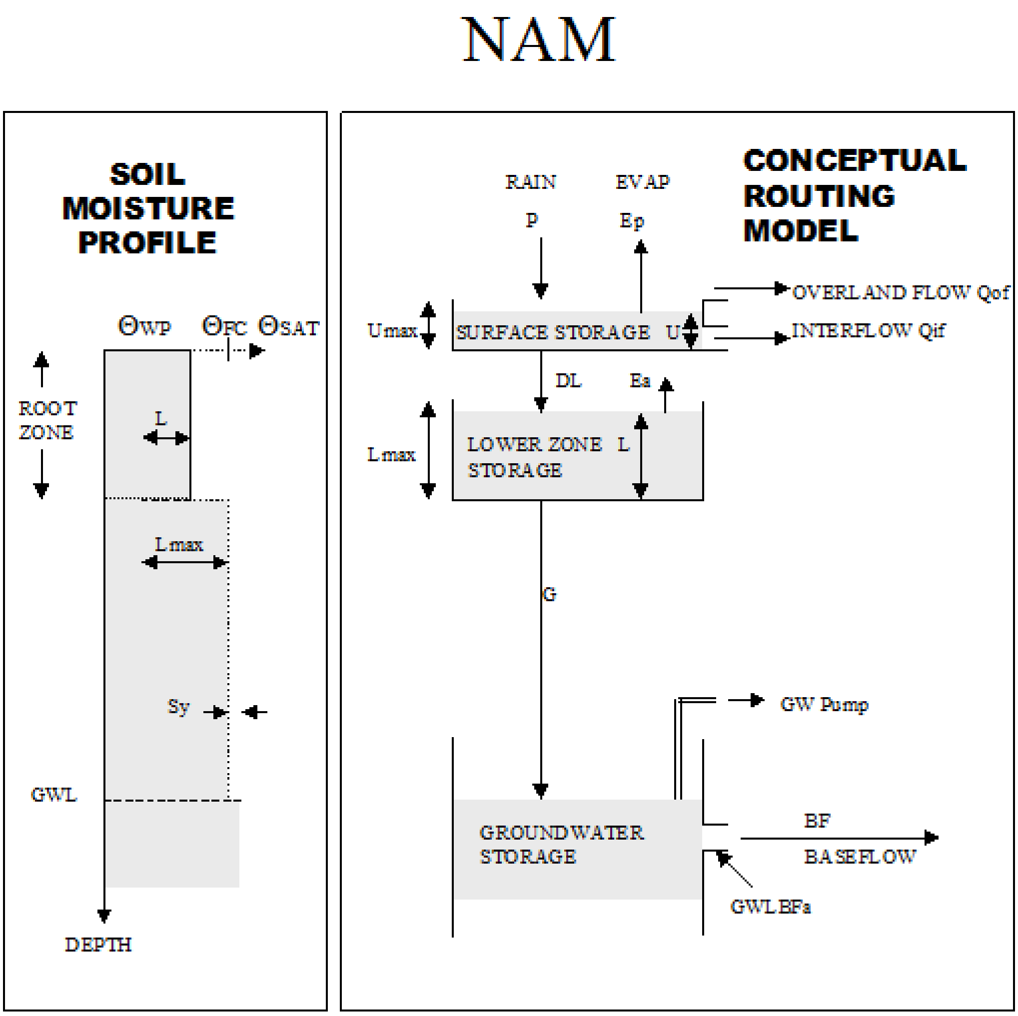

Figure 1.4 The structure of NAM.

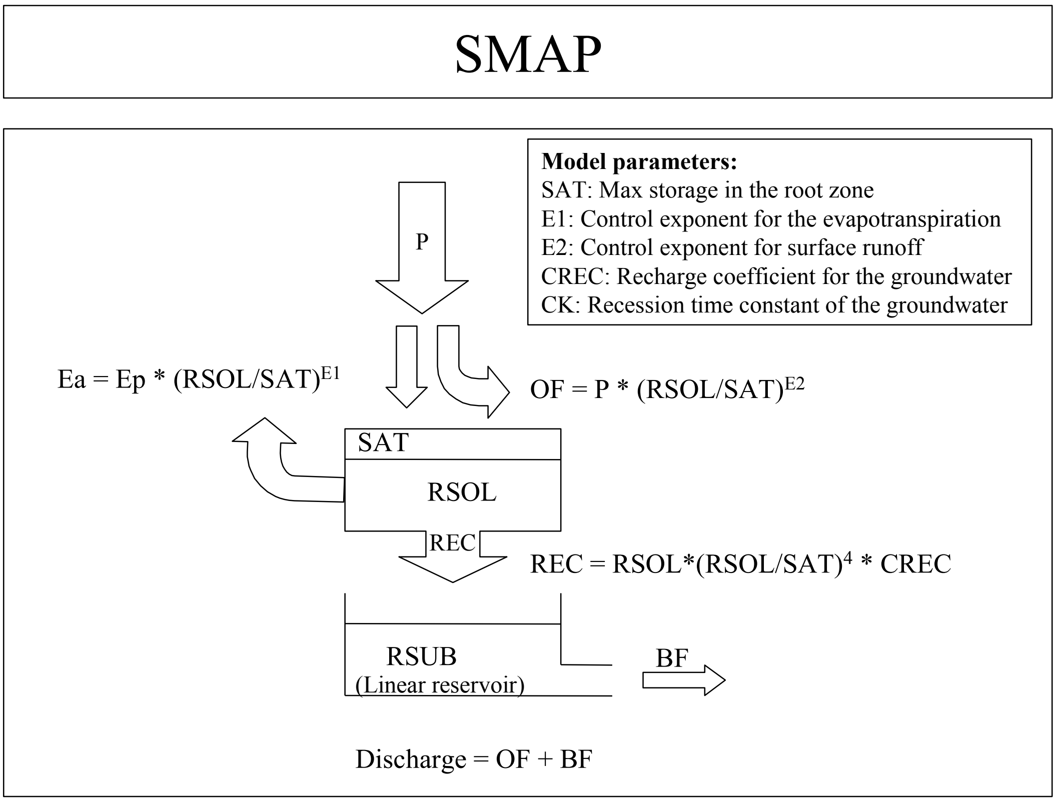

Figure 1.5 The structure of SMAP.

Model calibration

The rainfall-runoff models are calibrated on a period when there is simultaneous measured data for rainfall, evaporation and river discharges. The period should be at least 4 years long. Figure 1.6 illustrates the selection procedure for a catchment with two rainfall stations and one evaporation station.

The model parameters are adjusted by trial-and-error until the best fit is obtained between the modelled and measured:

- Accumulated runoff from the catchment.
- Peak flows.
- Recession curves.
- Low flows.

For the present project it is important that the accumulated runoff from the catchments is correct since this is the most important factor in the mass balance for the lake. The correct reproduction of the peak flows is important in flood studies, which is not the emphasis of the WQ Components.

Examples of the calibration of the models are given later in this chapter.

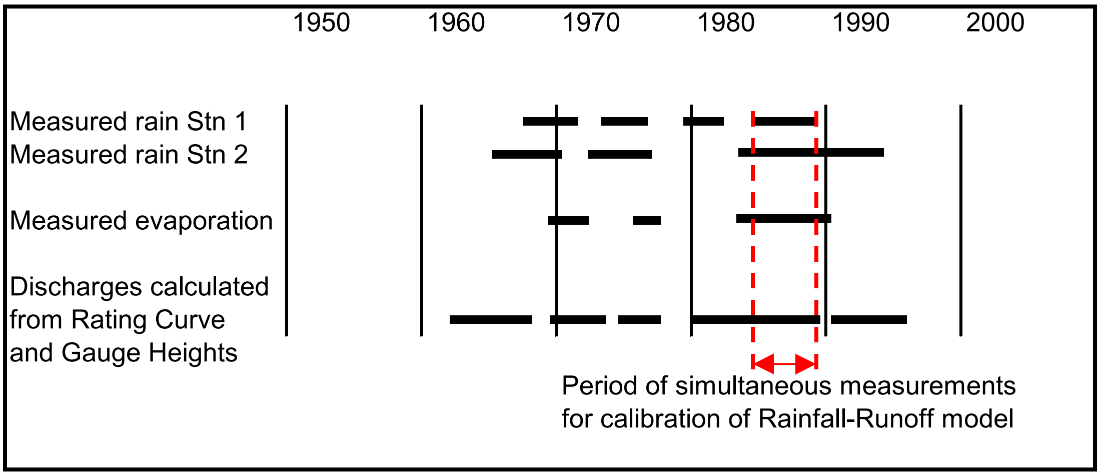

Figure 1.6 *Selection of calibration period for the rainfall-runoff models.*

Model application

The next step is to apply the calibrated model to compute the runoff at the gauging station for the full period 1950 - 2000. The application uses the final rainfall and evaporation which was generated for the full period (Figure 1.1). See Figure 1.7.

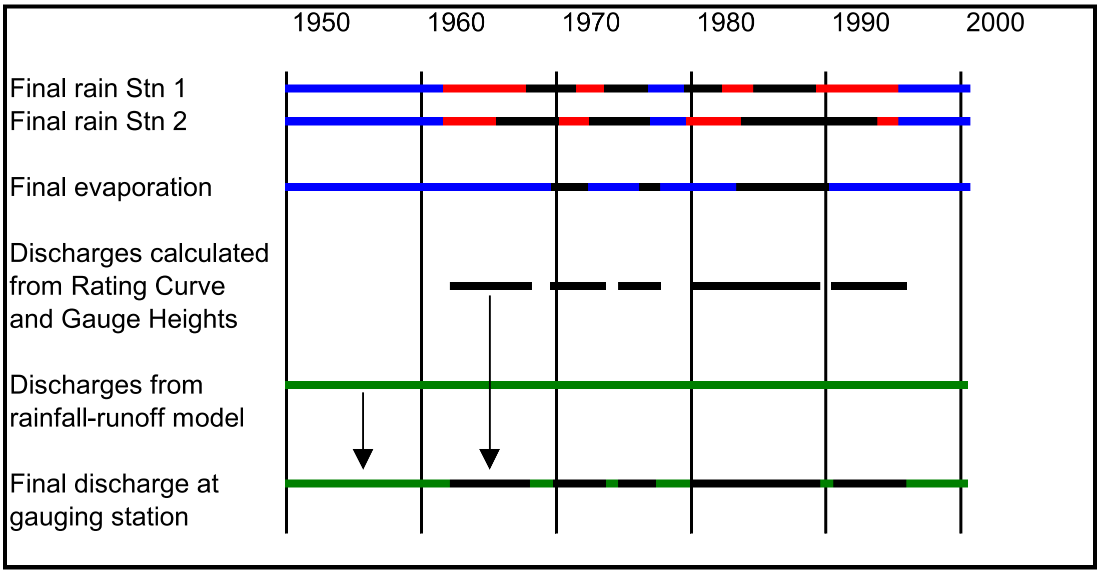

Figure 1.7 *Application of rainfall-runoff model to obtain final discharges at gauging station.*

Ungauged catchments

There are a number of ungauged catchments and basins around the lake where other methods are required to estimate the runoff. Most of the areas are composite basins consisting of a number of small rivers and wetlands along the lake shore. Some of the small rivers may have been gauged, but the data was generally insufficient, too inaccurate, or not representative of the whole basin area. Two methods were used to estimate the runoff in these basins:

1. One of the rainfall-runoff models was applied, using parameter values from an adjacent, similar catchment.

2. A simple empirical model that is a modified form of the Rational Formula was applied. The details are given later in this chapter.

1.2.5 Final River Basin Discharges

The previous section described the method of computing the discharges at the gauging station for the full period 1950-2000. However, the gauging station is mostly not exactly at the mouth of the river where it enters Lake Victoria, but somewhat upstream. For example, the gauging station used on the Mara River is at Mara Mines, approximately 100 km from the mouth. The catchment area upstream of Mara Mines is 10300 km^2, whereas the total area of the Mara River basin is 13393 km^2.

Consequently, the discharges at the gauging station must be increased to represent the total discharge from the river basin to the lake. The most common methods are:

1. Increase the gauging station discharges in proportion to the areas, ie

   Basin discharge = Gauging stn discharge * (basin area / gauging stn area)

2. Apply the rainfall-runoff model to the entire basin area using the same model parameter values as calibrated at the gauging station.

The first method is preferred since it uses the measured discharges at the gauging station in a more direct way. However, the choice may depend on the specific case. For example, if additional rainfall stations are needed to cover the full river basin, then the second method must be used.

1.2.6 Water Mass Balance

The final step is to sum all the inflows to, and outflows from Lake Victoria to generate the water mass balance for 1950-2000.

Inflows: Discharges from rivers.
Rainfall over the lake.

Outflows: Evaporation from the lake.
Discharge to the Victoria Nile.

The rainfall and evaporation are evaluated as a weighted sum of the records at stations around the lake and on islands in the lake. The actual weighting method is described in detail later in this chapter.

The summation is expressed as the daily/monthly change in water level in the lake and is compared with the recorded water levels (at Entebbe).

1.3 Definition of River Basins

The division of the Lake Victoria catchment into river basins is shown in Figure 1.8.

All the larger rivers are defined with their own basins, whereas the smaller catchments along the lake shores have been combined into four inhomogeneous areas.

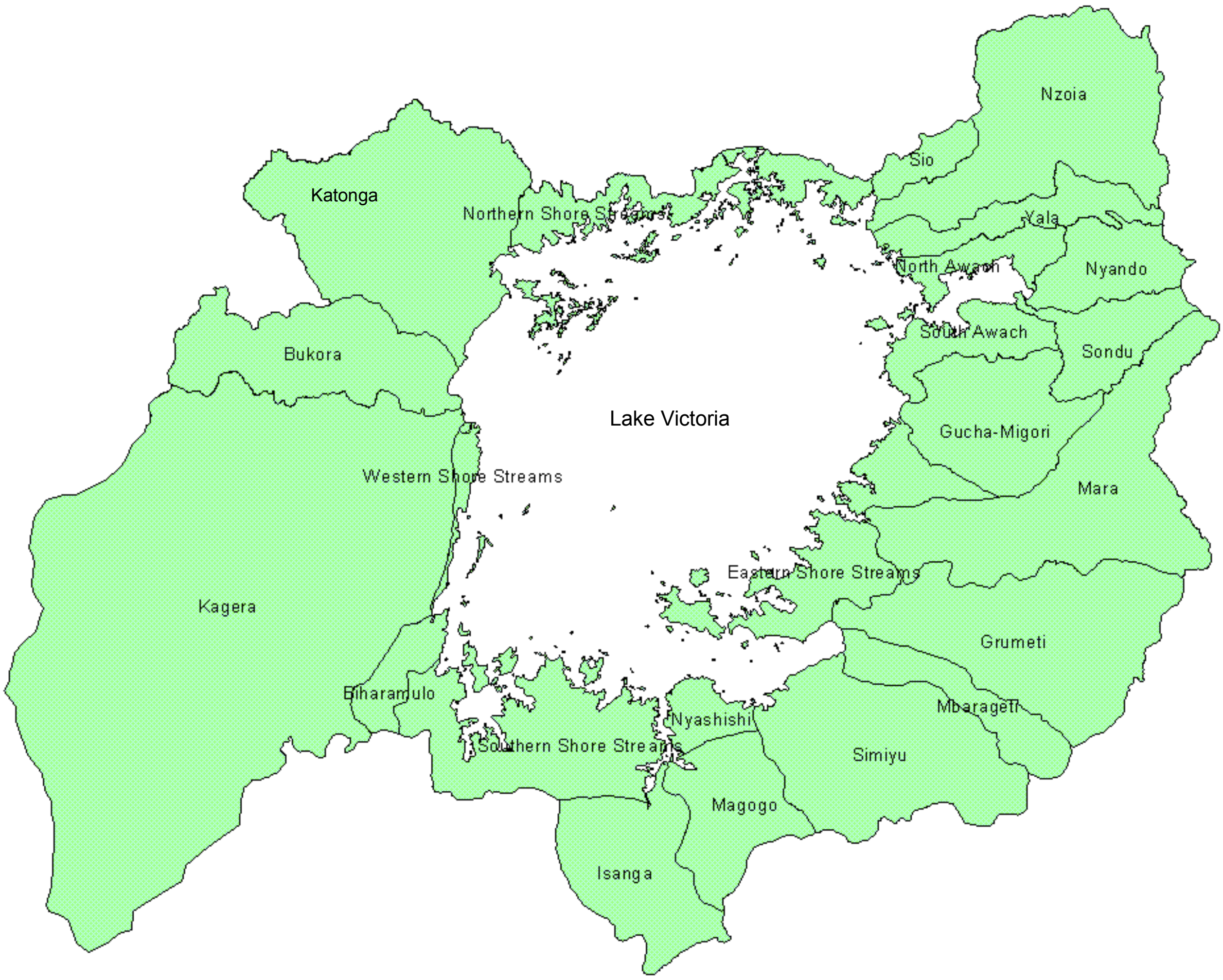

Figure 1.8 River Basins in the Lake Victoria Catchment

Country	Basin Name	Comments
Kenya/Uganda	Sio River	
Kenya	Nzoia River	
Kenya	Yala River	
Kenya	Nyando River	
Kenya	North Awach	Small streams on northern side of Winam Gulf. Includes Kibos River. Mostly ungauged.
Kenya	South Awach	Small streams on southern side of Winam Gulf. Includes Tende and Kibuon Rivers. Mostly ungauged.
Kenya	Sondu River	
Kenya	Gucha-Migori Rivers	
Kenya/Tanzania	Mara River	
Tanzania	Grumeti River	
Tanzania	Mbalageti River	
Tanzania	Eastern Shore Streams	Small streams on eastern side of Lake Victoria. Includes Mori and Suguti Riv-ers and Ukerewe Is. Mostly ungauged.
Tanzania	Simiyu River	
Tanzania	Magogo-Moame Rivers	
Tanzania	Nyashishi	Small streams east of Mwanza Gulf. Ungauged.
Tanzania	Issanga River	Ungauged catchment.
Tanzania	Southern Shore Streams	Small streams west of Mwanza Gulf. Ungauged.
Tanzania	Biharamulo River	Ungauged catchment.
Tanzania/Uganda	Kagera River	Includes Ngono River.
Tanzania	Western Shore Streams	Small streams between Ngono R and the lake. Ungauged.
Uganda	Bukora River	
Uganda	Katonga River	Includes Kisoma R. and Sango Bay area.
Uganda	Northern Shore Streams	Small streams along northern lake shore. Ungauged.

Table 1.2 River Basins in the Lake Victoria Catchment.

1.4 Rainfall

Examples of the preparation and analysis of the rainfall data are given in this section.

1.4.1 Rainfall Stations

The selected rainfall stations for each of the river basin and the lake are shown in Table 1.3 and the locations shown in Figure 1.9.

KENYA River Basin	Station Number	Station Name	Rain/Evap	Data (with gaps)	Reference Stn for correlation
Sio	8934161	Alupe Met Stn	R	Dec 74 - Nov 00	Kadenge
	8934134	Bungoma Water Supply	R	Jul 62 - Dec 00	Elgon Downs
	8934161	Alupe Met Stn	E	Feb 81 - Sep 90	not used
	8934134	Bungoma Water Supply	E	Jan 70 - Dec 90	not used
Nzoia	8934134	Bungoma Water Supply	R	Jul 62 - Dec 00	Elgon Downs
	8935133	Eldoret Exp Farm	R	Jan 57 - Dec 00	Elgon, Bungoma
	8834098	Kitale Met Stn	R	Jan 79 - Dec 00	Elgon Downs
	8934140	Kadenge	R	Sep 68 - Nov 00	Bungoma
	8834009	Elgon Downs	R	Jan 50 - Jun 96	not used
	8934134	Bungoma Water Supply	E	Jan 70 - Dec 90	not used
	8935133	Eldoret Exp Farm	E	Jan 71 - Dec 90	not used
	8934140	Kadenge	E	Jan 71 - Dec 90	not used
Yala	8935133	Eldoret Exp Farm	R	Jan 57 - Dec 00	Elgon, Bungoma
	8934140	Kadenge	R	Sep 68 - Nov 00	Bungoma
	9034011	Maseno Vet	R	Mar 59 - Dec 00	not used
	8935133	Eldoret Exp Farm	E	Jan 71 - Dec 90	not used
	8934140	Kadenge	E	Jan 71 - Dec 90	not used
Nyando	9035230	Koru Exp Stn	R	Mar 59 - Nov 00	Kericho Timbilil
	9034086	Kano Irr Stn - Ahero	R	Jan 67 - Dec 00	Kisumu Met
	9035244	Kericho Timbilil	R	Nov 63 - Mar 97	Koru, Sotik
	9035263	Tinderet Tea Estate	R	Jan 70 - Dec 90	Kericho Timbilil
	9034025	Kisumu Airport	E	Jan 70 - Aug 90	not used
	9035263	Tinderet Tea Estate	E	Jan 70 - Dec 90	Kericho Timbilil
	9035230	Koru Exp Stn	E	Jan 70 - Feb 86	Kano Irr Stn
North Awach	9034025	Kisumu Airport Met	R	Mar 59 - Dec 90	Kano Irr Stn
	8934140	Kadenge	R	Sep 68 - Nov 00	Bungoma
	9034011	Maseno Vet	R	Mar 59 - Dec 00	not used
	9034103	Rusinga Is.	R	Jan 68 - Jan 96	Homa Bay
	9034025	Kisumu Airport	E	Jan 70 - Aug 90	not used
	8934140	Kadenge	E	Jan 71 - Dec 90	not used
South Awach	9034103	Rusinga Is	R	Jan 68 - Jan 96	Homa Bay
	9034084	Homa Bay	R	Aug 61 - Dec 00	Muhuru Bay
	9034023	Oyugis	R	May 62 - Dec 00	Kisii W/S
	9034018	Gendie	R	Jan 75 - Aug 94	Kano Irr Stn
	9034103	Rusinga Is	E	Jan 70 - Dec 89	not used
Sondu	9035244	Kericho Timbilil	R	Nov 63 - Mar 97	Koru, Sotik
	9035013	Sotik Monieri	R	Jan 50 - Dec 00	Sotik W/S
	9034086	Kano Irr Stn - Ahero	R	Jan 67 - Dec 00	Kisumu Met
	9035244	Kericho Timbilil	E	Jan 70 - Dec 90	Tinderet
	9034086	Kano Irr Stn - Ahero	E	Jan 70 - Dec 90	Koru Exp Stn
Gucha-Migori	9134025	Migori Water Supply	R	Mar 59 - Sep 00	Muhoro Bay
	9134009	Muhuru Bay	R	Feb 59 - Mar 97	Homa Bay
	9034092	Kisii Water Supply	R	Jun 58 - Dec 00	Sotik Monieri
	9134009	Muhuru Bay	E	Jan 70 - Dec 90	not used
	9034080	Kisii Water Supply	E	Jan 70 - Dec 90	not used

Table 1.3 Rainfall and Evaporation Stations in the River Basins.

