Deltares
Enabling Delta Life

Annex A Eastern Nile Water Simulation Model

Hydrological boundary conditions

Contents

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1 Introduction

In this Annex the boundary conditions for the simulations with ENSWM for the Eastern Nile up to High Aswan dam / Lake Nasser in Egypt are dealt with.

For simulation of the effect of a selected number of development scenarios on the water availability in the basin a 103-year monthly rainfall, evapo(transpi)ration and flow series for the Eastern Nile sub-basins has been established covering the period 1900-2002. A long series is deemed necessary in view of climatic variations to arrive at a representative series for assessment of effects of basin developments.