TANZANIA River Basin	Station Number	Station Name	Rain/Evap	Data (with gaps)	Reference Stn for correlation
Mara	9035067	Keringet Tea Estate (KE)	R	Jan 70 - Dec 74	Kericho Timbilil
	9035265	Bomet (KE)	R	Jul 65 - Jul 96	Sotik Monieri
	9135013	Keekorok (KE)	R	Jan 65 - Jul 97	not used
	9134033	Mugumu	R	Nov 69 - Nov 00	Keekorok
	9133000	Musoma Airport	R	Jan 70 - Dec 97	Tarime Met
	9035244	Kericho Timbilil (KE)	E	Jan 70 - Dec 90	Tinderet
	9135013	Keekorok (KE)	E	Jan 70 - Dec 90	not used
	9133000	Musoma Airport	E	Oct 71 - Dec 97	not used
Grumeti	9234005	Seronera	R	Jan 70 - Dec 96	Maswa
	9134033	Mugumu	R	Nov 69 - Nov 00	Keekorok
	9234009	Issenyi	R	Nov 69 - Nov 89	Mugumu
	9135013	Keekorok	E	Jan 70 - Dec 90	not used
	9333005	Maswa Met	E	Jan 70 - Dec 93	not used
	9133000	Musoma Airport	E	Oct 71 - Dec 97	not used
Mbalageti	9234005	Seronera	R	Jan 70 - Dec 96	Maswa
	9233028	Mkula Dam	R	Jan 69 - Dec 85	Issenyi
	9135013	Keekorok	E	Jan 70 - Dec 90	not used
	9333005	Maswa Met Stn	E	Jan 70 - Dec 93	not used
E. Shore Streams	9134009	Muhuru Bay (KE)	R	Feb 59 - Mar 97	not used
	9134026	Tarime Met Stn	R	Jan 69 - Dec 97	Musoma Airp
	9133000	Musoma Airport	R	Jan 70 - Dec 97	Tarime Met
	9133013	Bwayi Pr School	R	Jan 77 - Jul 91	Musoma, Ukerewe
	9233028	Mkula Dam	R	Jan 69 - Dec 85	Issenyi
	9132002	Ukerewe Is. Met	R	Jan 70 - Dec 00	not used
	9134009	Muhuru Bay (KE)	E	Jan 70 - Dec 90	not used
	9134026	Tarime Met Stn	E	Jan 69 - May 91	not used
	9133000	Musoma Airport	E	Oct 71 - Dec 97	not used
	9132002	Ukerewe Is. Met	E	Mar 70 - Dec 00	not used
Simyu	9234000	Sagata	R	Feb 70 - Oct 89	Maswa
	9333005	Maswa Met Stn	R	Jan 69 - Dec 00	not used
	9233042	Igwata	R	Feb 71 - Dec 96	Maswa
	9333005	Maswa Met Stn	E	Jan 70 - Dec 93	not used
Magogo-Moame	9233001	Sumve T.T.C.	R	Jan 71 - Dec 00	Ngudu
	9233005	Ngudu Met Stn	R	Jan 69 - Dec 00	not used
	9233035	Mwanangwa	R	Jan 70 - Apr 00	Ngudu
	9333005	Maswa Met Stn	R	Jan 69 - Dec 00	not used
	9332011	Kharumwa Pr Sch	R	Jan 70 - Dec 00	Kahunda
	9333005	Maswa Met Stn	E	Jan 70 - Dec 93	not used
	9332011	Kharumwa Pr Sch	E	May 70 - Dec 76	Kahunda
Nyashishi	9232016	Mwanza Maji	R	Mar 69 - Dec 00	Mwanza Airp
	9232009	Mwanza Airport Met	R	Jan 69 - Oct 97	Mwanza Maji
	9233031	Nyanguge	R	Oct 69 - Dec 00	Maswa
	9232009	Mwanza Airport Met	E	Jan 70 - Aug 97	Ukerewe, Kahunda
Issanga	9332011	Kharumwa Pr Sch	R	Jan 70 - Dec 00	Kahunda
	9332011	Kharumwa Pr Sch	E	May 70 - Dec 76	Kahunda
S. Shore Streams	9232009	Mwanza Maji	R	Mar 69 - Dec 00	Mwanza Airp
	9232028	Nyehunge	R	Apr 70 - Dec 00	Maswa
	9232027	Kahunda Met Stn	R	Mar 70 - Dec 00	not used
	9231011	Biharamulo Met Stn	R	Jan 70 - Dec 91	Kahunda Met
	9232009	Mwanza Airport Met	E	Jan 70 - Aug 97	Ukerewe, Kahunda
	9232027	Kahunda Met Stn	E	Nov 70 - Dec 00	not used
	9231011	Biharamulo Met Stn	E	Jan 73 - Dec 80	Kahunda Met
Biharamulo	9231011	Biharamulo Met Stn	R	Jan 70 - Dec 91	Kahunda Met
	9131040	Biija	R	Jan 71 - Jun 91	Kishanda, Bukoba
	9231011	Biharamulo Met Stn	E	Jan 73 - Dec 80	Kahunda Met
Ngono	9131056	Kyaka Ferry (Met)	R	Apr 69 - Dec 95	4 stations
	9131048	Izigo Trading Centre	R	Jan 71 - Aug 90	Bukoba
	9131029	Kishanda Met	R	Jan 70 - Dec 90	Biija, Bukoba
	9131040	Biija	R	Jan 71 - Jun 91	Kishanda, Bukoba
	9131029	Kishanda Met	E	Jan 70 - Dec 90	not used
Western Shore Streams	9131002	Bukoba Met	R	Jan 50 - Dec 96	not used
	9131030	Rubafu	R	Jan 70 - Oct 84	Bukoba
	9131002	Bukoba Met	E	Jan 73 - Dec 97	not used
Kagera	9131032	Nyakanyasi	R	Apr 69 - Dec 97	Kayanga, Kyaka
	9131028	Kayanga Met	R	Jan 70 - Dec 96	Kyaka, Bija, Nyakanyasi
	9131040	Biija	R	Jan 71 - Jun 91	Kishanda, Bukoba
	9129519	Ruhengeri	R	Jan 76 - Oct 89	Kayanga
	9230504	Kibungu	R	Jan 76 - May 89	Rulenge
	9231011	Biharamulo Met Stn	R	Jan 70 - Dec 91	Kahunda Met
	9230011	Rulenge Met	R	Jan 71 - Dec 97	Biharamulo
	9329508	Fota	R	Jan 76 - Jun 81	Rulenge
	9131056	Kyaka Ferry, Kyakakera	E	Jan 74 - Dec 81	not used
	9131028	Kayanga Met	E	Jan 70 - Dec 96	not used
	9129519	Ruhengeri	E	Jan 76 - Dec 88	not used
	9230011	Rulenge Met	E	Jan 71 - Dec 96	not used

UGANDA River Basin	Station No.	Station	Rain/Evap	Data (with gaps)	Reference Stn for correlation
Bukora	9030014	Gayaza-Isingiro	R	Aug 50 - Jan 94	Kakuuto
	9031010	Kakuto	R	Jan 50 - Nov 76	Gayaza
	9031010	Kalisizo Gombolola	R	Jan 50 - Mar 73	Gayaza
	9031037	Kibanda DWD	R	Jun 65 - Oct 76	Gayaza
	9031043	Kaliro	R	Jan 73 - Dec 82	Gayaza
	9031037	Kibanda DWD	E	Jan 70 - Nov 74	not used
	8932075	Entebbe DWD	E	Jan 71 - Jan 98	not used
Katonga	8931012	Ntusi	R	Jan 50 - Jan 73	Nkozi Exp Farm
	9031005	Kako Tea Estate	R	Jan 50 - Oct 77	Nkozi Exp Farm
	9031007	Kalungu	R	Jan 50 - Oct 78	Nkozi Exp Farm
	9031010	Kalisizo Gombolola	R	Jan 50 - Mar 73	Gayaza
	9031015	Sembabule	R	Jan 50 - Aug 78	Nkozi Exp Farm
	9031023	St. Henry's Kitovu	R	Jan 50 - Oct 70	Nkozi Exp Farm
	9031034	Jubiya Forest Stn	R	Jun 64 - Apr 78	Nkozi Exp Farm
	9031036	Kako RFS	R	Jan 66 - Sep 79	Kako Tea Estate
	9031043	Kaliro	R	Jan 73 - Dec 82	Gayaza
	9032001	Nkozi Exp Farm	R	Jan 50 - Dec 78	Ntusi
				Aug 95 - Nov 98	
	9032003	Bukakata	R	Jan 50 - Jan 78	Nkozi Exp Farm
	8932075	Entebbe DWD	E	Jan 71 - Jan 98	not used
N. Shore Streams	9032001	Nkozi Exp Farm	R	Jan 50 - Dec 78	Ntusi
				Aug 95 - Nov 98	
	8932020	Kampala Municipality	R	Jan 50 - Oct 93	Kampala City Hall
	8932066	Entebbe Airport	R	Jan 50 - Jul 00	Jinja Met
	8933043	Jinja Met	R	Jan 50 - Aug 00	Buvuma
	8932075	Entebbe DWD	E	Jan 71 - Jan 98	not used
LAKE VICTORIA	**Station No.**	**Station**	**Rain/Evap**	**Data (with gaps)**	**Reference Stn for correlation**
Lake shore and	9034025	Kisumu Airport Met	R	Mar 59 - Dec 90	Kano Irr Stn
Islands	9034103	Rusinga Is	R	Jan 68 - Jan 96	Homa Bay
	9134009	Muhuru Bay	R	Feb 59 - Mar 97	Homa Bay
	9034084	Homa Bay	R	Aug 61 - Dec 00	Muhuru Bay
	9133000	Musoma Airport	R	Jan 70 - Dec 97	Tarime Met
	9233028	Mkula Dam	R	Jan 69 - Dec 85	Issenyi
	9132002	Ukerewe Is. Met	R	Jan 70 - Dec 00	not used
	9232009	Mwanza Maji	R	Mar 69 - Dec 00	Mwanza Airport
	9232027	Kahunda Met Stn	R	Mar 70 - Dec 00	not used
	9133011	Bukerebe Is	R	Jan 70 - Nov 78	Bukoba, Ukerewe
	9131048	Izigo Trading Centre	R	Jan 71 - Aug 90	Bukoba
	9131002	Bukoba Met	R	Jan 50 - Dec 96	not used
	9131030	Rubafu	R	Jan 70 - Oct 84	Bukoba Met
	8933005	Buvuma Is	R	Jan 50 - Dec 98	Jinja Met
	9032000	Kalangala Saza	R	Jan 50 - Apr 77	Entebbe Airport
	9032002	Bumangi	R	Jan 50 - Dec 77	Entebbe Airport
	8932066	Entebbe Airport	R	Jan 50 - Jul 00	Jinja Met
	9034103	Rusinga Is	E	Jan 70 - Dec 89	not used
	9134009	Muhuru Bay	E	Jan 70 - Dec 90	not used
	9133000	Musoma Airport	E	Oct 71 - Dec 97	not used
	9132002	Ukerewe Is. Met	E	Mar 70 - Dec 00	not used
	9232027	Kahunda Met Stn	E	Nov 70 - Dec 00	not used
	9131002	Bukoba Met	E	Jan 73 - Dec 97	not used
	9032010	Bukasa Ssesse Is	E	Jan 70 - Dec 76	not used
	9032011	Koome Is	E	Jan 70 - Dec 76	not used
	8932075	Entebbe DWD	E	Jan 71 - Jan 98	not used

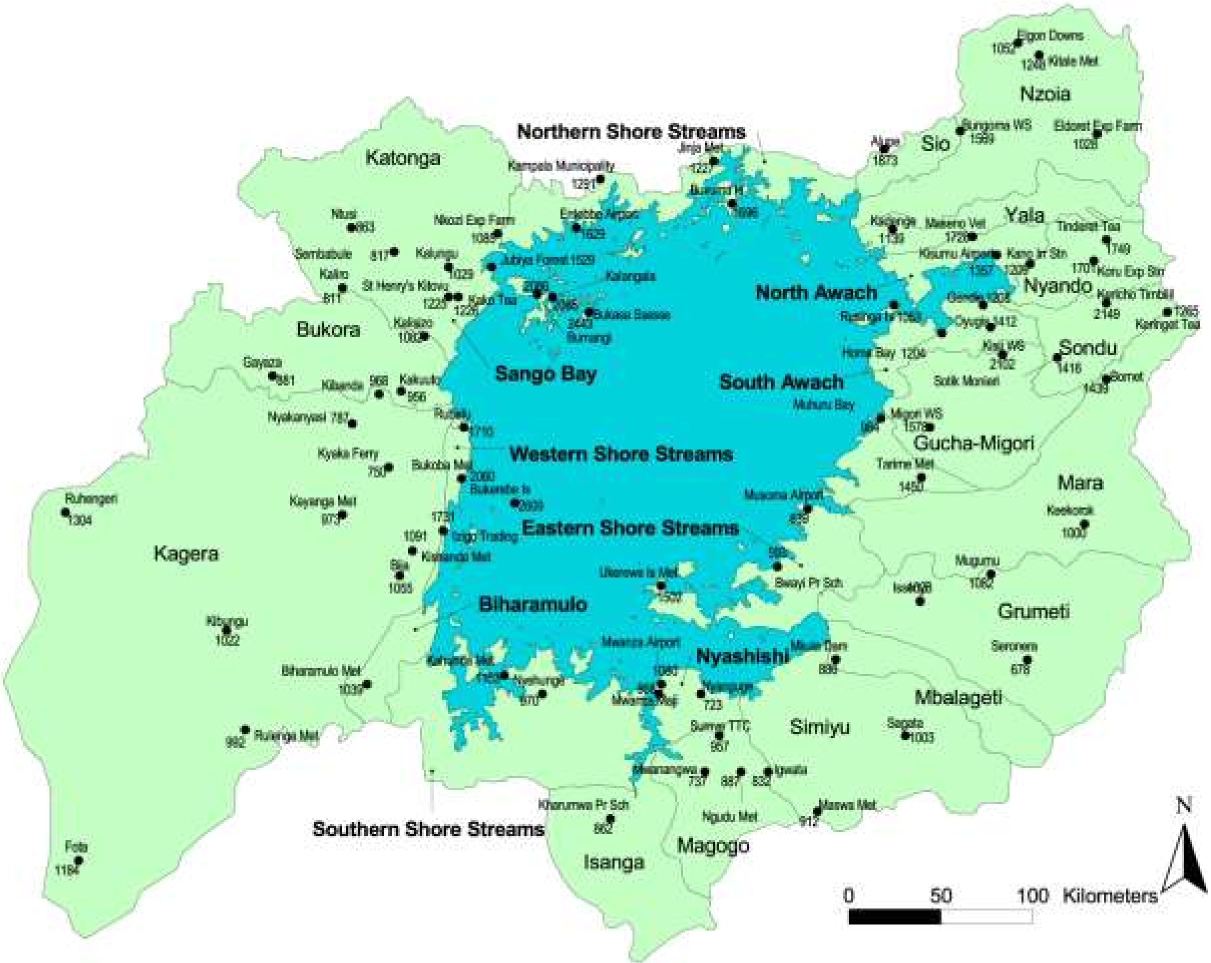

Figure 1.9 Locations of Rainfall Stations

The length of the record at each station is also shown in Table 1.3. However, it should be noted that there can be large gaps in the records, varying from one month to many years.

The sources of data are the Lake Victoria Basin Database, the Hydrology Departments of the Ministries responsible for water in each country and the Meteorology Departments in each country.

The number of stations at which records exist during 1950 - 2000 is shown in Figure 1.10. The figure shows clearly that the largest number of stations with observations occurs in the period 1970 to 1990, which was the period of the HYDROMET Project. In Kenya there were only two active stations before 1959, after which there was a gradual increase until 1970, and a gradual decrease after 1990 as the stations were progressively vandalised. In Tanzania there was only one active station before 1969, and again a gradual decrease in the numbers after 1990. In contrast, the Ugandan network of stations was active from 1950 until 1977-78 when it collapsed due to the Idi Amin war.

It is recommended the additional efforts should be made in Kenya and Tanzania to obtain data for the early years. Tanzania should also obtain the daily rainfall data that must be available somewhere.

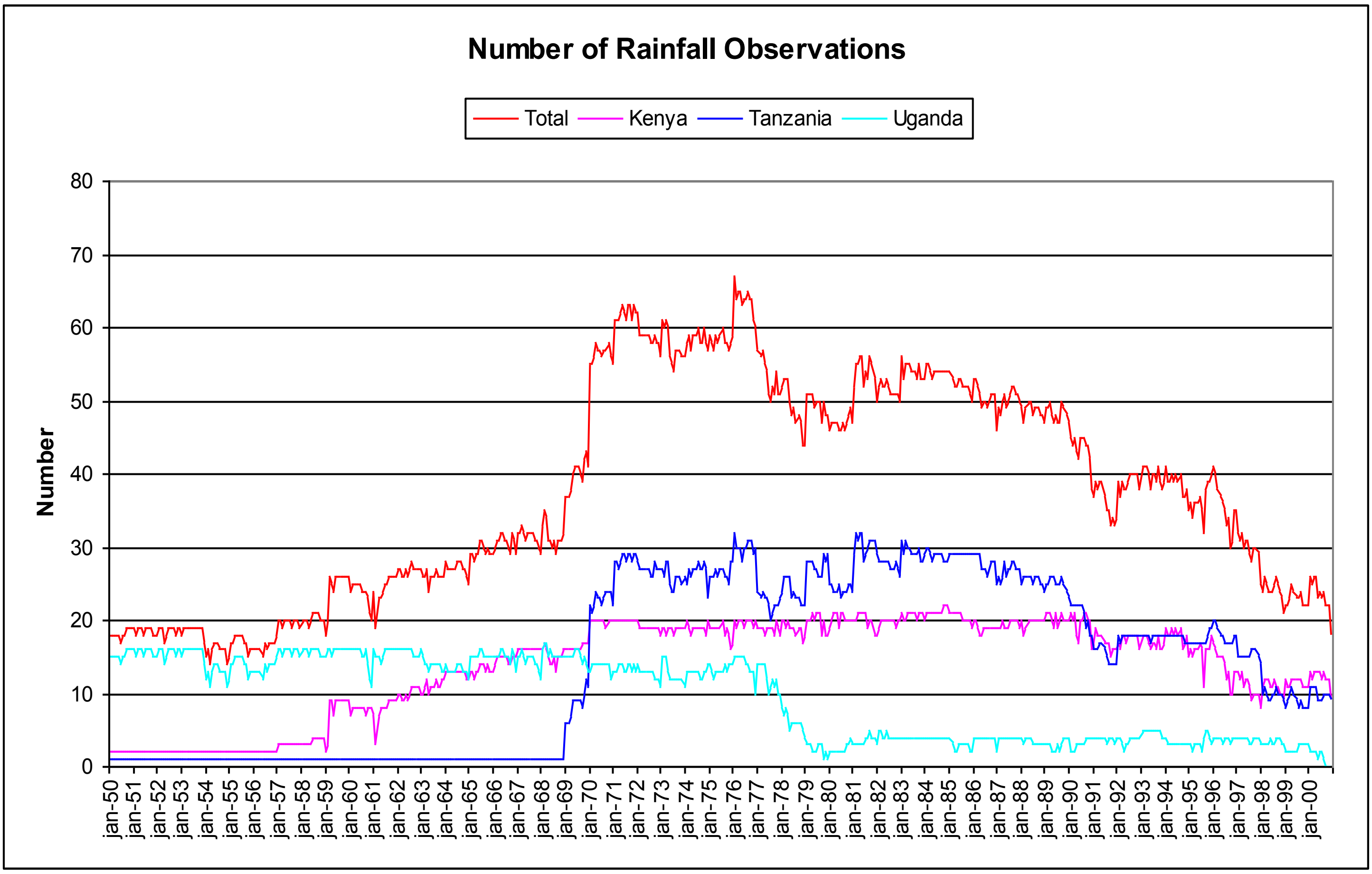

Figure 1.10 Number of Rainfall Stations with observations in the period 1950 - 2000.

1.4.2 Quality Control of Rainfall Data

The rainfall data was subjected to quality control during the processing and use of the data when most of the errors were discovered. Two examples of the types of quality control and errors discovered are given below.

Figure 1.11 is a column plot of the measured daily rainfall at Bukasa Ssesse Is. It shows that the data in 1950-52 is in error because it is significantly lower and has almost constant magnitude compared with the remainder of the data. Further, a closer examination revealed that the rainfall amounts of 25.4 mm and 50.8 mm reoccurred frequently. These correspond to 0.5 and 1.0 inches. If this represents the accuracy of the original data, then it is likely that the values have been guessed by the observer and, under all circumstances, are not sufficiently accurate for use in the study. On this basis, the Bukasa record was discarded.

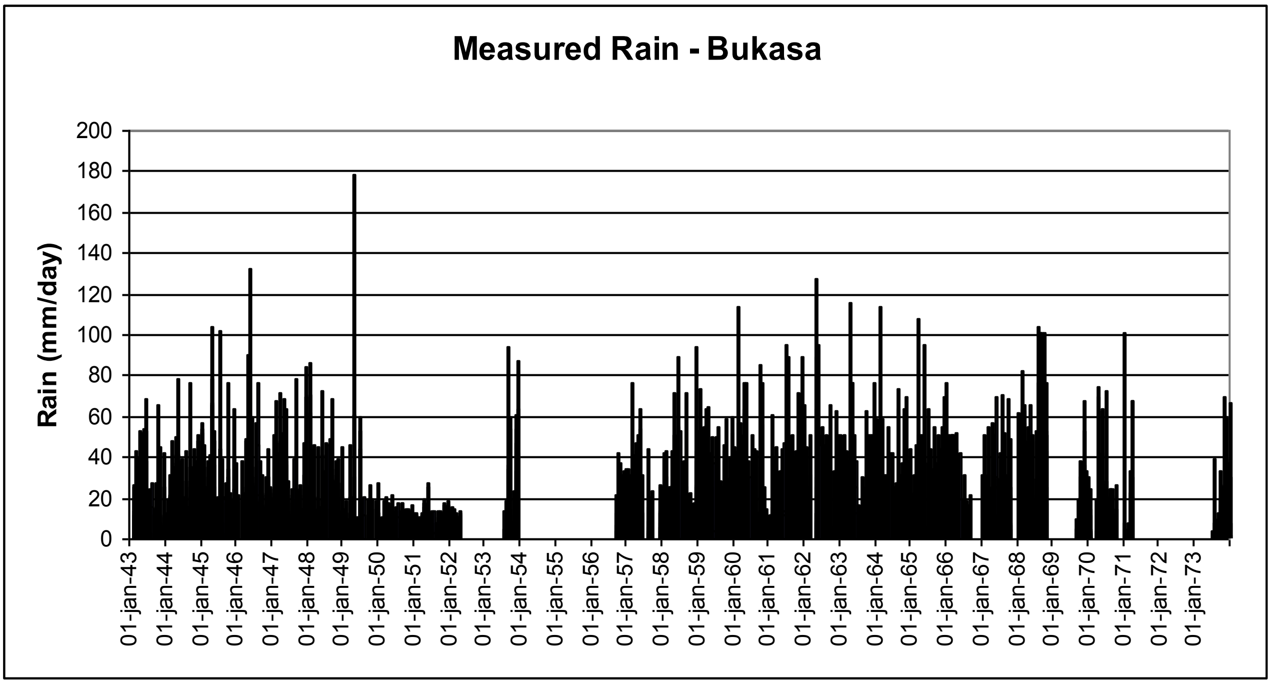

Figure 1.11 Rainfall observations at Bukasa Ssesse Is.

An example of an accumulated rainfall curve is shown in Figure 1.12 where it can be seen that there is a sudden change in the general rainfall magnitude in the last few years. The rainfall in the first period is in good agreement with adjacent stations, so this was accepted, but the last few years of data was rejected.

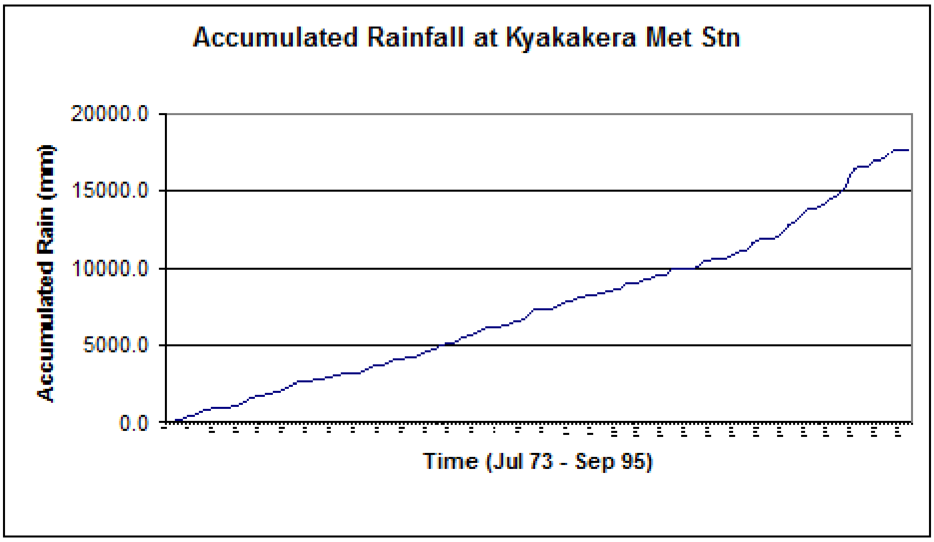

Figure 1.12 Accumulated rainfall at Kyakakera Meteorological Station.

1.4.3 Correlation to an adjacent Reference Station

It was found that the use of "Double Mass" curves gave very reliable correlation relationships between adjacent stations. An example is shown in F for Kitale Meteorological Station and Elgon Downs in the Nzoia catchment in Kenya.

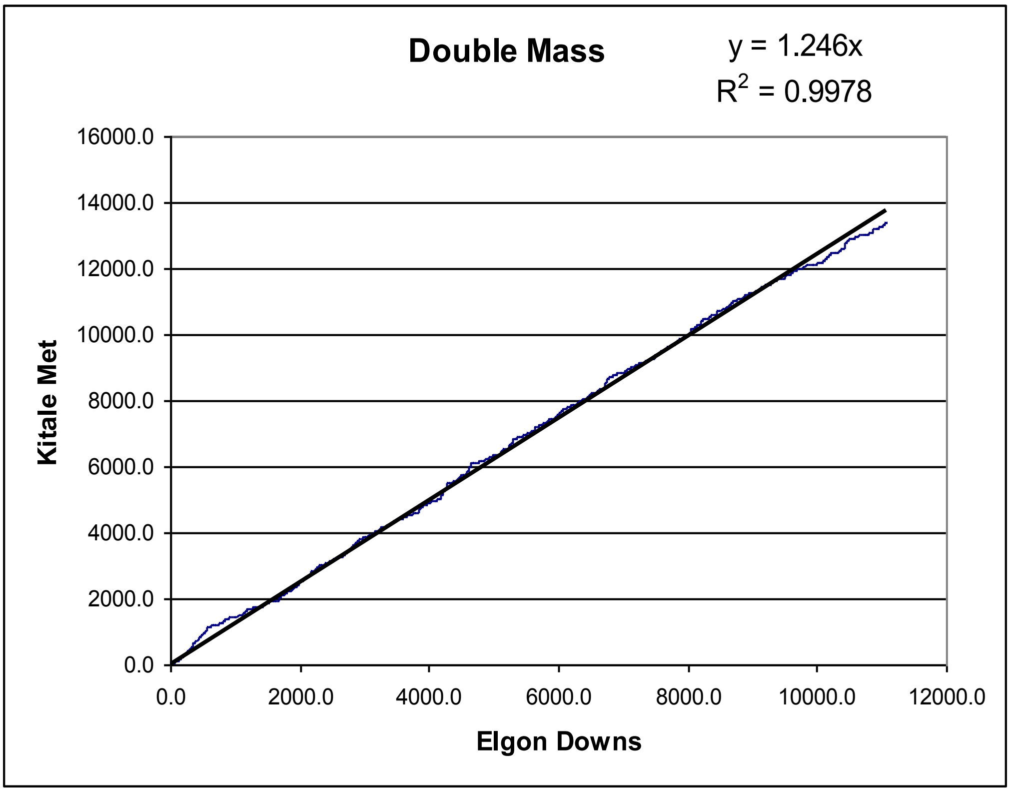

Figure 1.13 Double Mass curve for Kitale Meteorological Station and Elgon Downs

The equation of the trendline is shown in the figure and is used to extend the rainfall record at Kitale on the basis of the much longer record at Elgon Downs.

Kitale rain = 1.246 * Elgon Downs rain (mm)

The high R^2 value of the correlation confirms the visual impression that the trendline is a very good fit to the observations.

This method of correlation was used everywhere possible in the Lake Victoria catchment. In a few cases it was chosen not to use correlations, either because the station had an almost complete record, or because it was too far away from a station with a longer record. "Too far" in this sense means that the nearest station with a longer record is in a different rainfall zone.

1.4.4 Insertion of "Typical Year" Data

As already described above, "typical year" rainfall is used to fill the remaining gaps in the rainfall record of each station. The example of Kahunda Meteorological Station, Tanzania is given here. The choice of the typical years is shown in Table 1.4.

Table 1.4 Choice of Typical Rainfall Years at Kahunda Meteorological Station.

Hydrological Year (Oct-Sep)	Total Rain (mm)	Typical Year
1970-71	868.1	
1971-72	1062.2	
1972-73	1363.4	
1973-74	1296.5	
1974-75	1059.7	
1975-76	989.1	
1976-77	1231.2	
1977-78	1061.8	
1978-79	1384.3	
1979-80	971.9	
1980-81	1560.6	
1981-82	1105.3	
1982-83	1336.1	
1983-84	747.3	Dry Year
1984-85	1003.3	
1985-86	1198.1	
1986-87	1049.8	
1987-88	1382.4	
1988-89	1071.8	
1989-90	1418.9	
1990-91	1191.2	Average Year
1991-92	954.5	
1992-93	1281.0	
1993-94	1248.2	
1994-95	1268.3	
1995-96	1295.3	
1996-97	1278.4	
1997-98	1570.0	Wet Year
1998-99	820.3	
1999-00	859.3	
Mean	**1162.9**	

Oct 97 - Sep 98 is chosen as the wet year (the well-known El Nino year), Oct 83 - Sep 84 is the dry year and Oct 90 - Sep 91 is the average year. The rainfall data for these years is used to complete the rainfall record at Kahunda in the period 1950 - 1969. The result is illustrated in Figure 1.14.

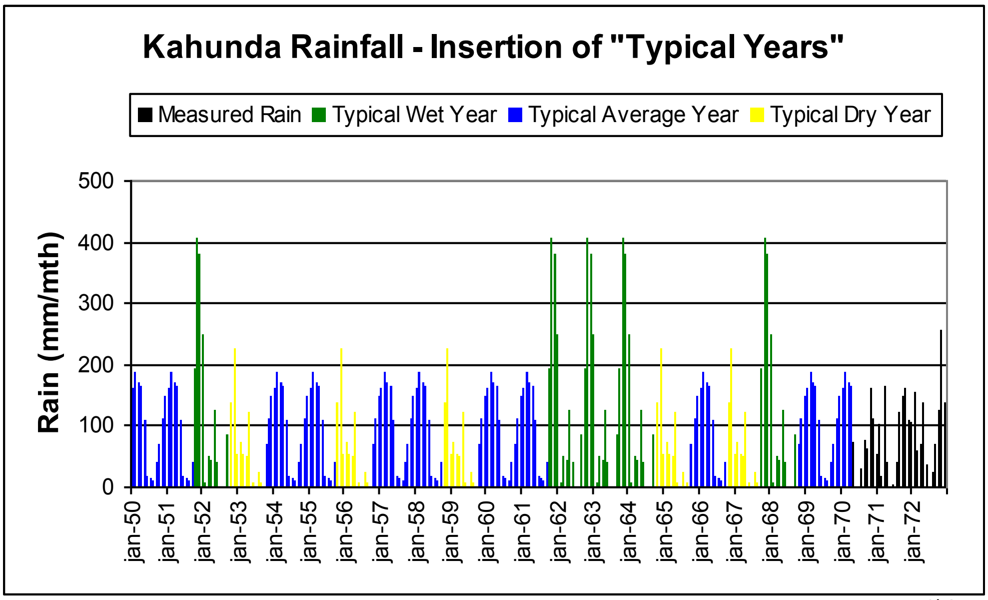

Figure 1.14   Insertion of "Typical Rainfall Years" to complete rainfall record.

1.4.5 Final Rainfall

Now the stage has been reached where the final rainfall record for 1950 - 2000 at each station has been generated on the basis of the actual measurements, correlation to an adjacent reference station and insertion of typical years.An example of the final rainfall hydrograph for Rusinga Is, Kenya is shown in Figure 1.15.

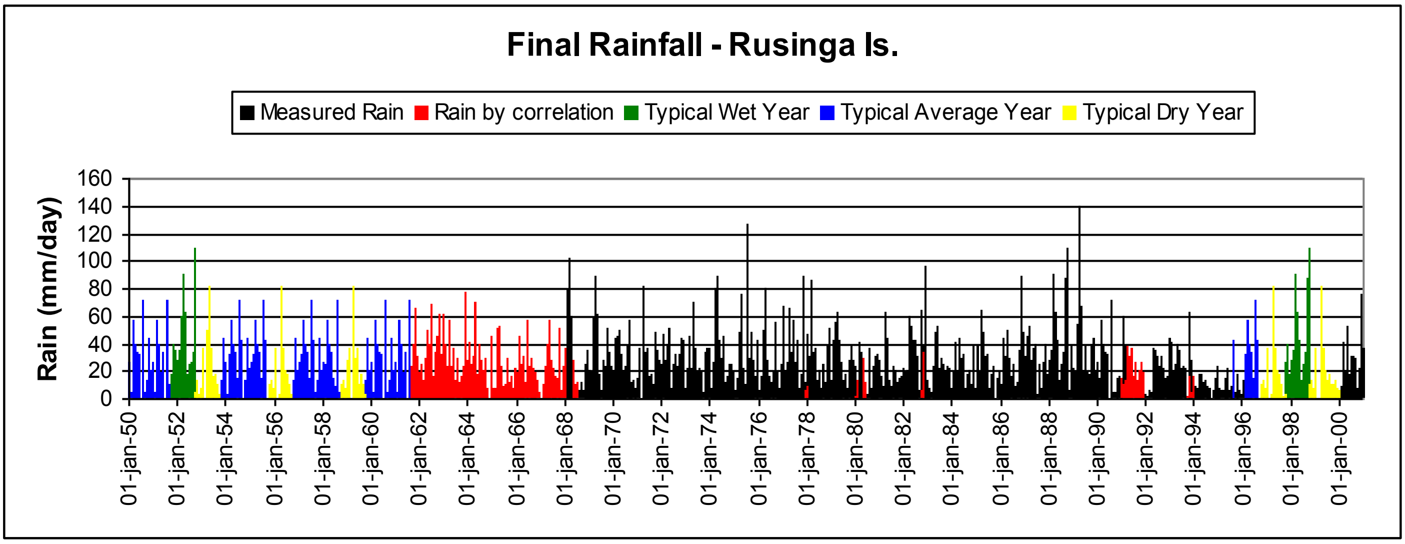

Figure 1.15   Final Rainfall Hydrograph at Rusinga Island.

1.4.6 Rainfall over River Basins

A single time series of rainfall that is representative for a river basin is required for use in the Rainfall-Runoff models. The time series is generated as a weighted mean of the selected stations in the catchment or basin area. The weighting for each station is primarily dependent the proportion of the area represented by the station, but also on the rainfall characteristics in the area.

In Kenya, all the rivers have a low, flat area near the lake and a high altitude area with irregular topography in the upper reaches. The weighting takes account of the different area characteristics.

As another example, the runoff in the dry Tanzanian catchments during low and medium rainfall events seems to be most affected by the rain falling near the gauging station, and less by rain falling far away from the gauging station. Such behaviour is physically reasonable, and is taken account of in the weighting of the rainfall stations.

1.4.7 Rainfall over Lake Victoria

The rain falling on the lake surface represents by far the largest inflow of water to the lake. Therefore it is most important that the estimates of the rain over the lake are as accurate as possible.

Unfortunately there is not a sufficient number of rainfall stations over the lake area to use them alone to draw isolines of annual rainfall. Additional qualitative knowledge of the regional meteorology and rainfall patterns is required. One of the Consultant's Support Specialists is a trained Kenyan meteorologist and was able to provide the knowledge.

The global wind patterns are sketched in Figure 1.16.

From October to December the wind approaches the lake from southeast and, as they cross the lake, they turn more towards north. At the same time there is a wind stream from Congo approaching the lake from southwest. These two wind streams meet in a convergence zone along the western side of the lake. As the wind crosses the lake from southeast, it picks up more moisture and deposits it as rain in increasing amounts from east to west. The rainfall intensity reaches a maximum in the convergence zone.

From February to May the main global wind flow is from east to west. Again, the air increases its moisture content from east to west and the rain intensity increases in the same way.

With this knowledge, it can be expected that the rainfall is highest along the west coast, and somewhat higher along the north coast than on the south. This enables the drawing of a consistent isohyetal map when combined with the rather rainfall observations around the lake shore and on islands.

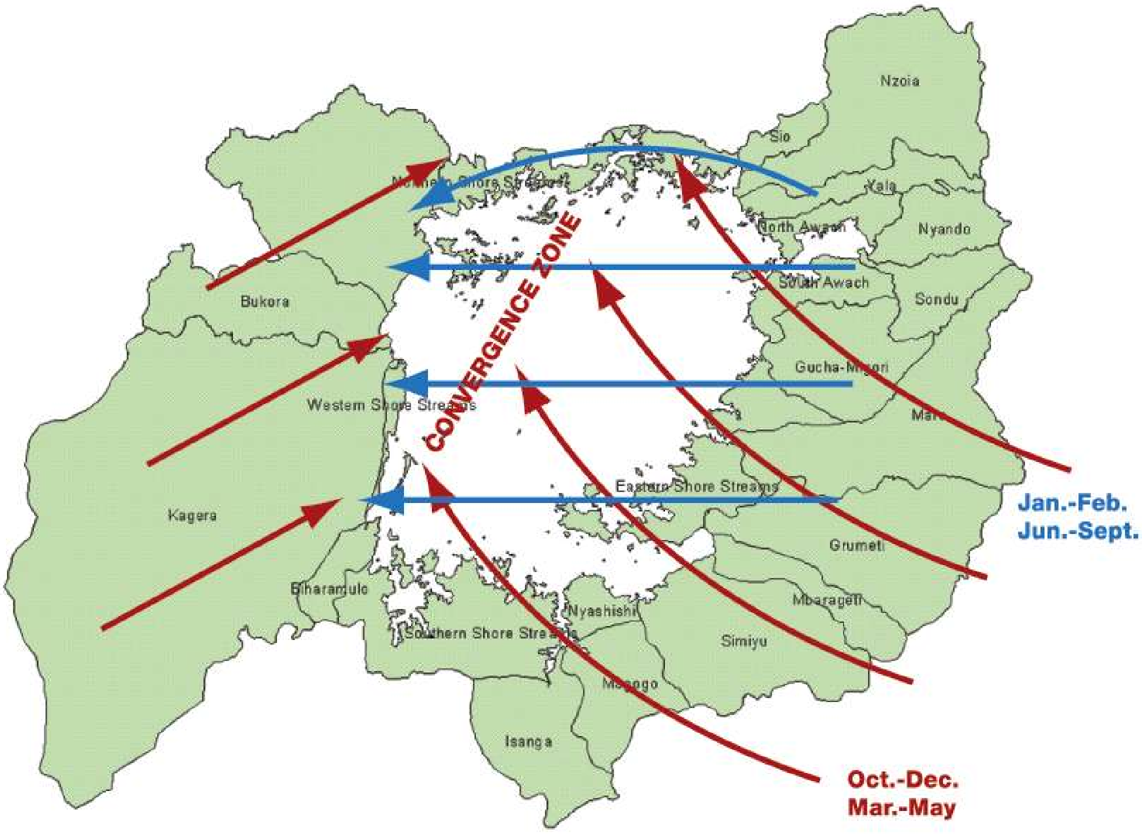

Figure 1.16 Global wind patterns over Lake Victoria

Figure 1.17 shows the rainfall stations in the lake catchment with their mean annual rainfall based on measurements alone and the corresponding isohyets. It also shows the division of the lake into a number of boxes that form the basis for estimating the total rainfall over the lake. Each box has a reference rainfall station. The following procedure was applied.

1. The mean annual rainfall in each box is estimated on the basis of the isohyetal curves.

2. The daily (or monthly) rainfall in each box is calculated using:

   $R_{box} = R_{ref} * MAR_{box} / MAR_{ref}$

   where R_{box} = Daily rainfall in box
   R_{ref} = Daily rainfall at reference station
   MAR_{box} = Mean annual rainfall in box
   MAR_{ref} = Mean annual rainfall at reference station

3. The average daily rainfall for the lake is calculated as the sum of the areal weighted means of the of the daily box rainfalls (R_{box}). See Table 1.5

   Lake Rain = Σ_i (R_{box} * Weight)

Table 1.5 Rainfall over Lake Victoria

Box No.	Name	Weight	MAR_{box} Mean annual rain for box (mm)	MAR_{ref} Mean annual rain for station (mm)	R_{ref} Mean annual rain (1950-2000) (mm)	Mean annual Lake Rain for each box
1	Muhuru	0.074	1250	964	981	94
2	Musoma	0.065	1300	839	852	86
3	Ukerewe	0.124	1600	1502	1513	200
4	Mkula	0.019	886	886	924	18
5	Mwanza	0.045	1000	958	976	46
6	Bukerebe	0.091	2400	2609	2442	204
7	Kahunda	0.083	1450	1163	1171	121
8	Izigo	0.023	1950	1731	1850	48
9	Bukoba	0.008	2400	2060	2035	19
10	Rubafu	0.022	2300	1710	1629	48
11	Kalangala	0.179	2100	2085	2143	386
12	Bumangi	0.037	1800	2086	2113	67
13	Entebbe	0.041	1950	1629	1636	80
14	Buvuma	0.095	1696	1696	1754	167
15	Rusinga	0.076	1230	1053	1037	92
16	Homa Bay	0.008	1204	1204	1164	9
17	Kisumu	0.01	1220	1357	1355	12
				Mean annual Lake Rain		**1698**

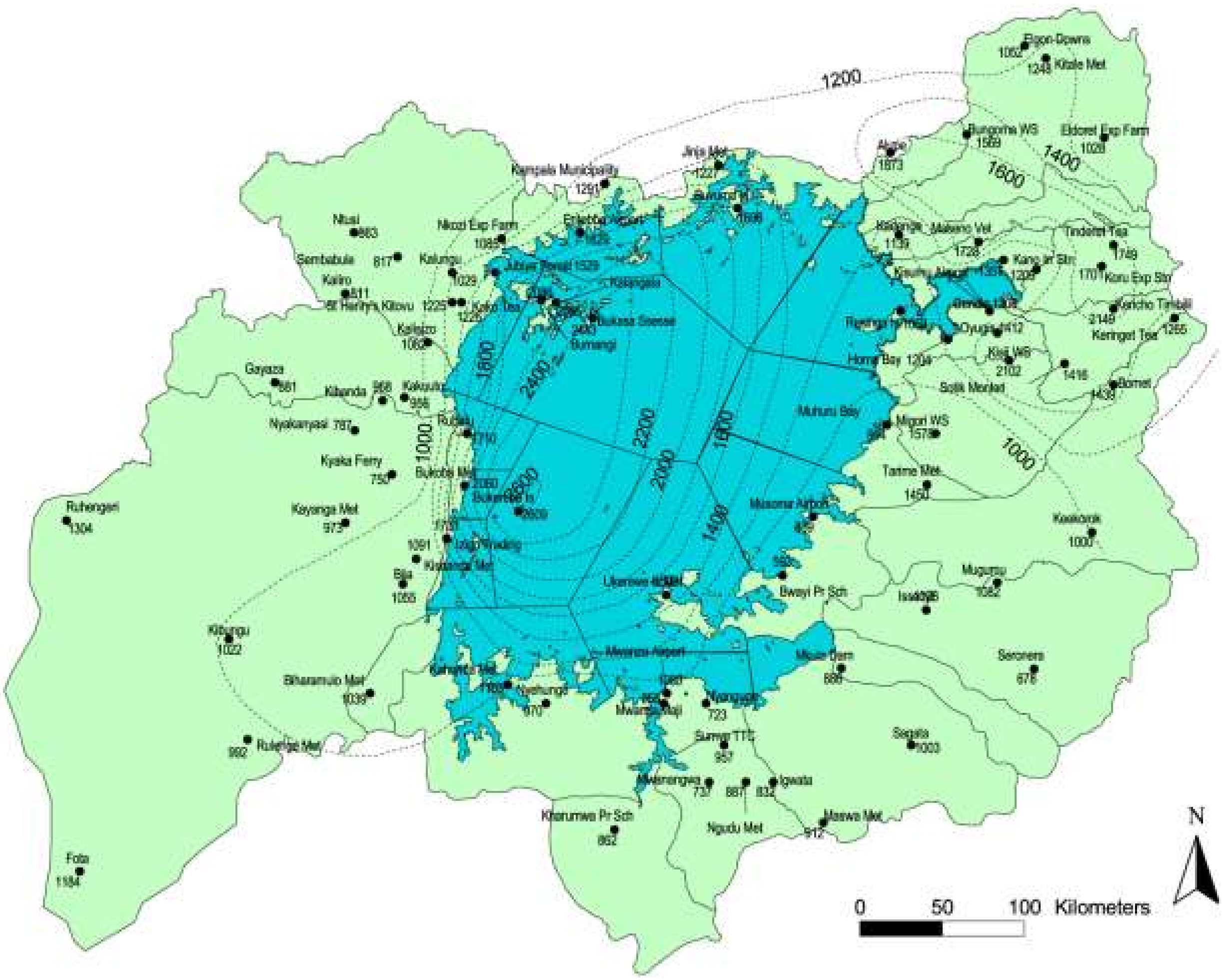

Figure 1.17 Mean Annual Rainfall over Lake Victoria

1.5 Evaporation

The procedure for the preparation and analysis of the evaporation data is essentially the same as that used for the rainfall. Only the differences are described below.

The selected evaporation stations are listed in Table 1.3 and the locations shown in F. The figure also shows the Mean Annual Evaporation (MAE) at each station, isolines of MAE over the lake and the boxes used to compute the average rainfall for the entire lake surface.

Sources of data

The main source of data was the Lake Victoria Basin Database (LVBD). Only in Tanzania was data available from another sources, namely the Hydrology Department of the Ministry of Water. No data was available in any of the countries before January 1970, ie the start of the HYDROMET Project. In a few cases only four years of data were available, 1970-74, while there were many with data in the period 1970-90 (with gaps).

Correlation

Since the number of stations is small, there is generally a large distance between them, and it is inappropriate to use correlations to extend records. Consequently, correlations were used in a few cases only.

Typical years

While the potential (pan) evaporation can vary significantly from day to day, the total annual evaporation varies only little. Further, it was not possible to find any consistent relationship between the evaporation and the occurrence of wet and dry rainfall years. For these reasons it was chosen to use the daily/monthly average evaporation to fill the gaps in the record. This means that, eg the average of all records on 1 January was used to fill all gaps on 1 January, etc.

Examples

Two examples of the final evaporation are shown in Figure 1.18. Kisumu has the maximum evaporation in the Lake Victoria catchment, and Bukoba has close to the minimum. These two examples clearly illustrate the characteristics of the evaporation as described above.

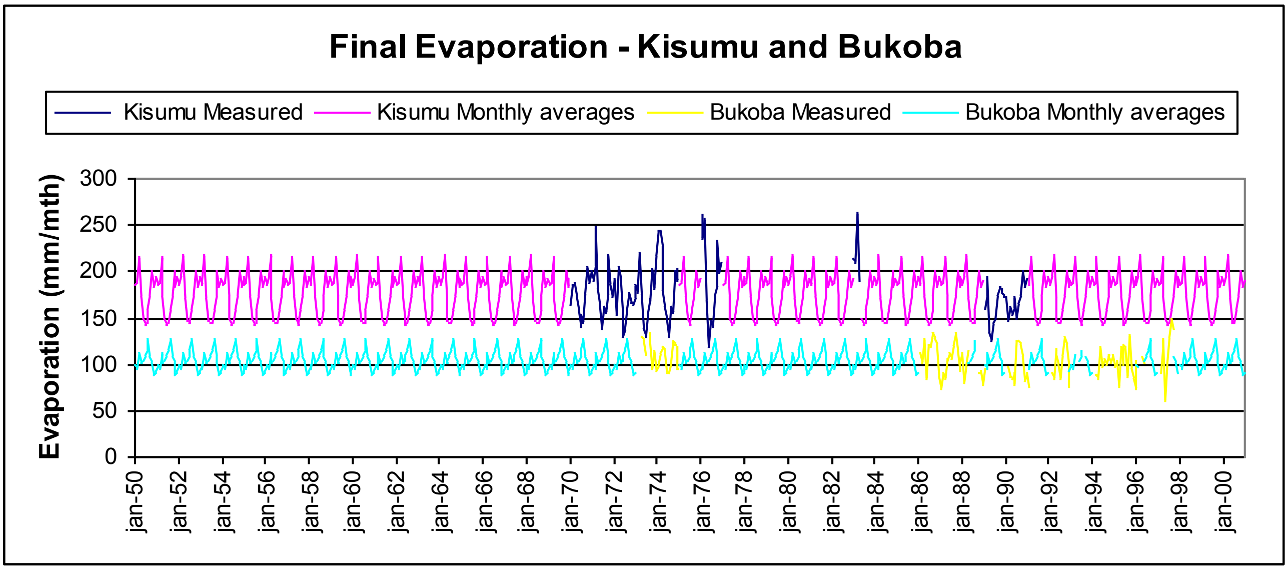

Figure 1.18 Monthly Evaporation at Kisumu and Bukoba Meteorological Stations.

Evaporation over Lake Victoria

Figure 1.19 shows the evaporation pattern over Lake Victoria based on the Mean Annual Evaporation at stations around the shores and on the islands. The tendency for higher evaporation on the drier eastern side and lower evaporation on the wetter western side is very clear.

The value of 2045 mm at Mwanza Airport could be questioned since it deviates strongly from the values at Ukerewe Is and Kahunda Met Station.

Figure 1.19 also shows the boxes used for calculating the average evaporation over the lake. The procedure described above for the rainfall is used and the corresponding values are shown in Table 1.6.

Table 1.6 Evaporation over Lake Victoria

Box No.	Name	Weight	MAE_{box} Mean annual evap for box (mm)	MAE_{ref} Mean annual evap for station (mm)	E_{ref} Mean annual evap (1950-2000) (mm)	Mean annual Lake Evap for each box (mm)
1	Muhuru	0.041	1850	2006	2006	76
2	Musoma	0.096	1630	1762	1762	157
3	Ukerewe	0.134	1380	1347	1347	185
4	Mwanza	0.085	1220	2045	2065	105
5	Kahunda	0.088	1300	1325	1325	114
6	Bukoba	0.120	1255	1255	1255	151
7	Bukasa	0.161	1250	1108	1110	202
8	Entebbe	0.020	1350	1399	1416	27
9	Koome	0.118	1450	1245	1247	171
10	Rusinga	0.124	1900	2093	2093	236
11	Kisumu	0.012	2118	2118	2118	25
				Mean annual Lake Evapooration		**1448**

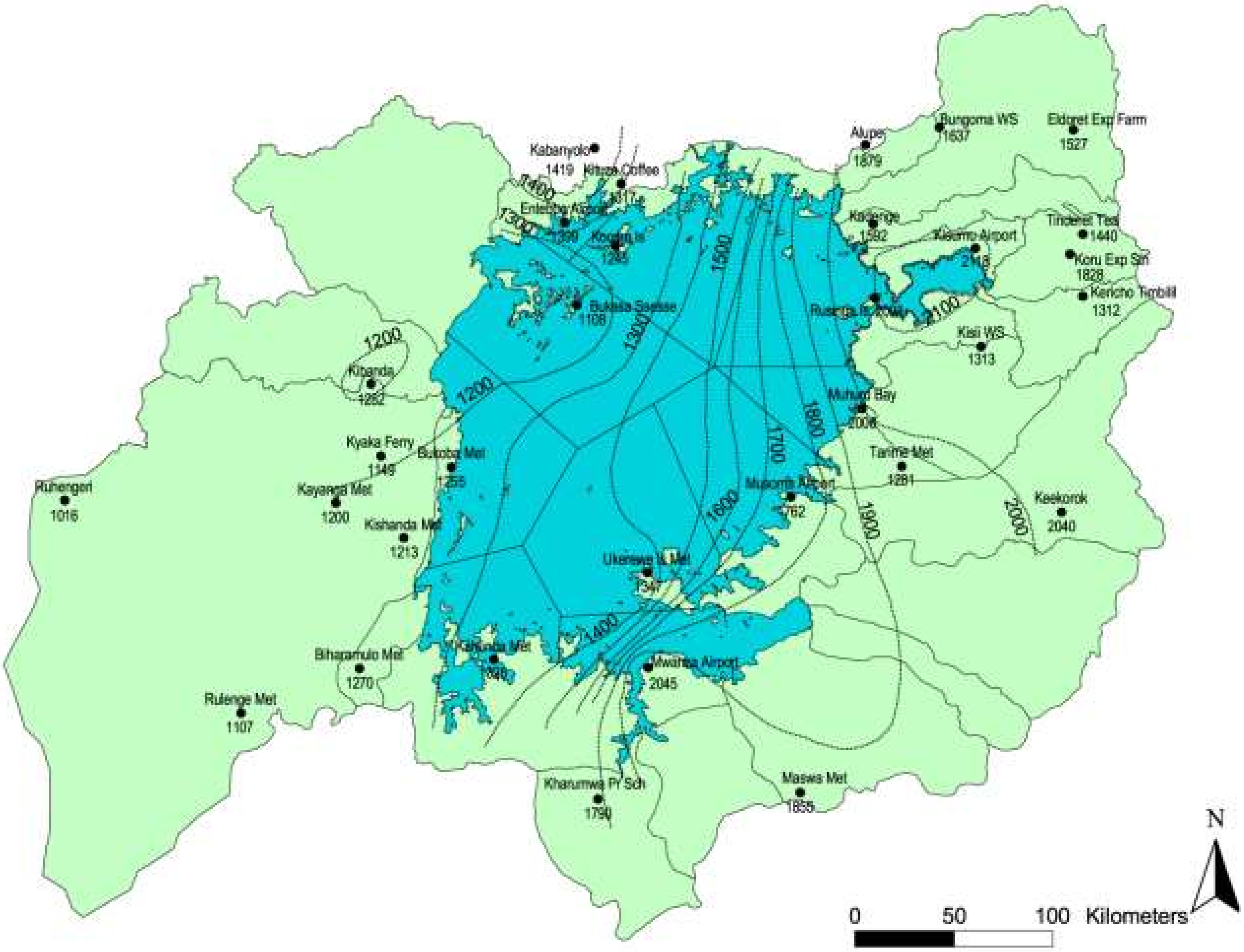

Figure 1.19 Mean Annual Evaporation over Lake Victoria

1.6 River Discharges

1.6.1 Gauging Stations

The gauging stations chosen for the study are those closest to the mouth of the rivers to the lake. They are listed in Table 1.7 along with the areas of the river basins and the area upstream of each of the stations. The locations of the stations are shown in Figure 1.20.

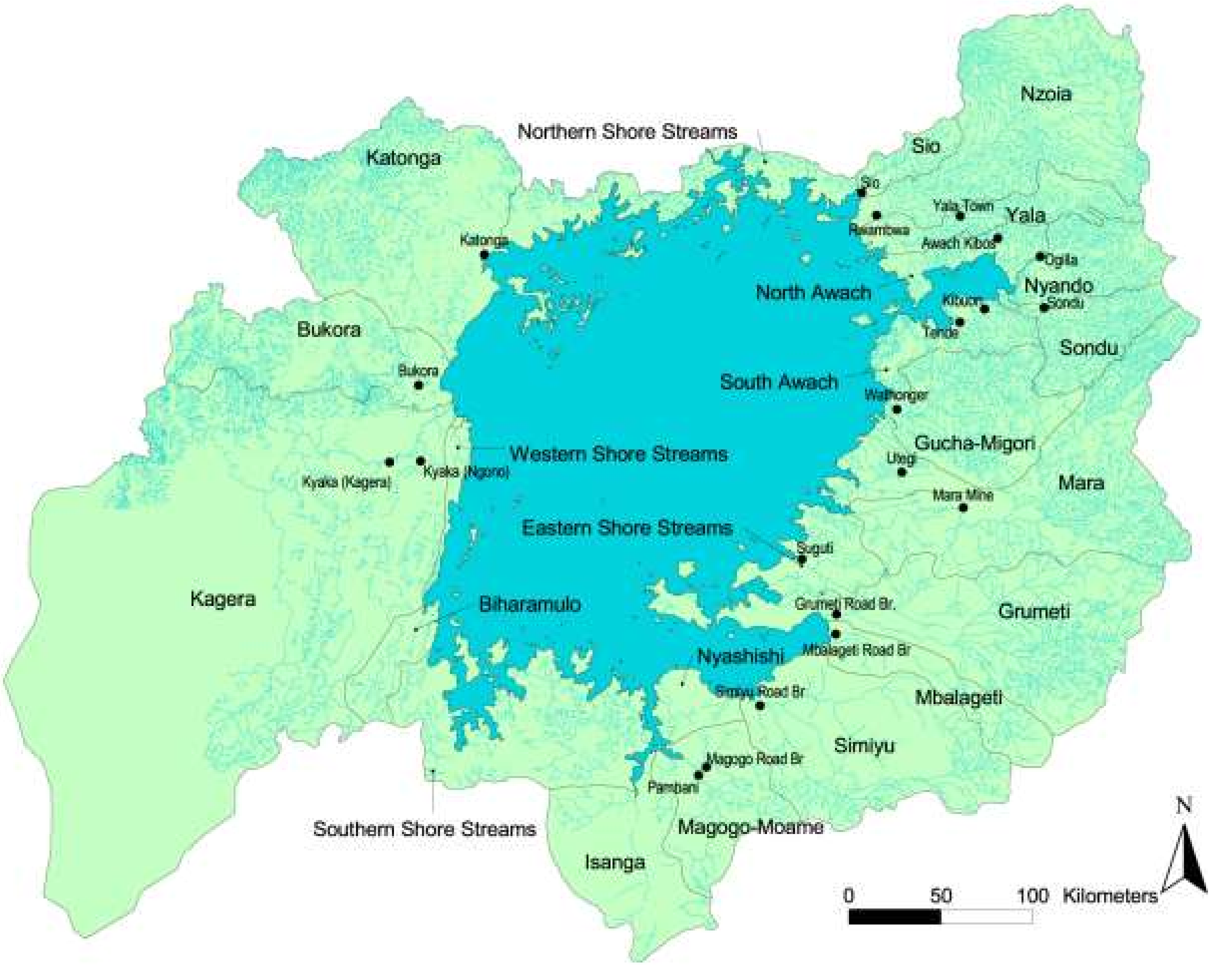

Figure 1.20 Locations of Gauging Stations

Table 1.7 Gauging stations and catchment areas.

River Basin	River Basin area (km^2)	Gauging Station	Catchment area upstream of gauging station (km^2)
KENYA			
Sio	1450	1AH01 Sio	1450
Nzoia	12676	1EF01 Rwambwa	12676
Yala	3351	1FG01 Yala Town	2388
Nyando	3652	1GD03 Ogilla	2625
North Awach	1985	1HA14 Awach Kibos	
South Awach	3156	1HE01 Tende	585
		1HD01 Kibuon	
Sondu	3508	1JG01 Sondu	3287
Gucha-Migori	6600	1KB05 Wathonger	6600
TANZANIA			
Mara	13393	107072 Mara Mine	10300
Grumeti	13363	110022 Road Bridge	11583
Mbalageti	3591	111012 Road Bridge	3348
E. Shore Streams	6649	208022 Mori R. at Utegi	464
		109012 Suguti R at Suguti	1033
			Subcatchment areas
		Mori River area	2436
		Mugango area	1141
		Suguti River area	1033
		Bunda area	1455
		Ukerewe Is area	584
		Total area	6649
Simyu	11577	112022 Road Bridge	10659
Magogo-Moame	5170	113012 Road Bridge (Magogo)	1350
		113022 Pambani (Maome)	2990
			Subcatchment areas
		Magogo River area	1810
		Moame River area	3360
		Total area	5170
Nyashishi	1565	Ungauged	
Isanga	6812	Ungauged	
S. Shore Streams	8681	Ungauged	
Biharamulo	1928	Ungauged	
Kagera	59682		Subcatchment areas
		115022 Kagera R at Kyaka Ferry	55907
		115182 Ngono R at Kyaka Road Br.	2608
		Area between Kyaka and lake	1167
		Total area	59682
W. Shore Streams	733	Ungauged	
UGANDA			
Bukora	8392	81270 Bukora	7395
Katonga	15244		Subcatchment areas
		81259 Katonga	13930
		Area from 81259 to lake	209
		Kisoma (Sango Bay) area	1105
			15244
N. Shore Streams	4288	Ungauged	

1.6.2 Rating Curves

The purpose of the rating curves at each gauging station is to convert the observed daily river water levels to discharges. In Kenya and Uganda the rating curves and discharges had already been calculated by the Hydrology Deparments and no further work was required on this task.

The Tanzanian rating curve data was provided in raw form and a full quality control and analysis was required. Some examples are given below.

Figure 1.21 shows the raw data for the rating curve on the Simiyu River at the main Mwanza - Musoma road bridge. The lines between the symbols are drawn to indicate the sequence in which the measurements were made. The collection of measurements with low discharges and gauge heights all over 14 m looks incorrect and was subjected to closer study. The original data on the paper file showed that the computer operator who had punched in the data had moved the decimal point one place to the left for all discharges over 100 m^3/s. When this was corrected it proved to be a good data set with only a few outliers which were removed or corrected in other ways. The same error was found in some of the other rating curves.

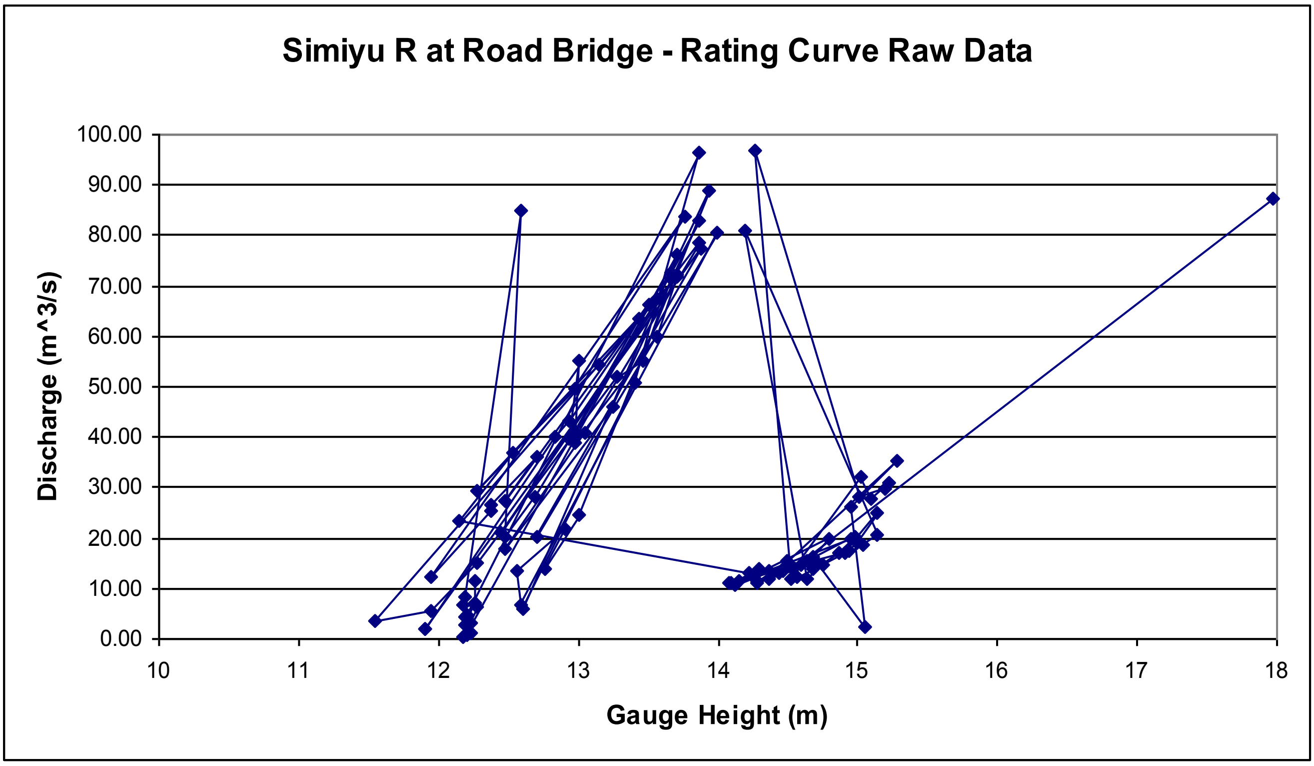

Figure 1.21 Rating curve raw data for Simiyu River at Road Bridge.

The rating curve was estimated after correction of the raw data with the result shown in F. The equation of best fit was:

$$Q = 12.0 * (h - 11.1)^{2.0} \ m^3/s$$

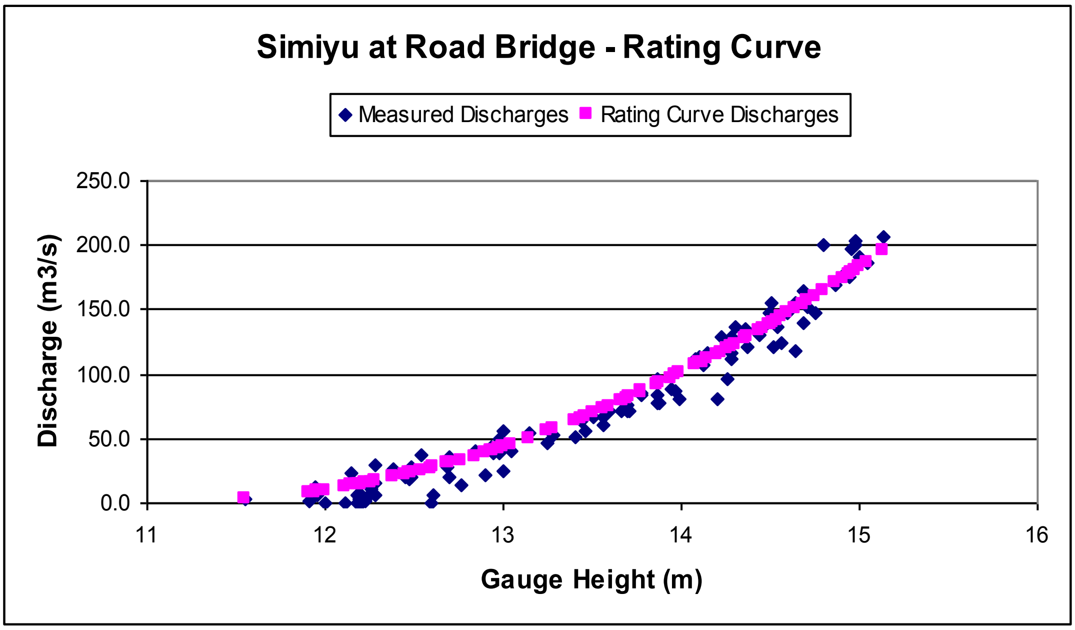

Figure 1.22 Rating Curve for Simiyu River at Road Bridge.

1.6.3 River discharges

The rating curve estimated above is then used to compute the river discharges from the observed daily gauge heights. The example of the Simiyu River is shown in Figure 1.23 and Figure 1.24.

Discharges were calculated in a similar way from the rating curves and gauge height data on the Mara, Grumeti, Mbalageti, Magogo, Moame, Ngono and Kagera Rivers. The actual process facilitated a quality control check of the data.

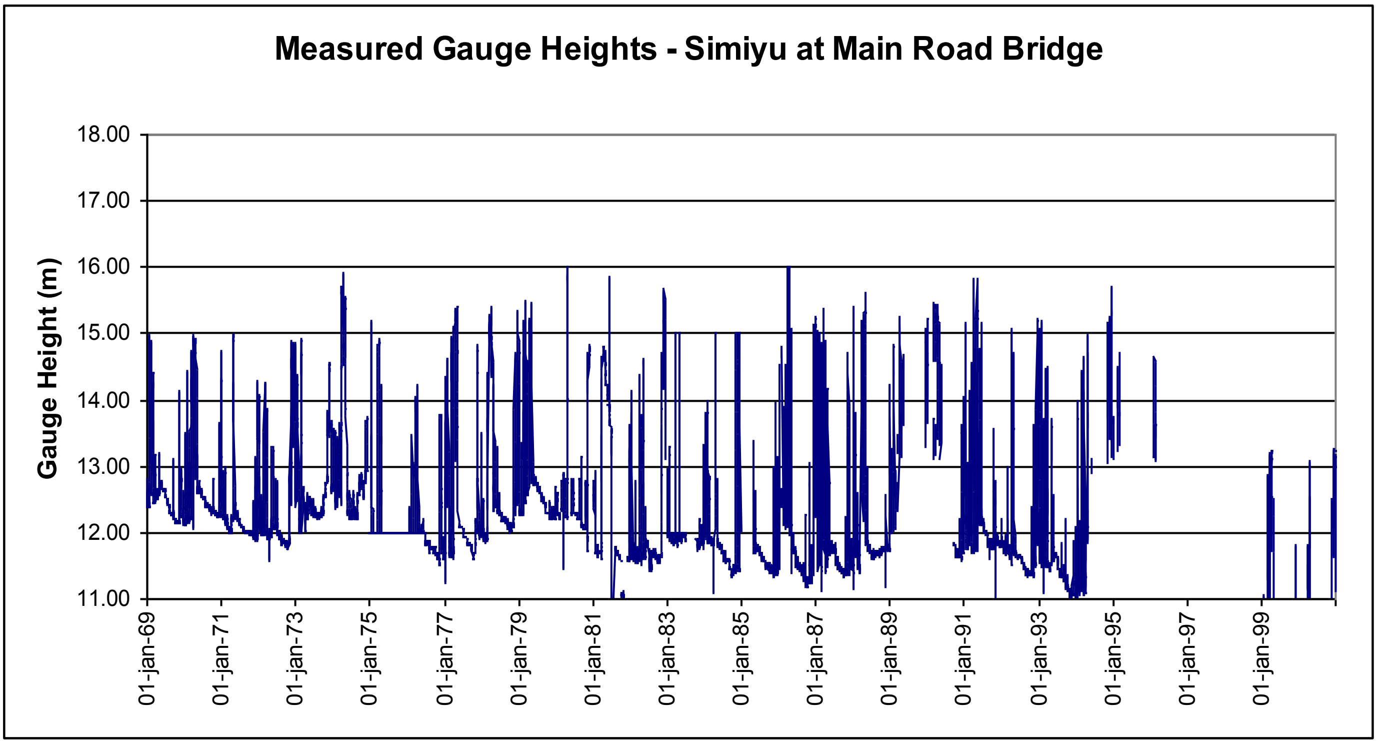

Figure 1.23 Time series of measured gauge heights on the Simiyu River at the main Mwanza - Musoma road bridge.

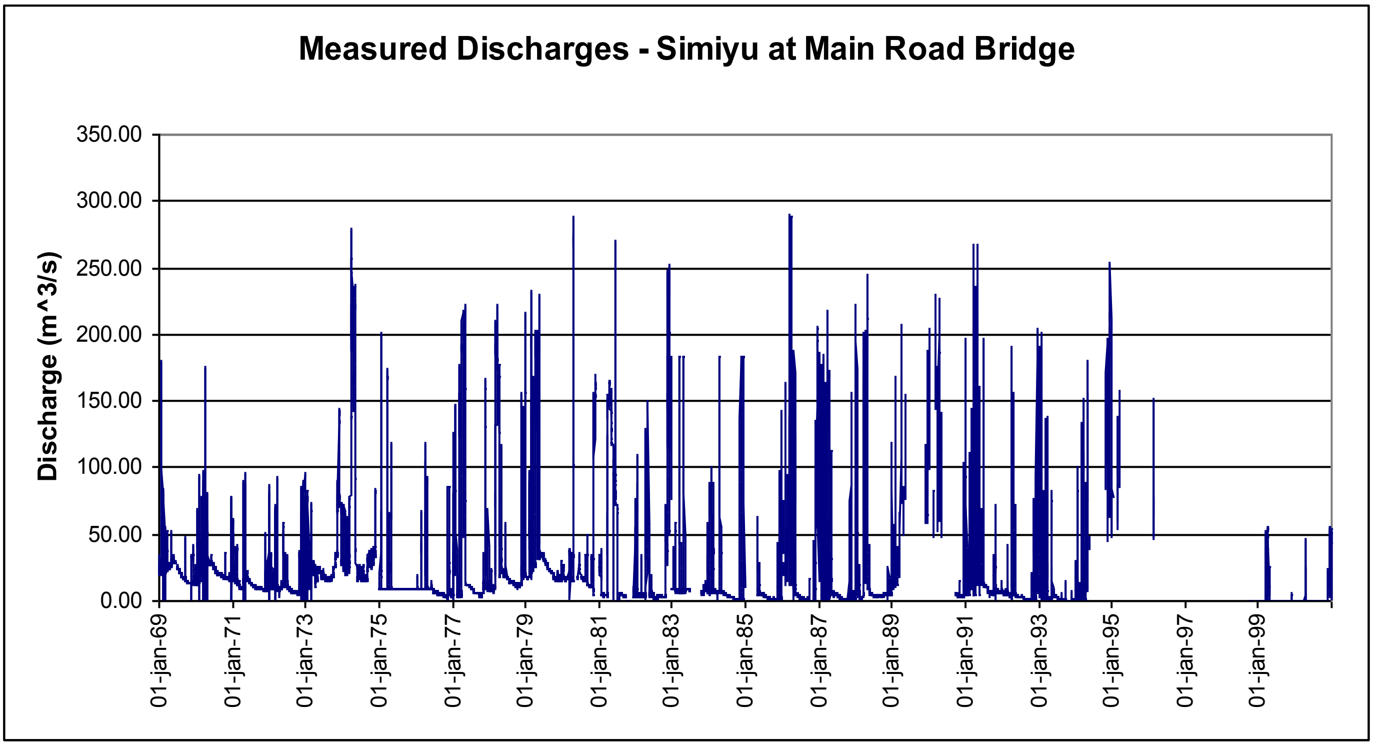

Figure 1.24 Time series of measured discharges for the Simiyu River at the main Mwanza - Musoma road bridge

1.7 Rainfall-Runoff Modelling

Reference is made to the Users Guides for instructions for calibrating and applying the NAM and SMAP models. The methods were described above and only a few examples will be given here.

1.7.1 Model Calibration

Figure 1.25 and Figure 1.26 show examples of the results of the calibration of the NAM model on the Nzoia River in Kenya.

It is seen that the model accurately reproduces the measured discharges, both the peaks and recession curves. The excellent calibration is due to the existence of good quality data on rainfall, evaporation and discharges for the Nzoia. The Nzoia is also known to be a "well-behaved", homogeneous catchment, which makes it suitable for use with lumped conceptual models. Not all calibrations were as good as this one.

It is also seen that the model accurately reproduces the accumulated discharges, which are the most important for the study. It is important that the total amount of water and pollutants is correctly simulated rather than the short term peaks. The short term peaks are more important for flooding studies.

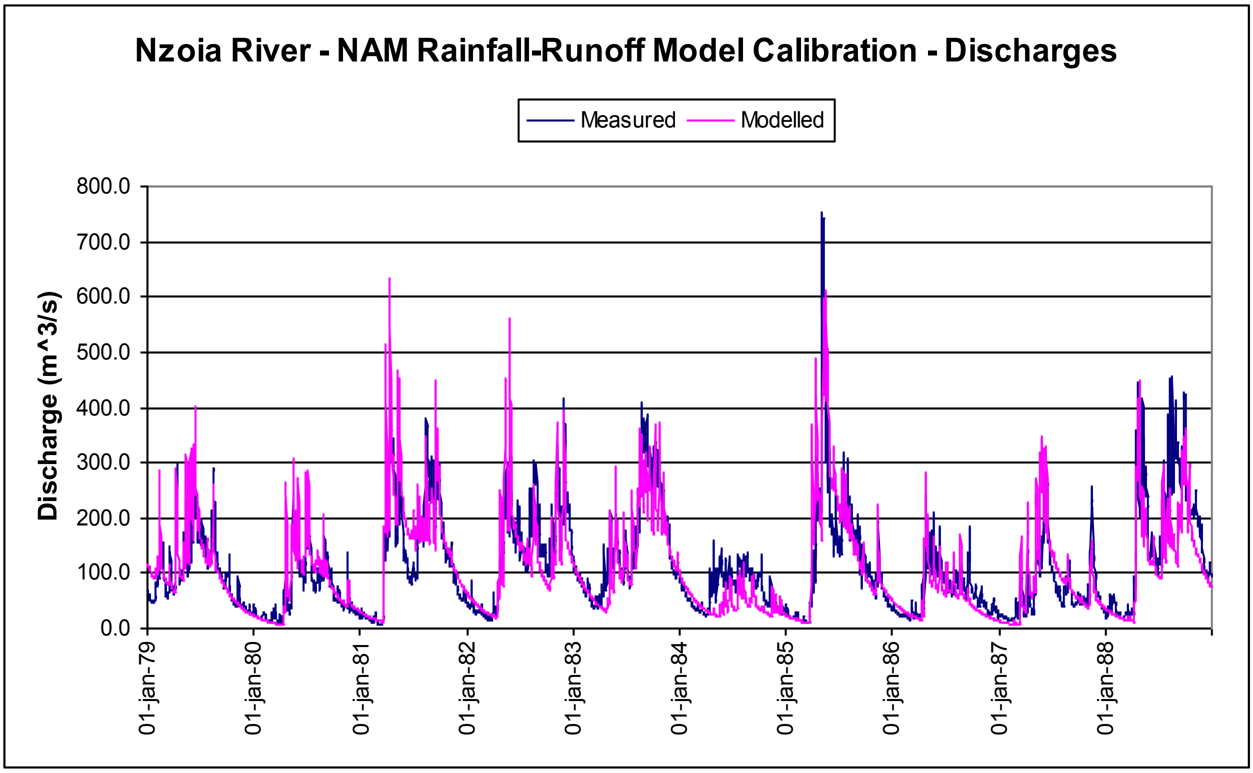

Figure 1.25 NAM calibration results for discharges in Nzoia River.

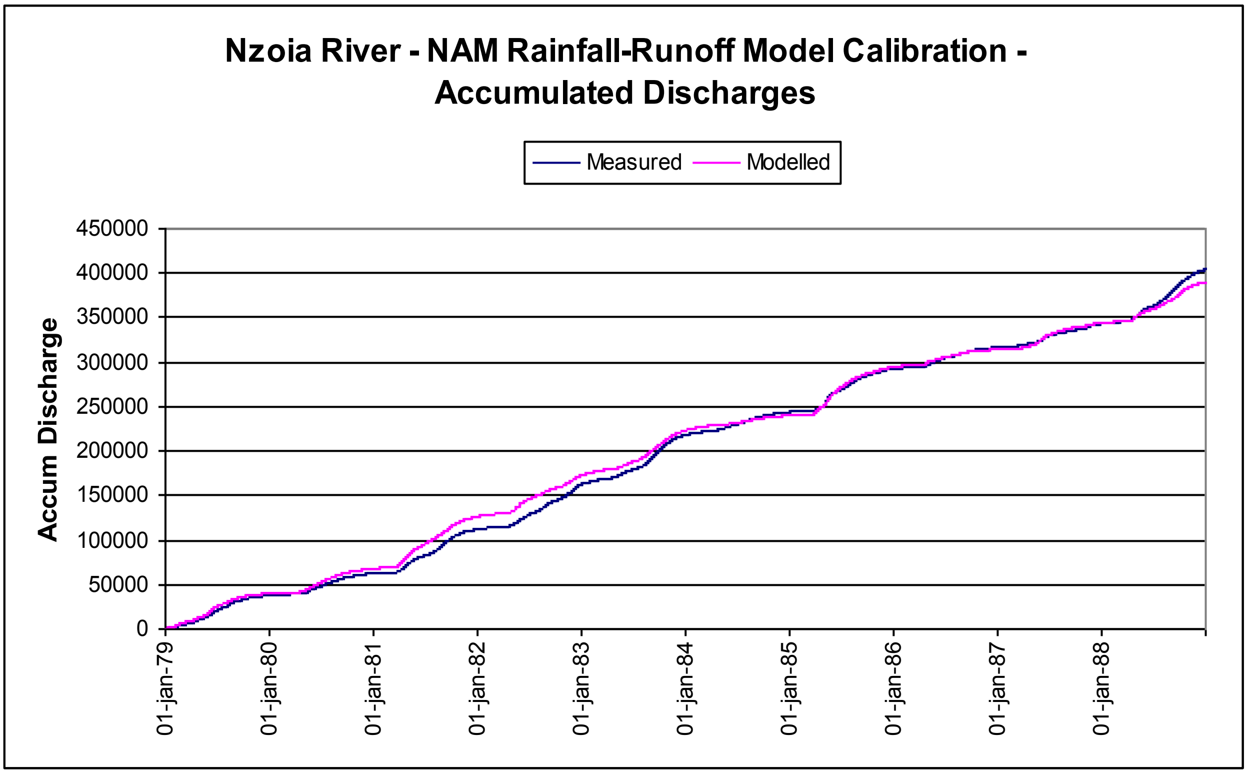

Figure 1.26 NAM calibration results for accumulated discharges in Nzoia River.

A second example of the calibration of NAM is shown in Figure 1.27 for the Katonga River in Uganda. The interesting point here is that the Nzoia and Katonga catchments have similar areas and similar rainfall and evaporation, but the runoff from the Katonga is one to two orders of magnitude less. The reason for the low runoff is that much of the Katonga catchment is wetland where there is very high retention and evaporation of the rainfall. Even under these extremely different conditions the NAM had managed to simulate the runoff correctly.

An example of the calibration of the SMAP model is shown in Figure 1.28 and Figure 1.29 for the Mara River at Mara Mine. SMAP is based on the use of monthly data rather than daily. Even so, it is capable of reproducing the accumulated runoff accurately for most of the period. The plot of discharges shows that the monthly model is not as good as the daily model for simulating the peak flows, although it is still quite acceptable.

Figure 1.29 also shows a problem which was experienced in all the models, namely that sometimes the measurements show a peak which the model almost completely misses, and vice versa. In all such cases, a closer examination of the measurements shows that low rainfall was recorded everywhere in the catchment while, at the same time, a large runoff was observed, or the opposite; high rainfall and almost no runoff. Such cases can only be explained by inconsistencies in the measurements, most probably in the gauge heights (discharges) because it is unlikely that all the rainfall measurements in a catchment are in error.

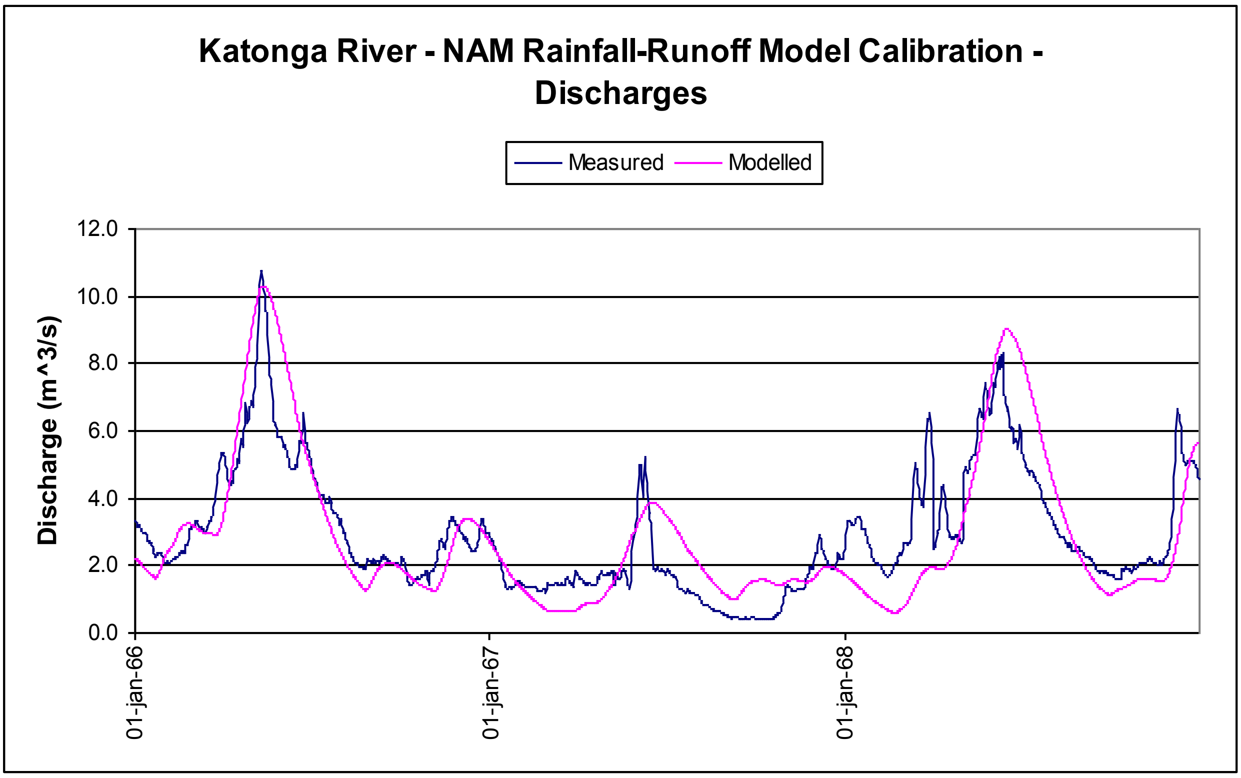

Figure 1.27 NAM calibration results for discharges in Katonga River.

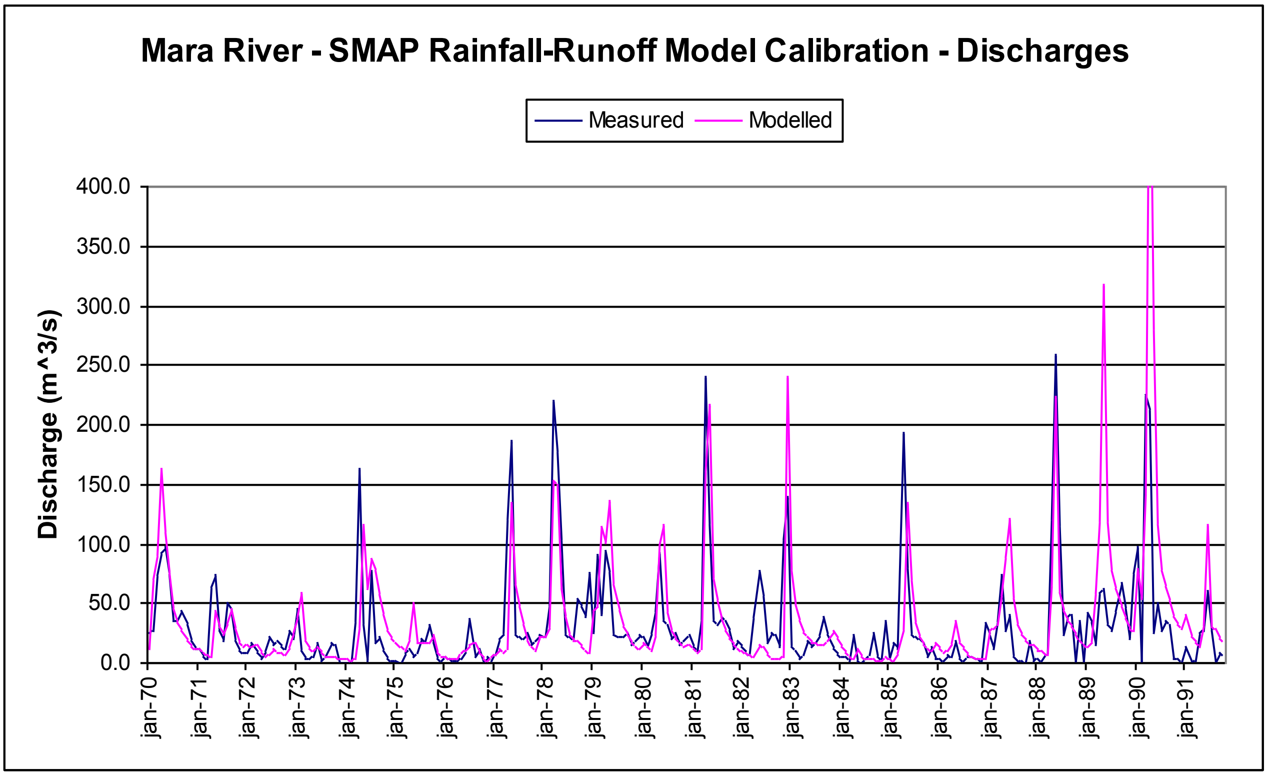

Figure 1.28 SMAP calibration results for discharges in Mara River at Mara Mine.

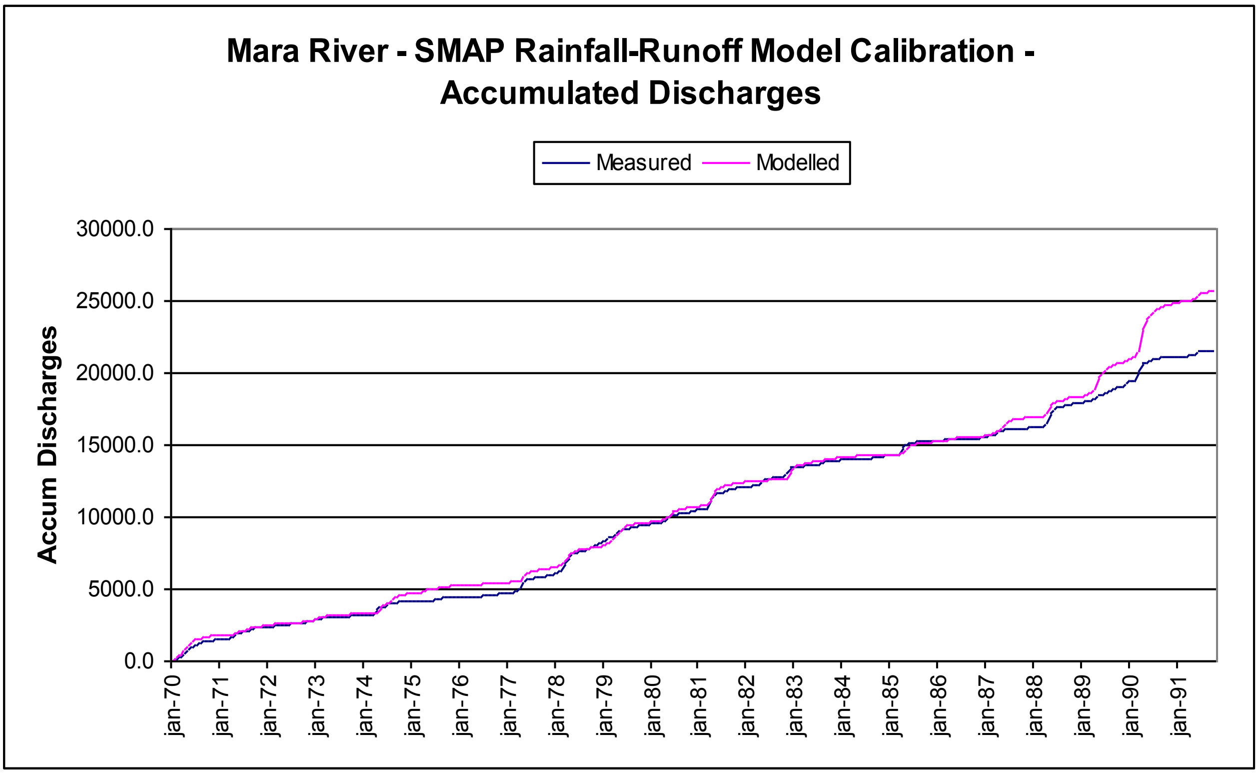

Figure 1.29 SMAP calibration results for accumulated discharges in Mara River at Mara Mine.

The use of a monthly model could also be part of the reason for the discrepancies in the peak flows, particularly in small catchments. Finally, the calibration of the model on the dry Tanzanian catchments showed that the runoff seemed to be heavily dependent on local rainfall near the gauging station and less dependent on rainfall at distant locations in the catchment. In such cases it is possible that none of the selected rainfall stations were close to the gauging station and the local rainfall was thus not recorded.

The difference in the measured and modelled accumulated discharges at Mara Mine in the last 3 years (Figure 1.29) is due to the phenomena just described above. There was high rainfall everywhere in the catchment, but low runoff, which would indicate an error in the gauge height recordings during these years, or a change in the river morphology at the gauging station with a corresponding change in the rating curve which has not yet been measured.

1.7.2 Model Application

The second step in the use of the models is to apply them to the computation of the discharges at the gauging station for the full period, 1950 to 2000. The inflow to the model is the rainfall and potential evaporation for the full period and the model parameters determined by the calibration. Examples of the results are shown in Figure 1.30 for the Gucha-Migori River, Kenya (NAM) and in Figure 1.31 for the Kagera River, Tanzania (SMAP).

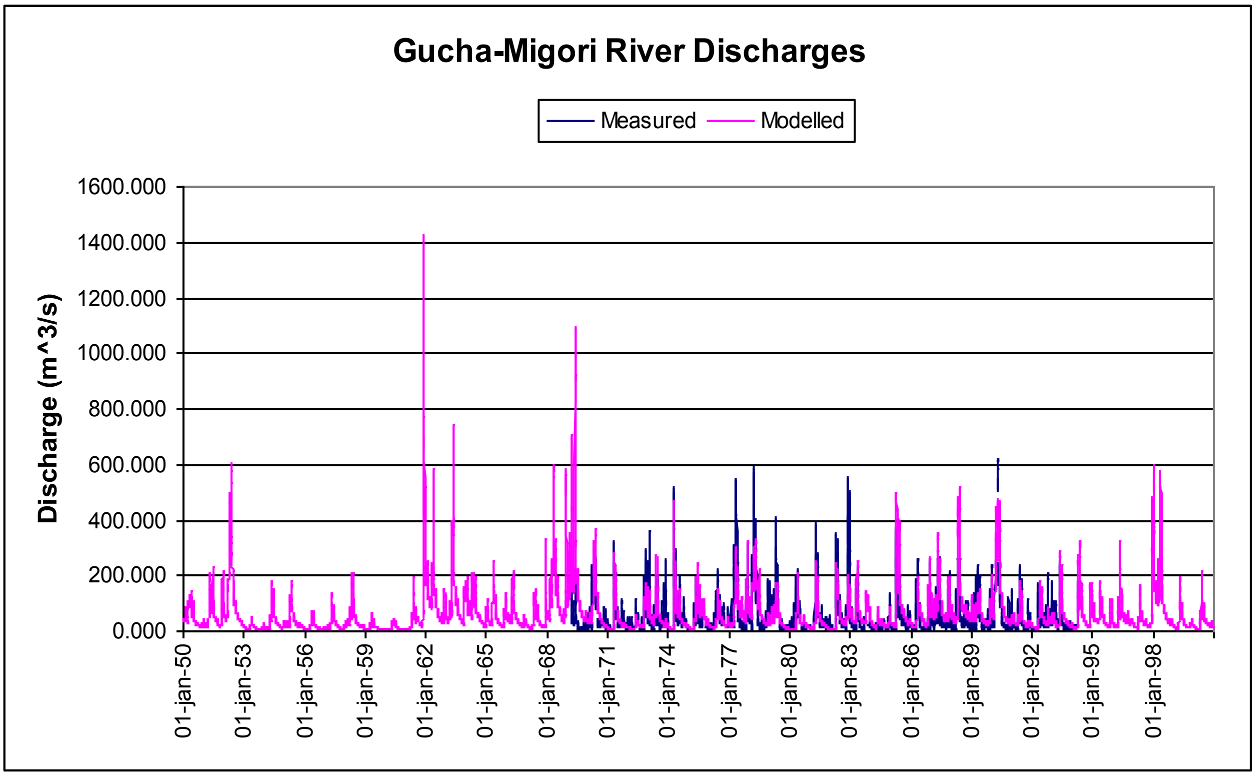

Figure 1.30 Measured and modelled discharges in the Gucha-Migori River at Wathonger.

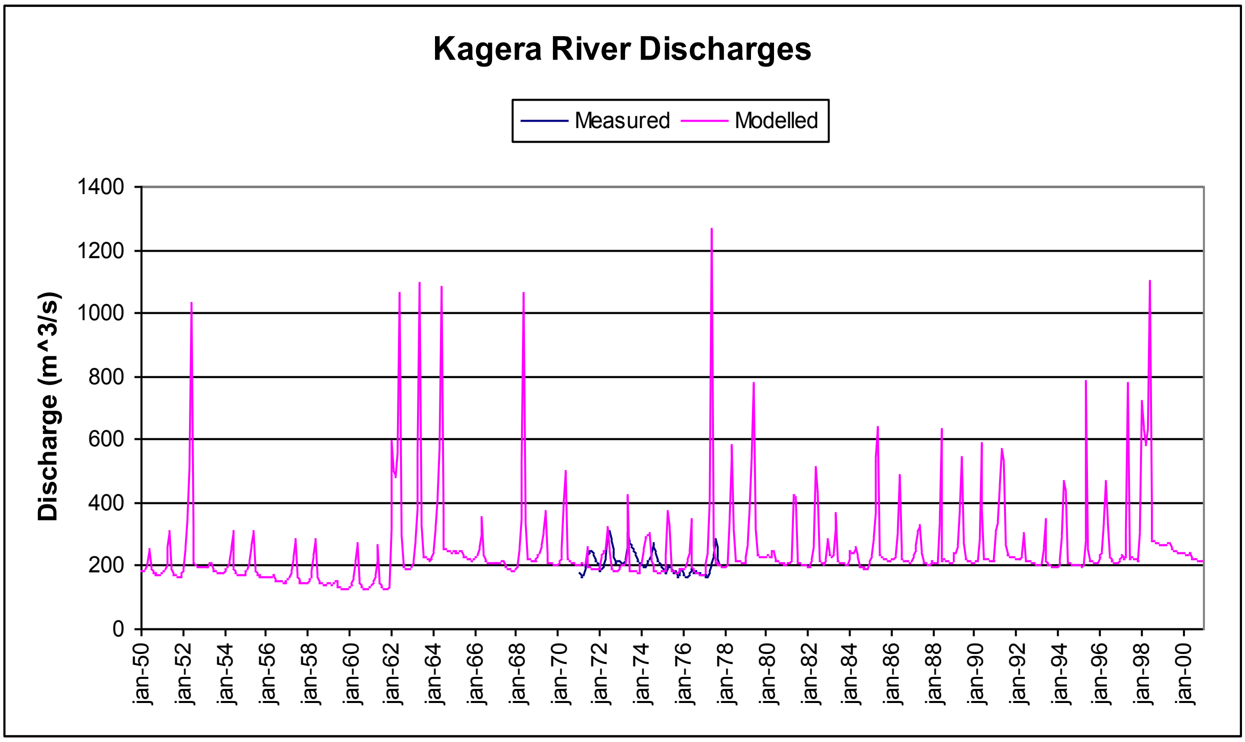

Figure 1.31 Measured and modelled discharges in the Kagera River at Kyaka Ferry.

The final discharge at the gauging station is represented by either the measured or the simulated values. In general, the measured values are used, and the gaps are filled with the modelled values. In cases where the measured values are considered unreliable, they are replaced by the modelled values.

Some comments about the Kagera River results are required. First, the period for which there are measurements, 1971-74, was a dry period with no significant peaks in the flow. This means that the SMAP model could only be calibrated to reproduce the base flow accurately, but not the peaks. Consequently, there can be some doubt about the overall accuracy of the model and the total runoff from the catchment, which is most unfortunate since the Kagera contributes 33% of the runoff to Lake Victoria. On the other hand, the flow is dominated by the base flow due to the size of the catchment, and if the base flow is correct, the greatest part of the runoff will also be correct.

1.7.3 Ungauged Catchments

As described above, two different methods were applied to estimate the runoff from ungauged catchments.

Transferred Rainfall-Runoff Model Parameters

In cases where there is an adjacent catchment of similar hydrologic characteristics that is gauged and has been modelled, the model parameter values are simply transferred to the ungauged catchment or basin. The model is of course applied with the relevant rainfall and evaporation data. The list of the basins, and the catchments within the basins together with the reference catchment is given in Table 1.8.

Table 1.8 Ungauged basins and catchments with transferred model parameter values

Basin	**Sub-catchment**	**Model**	**Reference Model for Parameter Values**
Eastern Shore Streams (TZ)	Mori R area Mugano area Suguti R at Suguti Bunda area Ukerewe Is area	SMAP SMAP SMAP SMAP SMAP	Mori R at Utegi Suguti R at Suguti Gauged and modelled Suguti R at Suguti Suguti R at Suguti
Nyashishi (TZ)	Entire basin	SMAP	Magogo R at Road Bridge
Issanga (TZ)	Entire basin	SMAP	Moame R at Pambani
Southern Shore Streams (TZ)	Entire basin	SMAP	Moame R at Pambani
Biharamulo (TZ)	Entire basin	SMAP	Ngono R at Kyaka Road Bridge
Western Shore Streams (TZ)	Entire basin	SMAP	Ngono R at Kyaka Road Bridge
Northern Shore Sreams (UG)	Entire Basin	NAM	Bukora R

Modified Rational Formula

In Kenya, there are two major lakeshore catchments, namely, the North Awach on the northern shores bordering the Nzoia and Nyando river basins and the South Awach shore catchment which lies on the eastern shores of Lake Victoria and borders the Sondu basin to the north and northeast and the Gucha-Migori river basin to the east and southeast.. The North Awach catchment has a drainage area of about 1985 km^2 and a mean annual flow of about $280x10^6$ m^3/year, while the South Awach catchment has a drainage area of about 3156 km^2 and an annual mean flow of about $450x10^6$ m^3/year.

The North Awach has several small and short rivers most of which are seasonal except for the Kibos, Awach Seme, Kisian and Mugruk rivers which are perennial. The Kibos River is larger than all the others in this catchment and notoriously floods the Kisumu area frequently. In the South Awach catchment, the main perennial rivers are the Kibuon, Awach Tende and Awach Kano rivers.

The hydrometric records in these catchments are very poor. This makes it difficult to calibrate and apply the NAM model in these catchments. Consequently, an empirical model, based on the mass balance concept was adopted for simulating monthly flows in these catchments. This empirical model is a modification of the Rational Formula, and has the form

$$Q=CA(R-k)$$

where Q is the flow in m^3/sec,
C is a constant coefficient,
A is the catchment area in km^2,
k is a lumped rainfall loss parameter which also acts as a monthly rainfall threshold value for the generation of Q and
R is an autoregressively weighted monthly rainfall.

This empirical model was tested with monthly rainfall and discharge data in the Nzioa, Sondu, Kibuon and Sio river basins. In all these cases, the model showed a good fit which accounted for more than 75% of the variance in observed Q. The coefficient C was generally a constant and equal to about 0.004 in all the test cases. However, the threshold parameter k varied within the range 1.8-2.8 mm. The value of k seemed to depend more on the slope of the basin than on the catchment area. Basins with a high average slope had a low value of k while those with gentle average slope had relatively larger values of k. A value of k=1.8 mm was adopted for the South Awach catchment while a value of k=2.5 was adopted for the North Awach catchment. The set (0.3,0.23,0.30.0.17) of autoregressive coefficients for the monthly rainfalls was predominant in the northern basins (and adopted for the North Awach) while the set (0.35,0.38,0.14,0.13) was characteristic of the southern basins (and adopted for the South Awach). The simulated flows (with C=0.004) in the North and South Awach lakeshore catchments were consistent with the estimates by the Department of Water Development in Kenya Ministry of Environment and Natural Resources.

1.8 Final River Basin Discharges

The next step is to calculate the discharge from the entire river basin. As already mentioned in Section 1.2.5, the gauging stations are not placed exactly at the river mouth and the discharge is not representative for the entire river basin area. Further, in several cases the basin is divided into several subcatchments, each with its own gauging station, and the discharges from the subcatchments must be added and then increased to represent the total discharge for the basin.

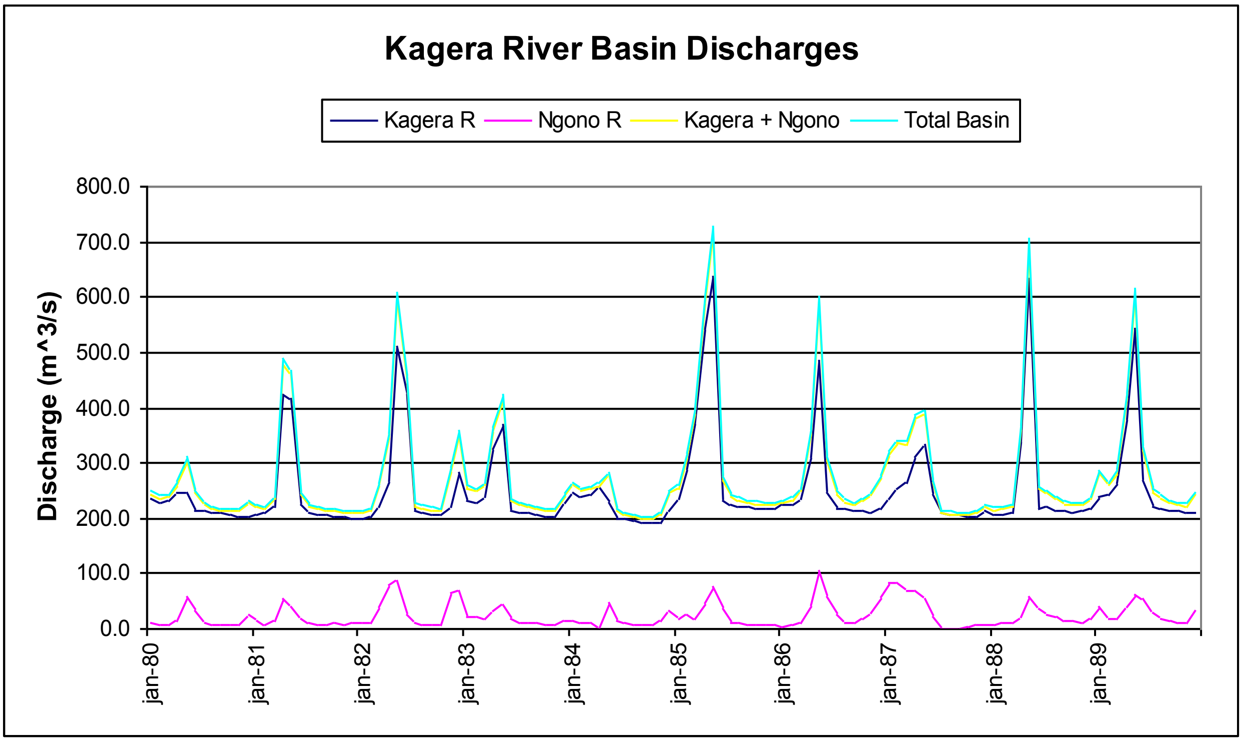

Figure 1.32 Final discharge for the Kagera River Basin.

The example of the Kagera River Basin is shown in Figure 1.32. The Ngono River joins the Kagera near Kyaka and the two gauging stations are just upstream of the confluence. Bewteen Kyaka and the river mouth is an ungauged area which is 2% of the total river basin area (see Table 1.7). The discharge from the total basin is therefore calculated as the sum of the Kagera and Ngono discharges increased by a factor 1.02.

Kagera basin discharge = (Kagera at Kyaka + Ngono at Kyaka) * 1.02

Another example for the Magogo-Moame is shown in F where a slightly different procedure was applied. The river basin is divided into two distinct areas, one represented by the Magogo and the other by the Moame. Therefore the discharges at the gauging stations were first increased to give the discharge for the area represented by each tributary, and then the discharges thus computed were summed.

Magogo-Moame basin discharge = (Magogo * 1.34) + (Moame * 1.12)

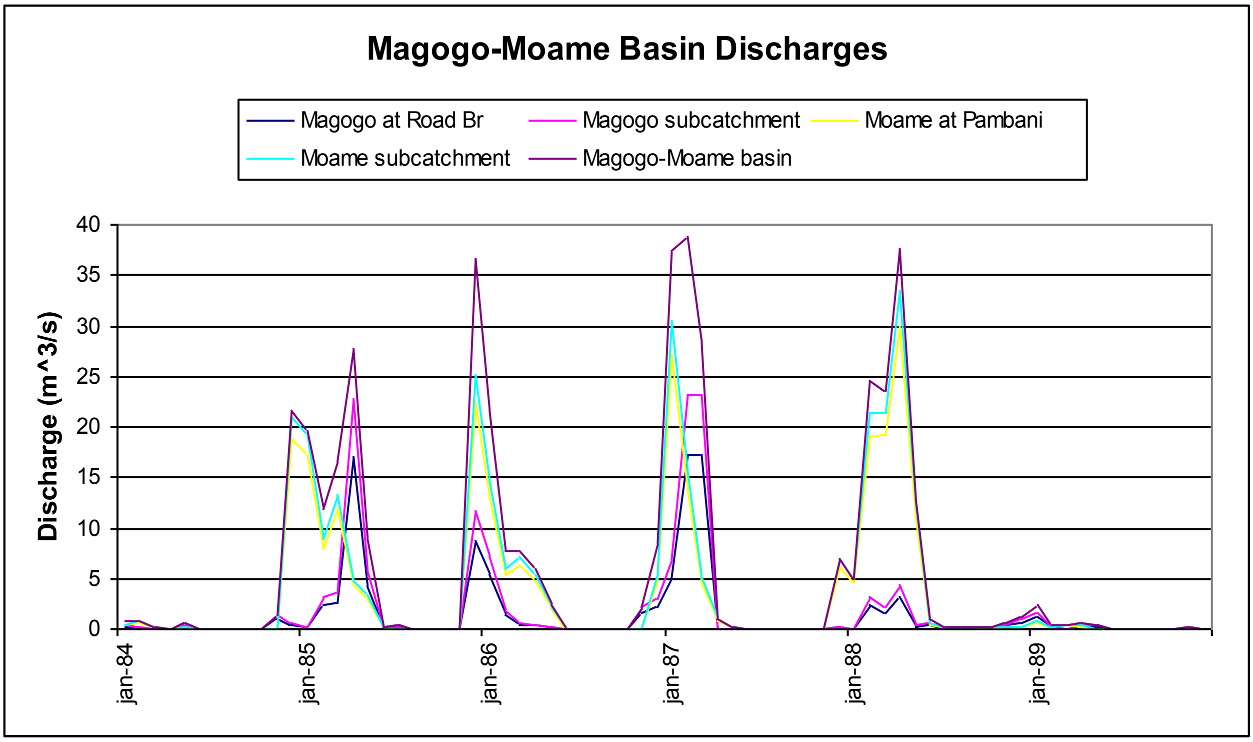

Figure 1.33 Final discharge for Magogo-Moame Basin.

The long term average discharges for each of the basins are shown in *Table 1.9* and the monthly average discharges in Figure 1.34 (Kenya), Figure 1.35 (Tanzania) and Figure 1.36 (Uganda). The Kagera discharge is repeated in each figure to enable a direct comparison of the magnitudes.

Country	Basin	Discharge (m^3/s)	Percent
KENYA	Sio	11.4	1.5
	Nzoia	115.3	14.8
	Yala	37.6	4.8
	Nyando	18.0	2.3
	North Awach	3.7	0.5
	South Awach	5.9	0.8
	Sondu	42.2	5.4
	Gucha-Migori	58.0	7.5
TANZANIA	Mara	37.5	4.8
	Grumeti	11.5	1.5
	Mbalageti	4.3	0.5
	E. Shore Streams	18.6	2.4
	Simyu	39.0	5.0
	Magogo-Moame	8.3	1.1
	Nyashishi	1.6	0.2
	Issanga	30.6	3.9
	S. Shore Streams	25.6	3.3
	Biharamulo	17.8	2.3
	W. Shore Streams	20.7	2.7
	Kagera	260.9	33.5
UGANDA	Bukora	3.2	0.4
	Katonga	5.1	0.7
	N. Shore Streams	1.5	0.2
	Total	778.3	100.0

Table 1.9 Long term average discharges from river basins.

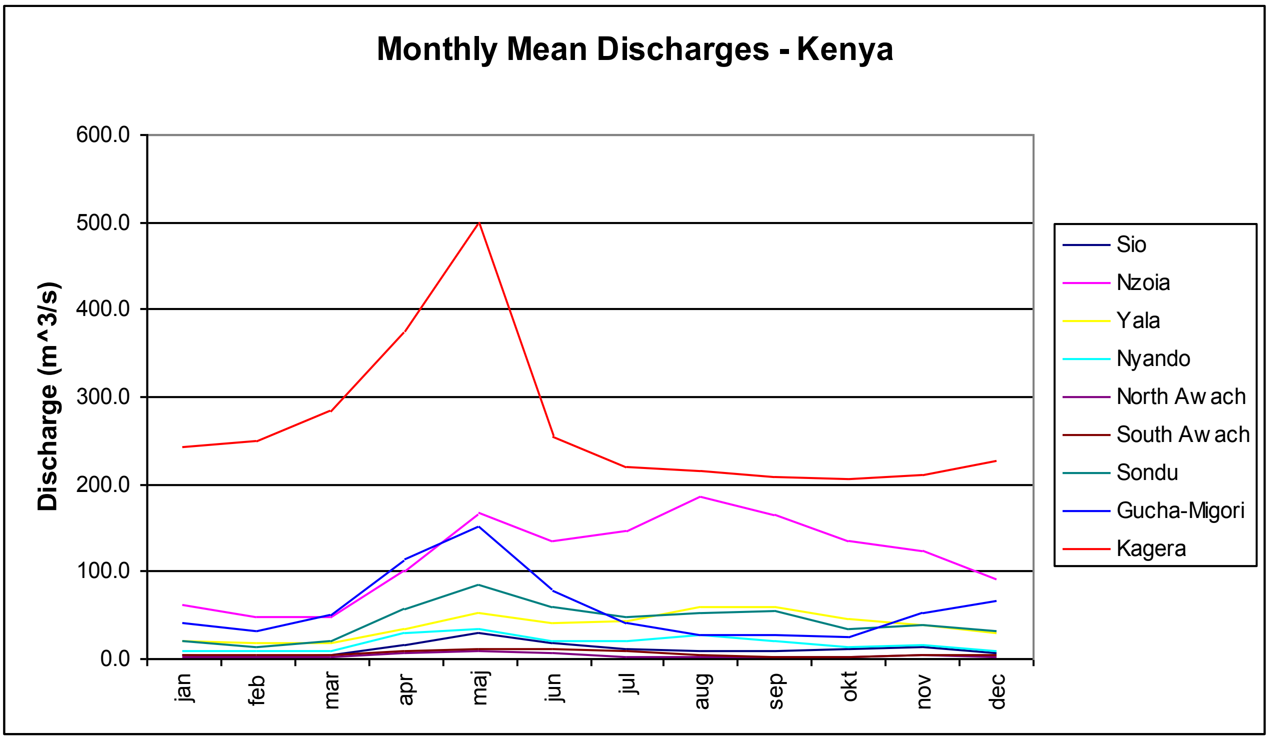

Figure 1.34 Mean monthly discharges for Kenyan basins.

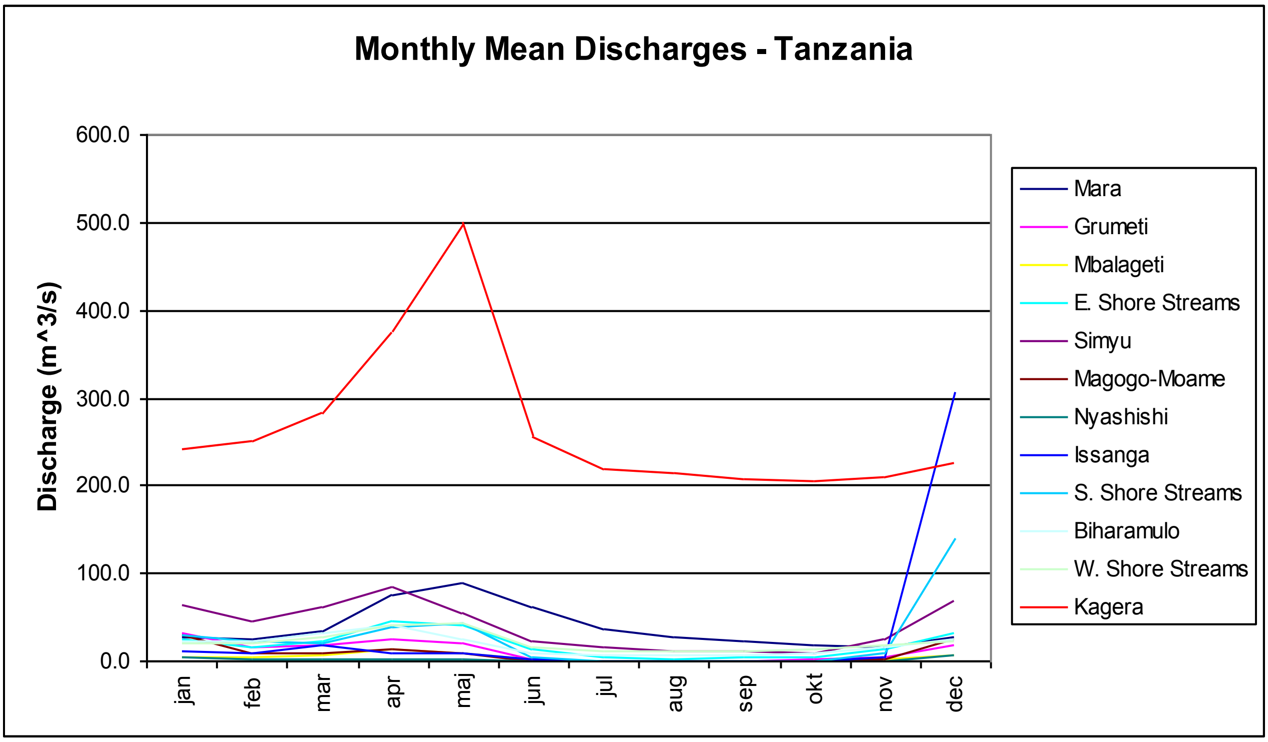

Figure 1.35 Mean monthly discharges for Tanzanian basins.

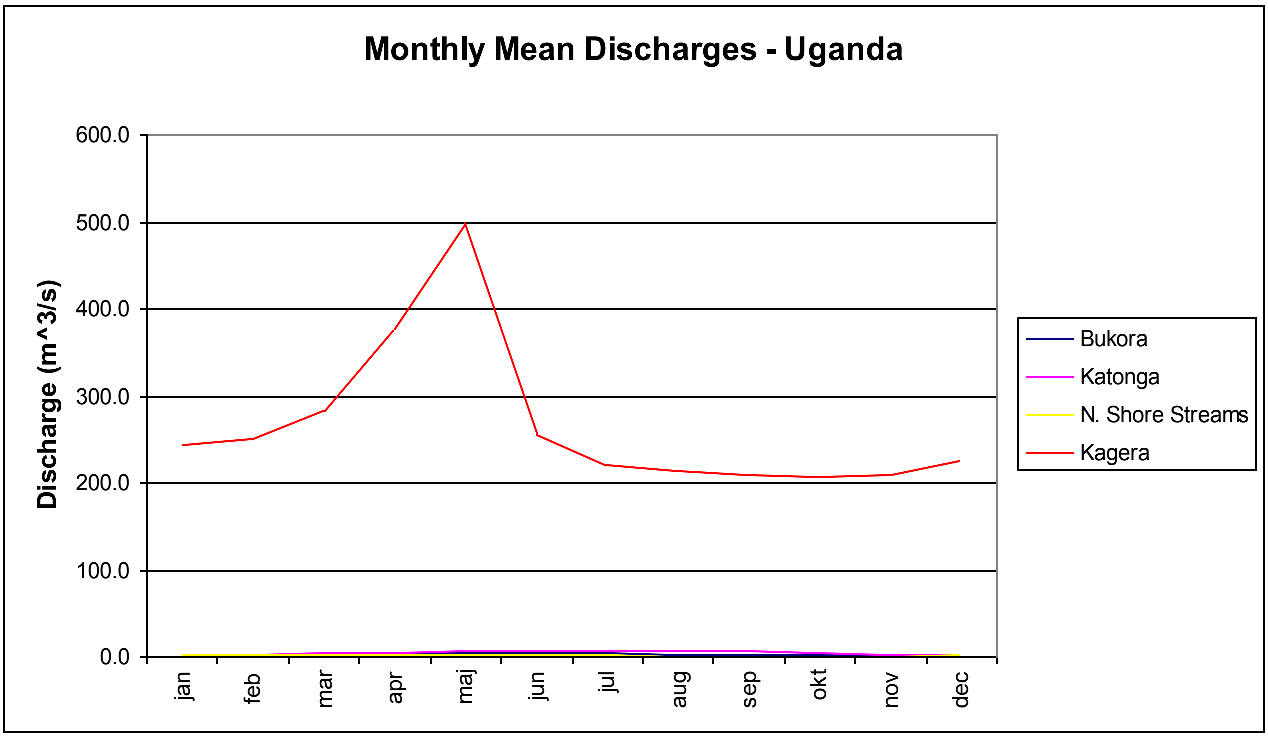

Figure 1.36 Mean monthly discharges for Ugandan basins.

The dominance of the Kagera discharges becomes clear. The varying rainfall and runoff characteristics of the various regions around the lake can also be seen. The wetter Kenyan rivers (all except the Gucha-Migori) show a continuous higher magnitude runoff between April and December. The drier basins (Gucha-Migori and all the Tanzanian basins except Kagera) show peaks in April-May and December, but little runoff for the rest of the year. The Kagera has a peak in May, but a base flow that is higher than monthly peaks of almost all other river basins. Finally, the Ugandan basins contribute almost no water to the lake.

1.9 Victoria Nile Outflow

Basically, there are two data sets, which represent the outflow out of lake Victoria into the Victoria Nile. There is a data set, which dates back to the 1948 which is based on an empirical Q-H relationship (rating curve) between the outflow and the lake levels at the Jinja Pier. This data is commonly referred to as the "natural outflows" out of the lake and is used to regulate the dam operation at the Owen falls. This data has some major gaps in 1978 and 1979. These gaps were filled using a relationship between the natural outflows at Jinja Pier and lake levels at Kisumu where lake level data during these periods was available.

On the other hand, the Owen Falls power generation management has been giving data on actual water releases through the power generation system since January 1970 to date. However, this data on the actual releases into the Nile is consistent only during the period January 1989 to date.

The Owen Falls Reservoir operation not only depends on the current lake level but also on the near future lake level projections. In the past, 7-day lake level projections were used. Currently, 30-day lake level projections are being used.

Understandably, the Owen falls releases depend and also determine to some extent the lake levels. Thus, the two data sets differ significantly in some cases but also show some similarities in others. Notwithstanding, the 30-day running means of the two data sets were essentially the same in both cases. Consequently, the lake outflow time series for the period 1950-2000 was developed from the 30-day running means of the actual Owen Falls releases whenever it was available, otherwise the 30-day running means of the natural outflows were used to construct the series.

The resulting outflow into the Victoria Nile is plotted in Figure 1.37.

1.10 Lake Victoria Water Mass Balance

At this stage all the inflows to and outflows from Lake Victoria have been calculated. The calculations have been based on measurements, correlations, artificial "typical year" data, rating curves, rainfall-runoff modelling and other approximations. Although the approximations all have a sound physical basis, there is plenty of room for errors, and a method is needed for checking the accuracy of the resulting inflows and outflows.

Fortunately, a method is readily available. All the inflows and outflows to/from Lake Victoria can be summed, converted to a change in lake water level and compared with the recorded water levels over the period 1950 to 2000.

Figure 1.37 shows all the inflows and outflows expressed in m^3/s. A 12 month running mean has been applied to smooth the curves. It is seen that the rainfall and evaporation over the lake far exceed the discharges from the river basins and the outflow in the Victoria Nile. The rainfall over the lake is slightly more than the evaporation, and the outflow in the Victoria Nile is correspondingly slightly more than the discharges from the basins.

Table 1.10 shows the long term average values and the percentages. It shows that the rain on the lake surface accounts for 82% on the inflow and evaporation for 76% of the outflow, compared with the commonly assumed values of 80% for both.

The sum of the inflows and outflows gives a positive inflow of 33 m^3/s which accounts for the rise in the lake water level of 0.98 m.

Table 1.10 Average inflow to and outflows from Lake Victoria.

Average 1950-2000	**Flows m^3/s**	**Percent %**
Inflows		
Rain over lake	3631	82
Basin discharges	778	18
Outflows		
Evaporation from lake	-3330	76
Victoria Nile	-1046	24
Sum	33	

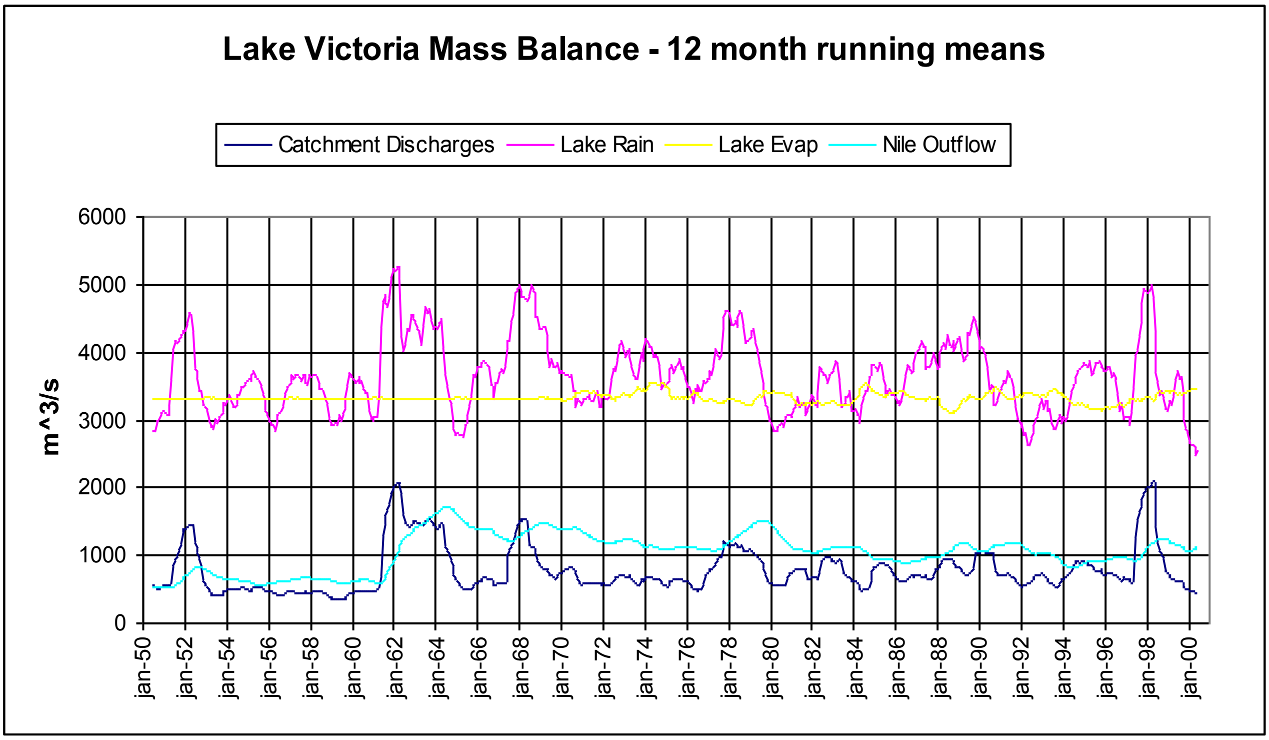

Figure 1.37 Time series of inflow to and outflows from Lake Victoria.

The relative magnitudes of the inflows and outflows are also illustrated in Figure 1.38 where the dominance of the Kagera compared with the other basins is again very clear. The discharge vectors for the basins and the Victoria Nile are in scale, while the rainfall and evaporation over the lake are not to scale for obvious reasons.

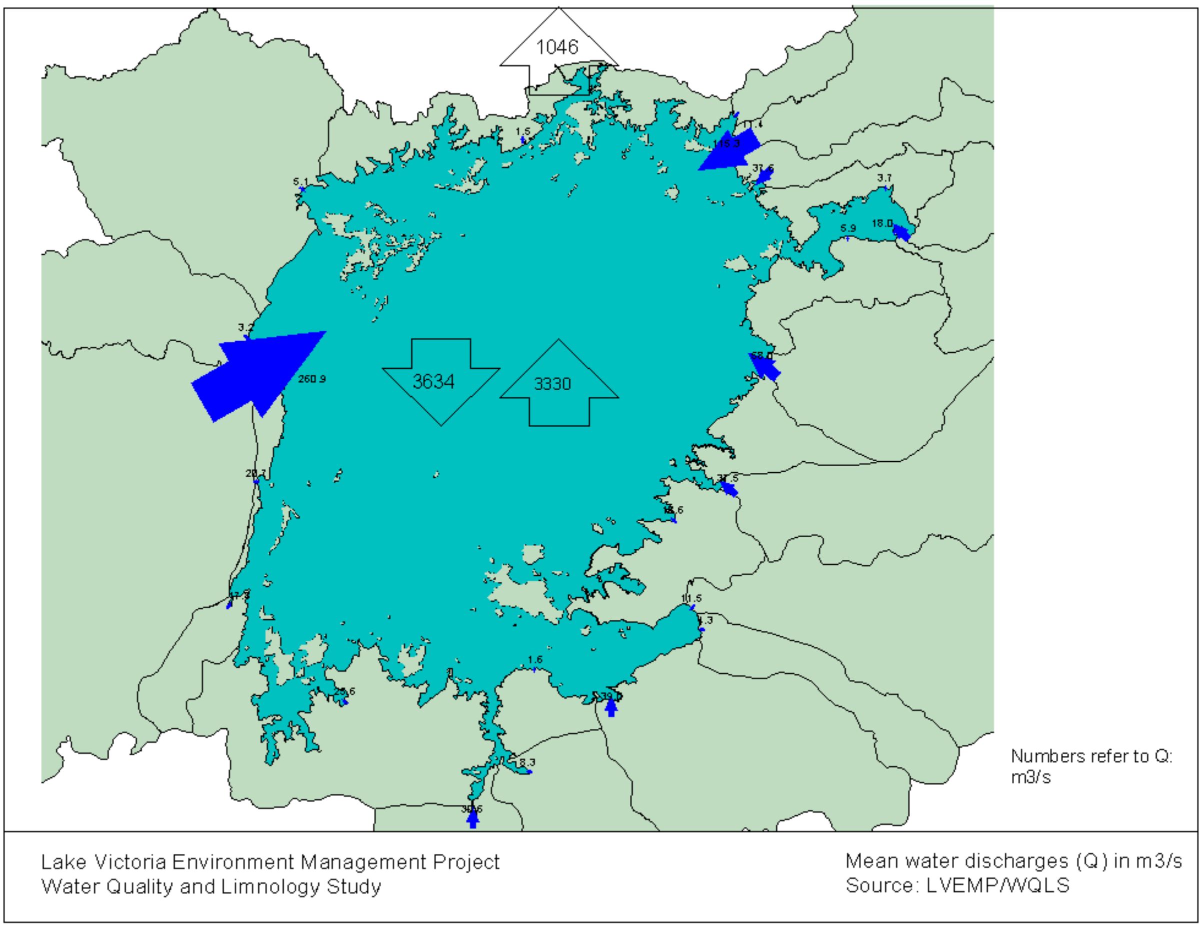

Figure 1.38 Mean annual inflows to and outflows from Lake Victoria

Figure 1.39 shows the measured and calculated water levels at Entebbe when all the inflows and outflows are summed and converted to water levels. The two curves compare very well in the period 1970 to 1988 when there is the largest number of actual measurements of rainfall, evaporation and discharges. A closer examination reveals that the major differences occur in the periods 1950-52, 1961 and 1989-2000.

In view of the possible sources of error described above, it is common practice in mass balance studies to apply correction factors to the various contributions to the balance. The following assumptions were made in order to simplify the number of combinations of correction factors that could be applied:

- The outflow in the Victoria Nile is assumed to be correct since it is based on a well established and widely accepted rating curve.

- The evaporation over the lake is assumed to be correct. The evaporation varies little from year to year, and it does not seem justified to adjust it by application of a correction factor in one year and not others. Further, an adjustment of the evaporation is equivalent to an opposite adjustment of the rainfall, and it is therefore preferable to apply factors to just one of them.

- Since the runoff from the basins is primarily dependent on the rainfall it was decided to apply the same factors to both the discharges and the rainfall over the lake.

After some trials, the correction factors in Table 1.11 were found to give an excellent result as shown in Figure 1.40.

Table 1.11 Correction factors.

Period	**Correction factor**	**Comments**
1 Jan 1950 - 31 Dec 1951	0.80	There is no clear reason for this 20% reduction of rain and discharges in 50-51. The number of active rain stations is almost the same in 52-58 and no correction is required for that period.
1 Jan 1952 - 30 Sep 1961	1.00	Rainfall over lake and discharge from basins are correct.
1 Oct 1961 - 31 Dec 1961	1.30	This is a period of exceptionally high rain which caused the lake level to rise by 1 m. Few rain stations were operating in Kenya and Tanzania, and the use of "typical wet years" did not give sufficient amounts of rain.
1 Jan 1962 - 31 Dec 1988	1.00	Rainfall over lake and discharge from basins are correct.
1 Jan 1989 - 31 Dec 2000	0.94	This corresponds to the period after the HYDROMET Project when the number of rain stations gradually decreased from 50 to 18. The correction of 6% is less than the normal accuracy of rainfall measurements which is 8-10%.

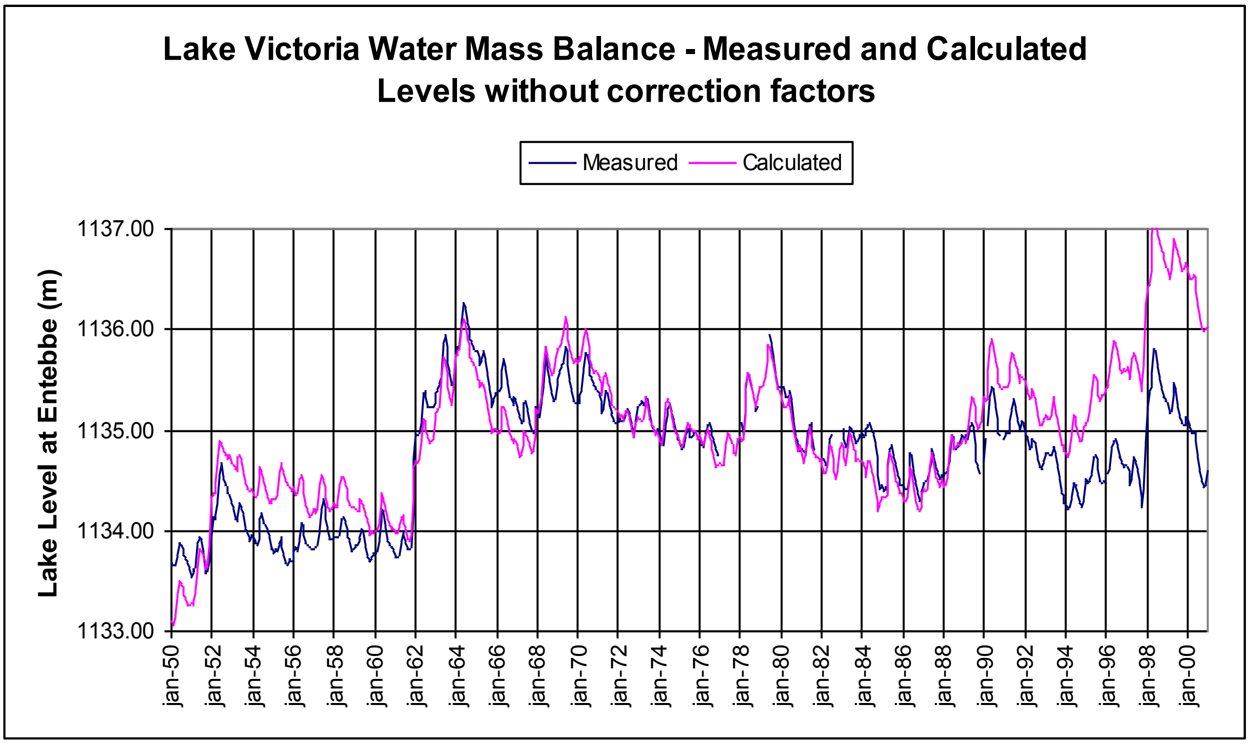

Figure 1.39 Measured and modelled water levels in Lake Victoria without correction factors.

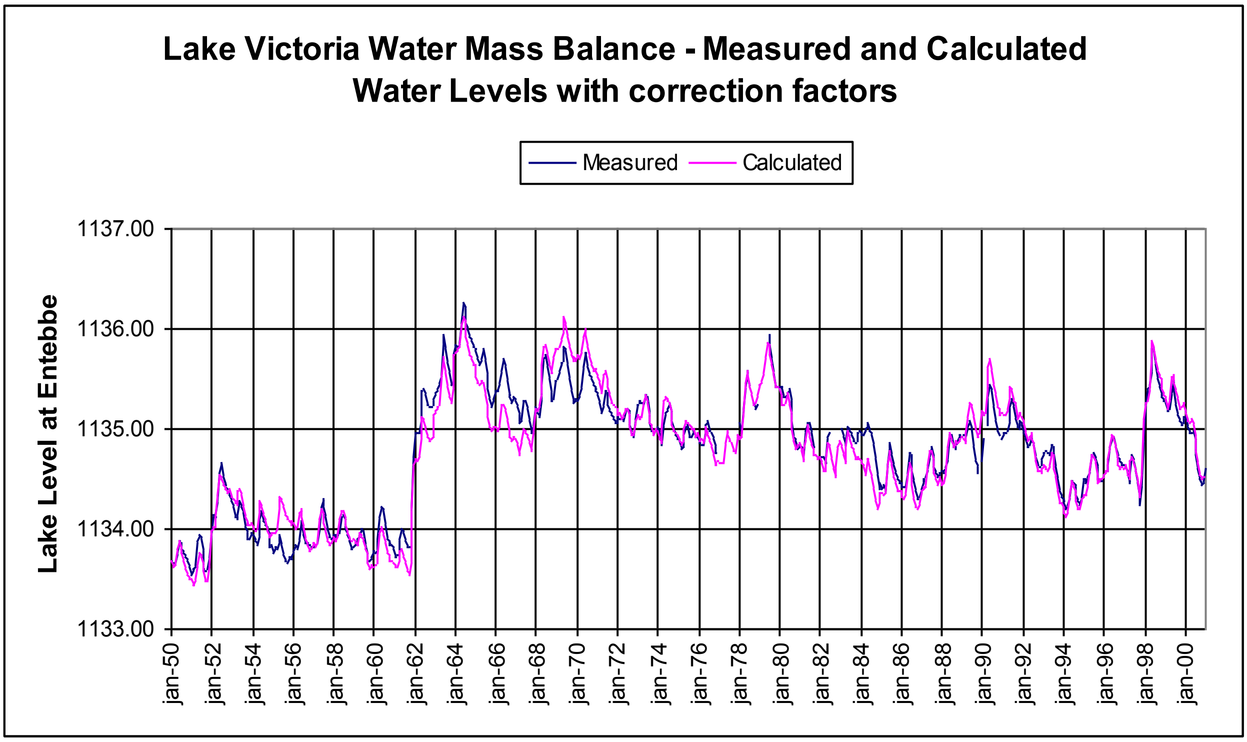

Figure 1.40 Measured and modelled water levels in Lake Victoria with correction factors.

The accuracy of the Lake Victoria mass balance as expressed in Figure 1.40 is indeed remarkable. Not only are the long term changes over 51 years well reproduced, but also the short term variations during each year. The common pattern of a rise in the water level during the "short rains" in October-December is correctly reproduced in the model, and is followed by constant water level in January and a further, larger rise during the "long rains" in February to May. Further, the years that do not follow the common pattern are also well reproduced. There are only two years when the pattern is incorrect, namely 1955 and 1983-84.

1.11 Conclusions and Recommendations

In short it can be concluded that a successful method has been developed for computing the water mass balance for Lake Victoria.

In more detail, the conclusions are:

- A very large amount of data on rainfall, evaporation and river discharges has been collected, collated, analysed, quality controlled, and distributed to the WQ Components in the three riparian countries.

- Data gap filling techniques with a solid physical basis have been developed and applied with success. The techniques are:

  - Correlation to adjacent stations to extend rainfall/evaporation records.

  - Use of changes in Lake water levels to choose typical wet, average and dry years.

  - Insertion of typical rainfall/evaporation data to fill remaining gaps.

  - Rainfall-runoff modelling to extend river discharge records.

- New mean annual rainfall and evaporation maps for Lake Victoria have been developed along with the subdivision of the lake area into rainfall and evaporation boxes.

- The resulting time series of basin discharges and rain/evaporation distribution over the lake provide an excellent basis for the water quality studies, particularly the estimation of non-point pollution loadings, atmospheric deposition of nutrients, and the prioritisation and choice of remedial measures.

The following recommendations are given for the future activities:

- Efforts should be continued in all countries to fill the data gaps with real data instead of the approximations.

- In Kenya it is known that more rainfall and evaporation data is available at the Meteorology Department for the periods before 1970 and after 1990. Attempts should be made to overcome the problems caused by the cost of purchasing the data.

- In Tanzania there is almost no data before 1970 but it is certain that data is available at the Meteorology Department, and this should be obtained for LVEMP. Further, the daily rainfall and evaporation data should be obtained to replace the monthly data. The rainfall-runoff modelling can then be repeated with the NAM model to give more accurate discharge data.

- Particular attention should be given to the important Kagera catchment where there is a rather poor data coverage. Longer time series of rain fall and evaporation data are required along with gauge height data and rating curves at higher discharges.

- Gauging stations for the ungauged catchments south of the lake (Nyashishi, Issanga, Southern Shore Streams and Biharamulo) should be established as soon as possible.

- In Uganda there is a particular lack of evaporation data in the catchments and on the islands. Searches should be made for additional historical data.

- In general, rating curves should be updated for all rivers in all countries.

- The data analysis procedures revealed many cases of erroneous data, but it is certain that not all the erroneous data has been discovered and corrected. Detailed quality control of all the data is required.

- Finally, it is recommended that the mass balance should be continuously updated as additional historical data is collected, and extended each year as new data becomes available.

- More efforts should be put in capacity building in terms of data management, processing and analysis and modeling (particularly Kenya and Tanzania)

- Create public awareness on the importance of Hydrology and Meteorology. It is apparent that some of the data gaps are caused by vandalism of data collection equipment installed at various field stations

- Updating of the data collection and processing tools

- The three governments should put more commitment in maintenance of data monitoring networks. Acquisition of instruments and equipment for monitoring river flows and meteorological parameters should be speeded up, particularly in the case of Kenya.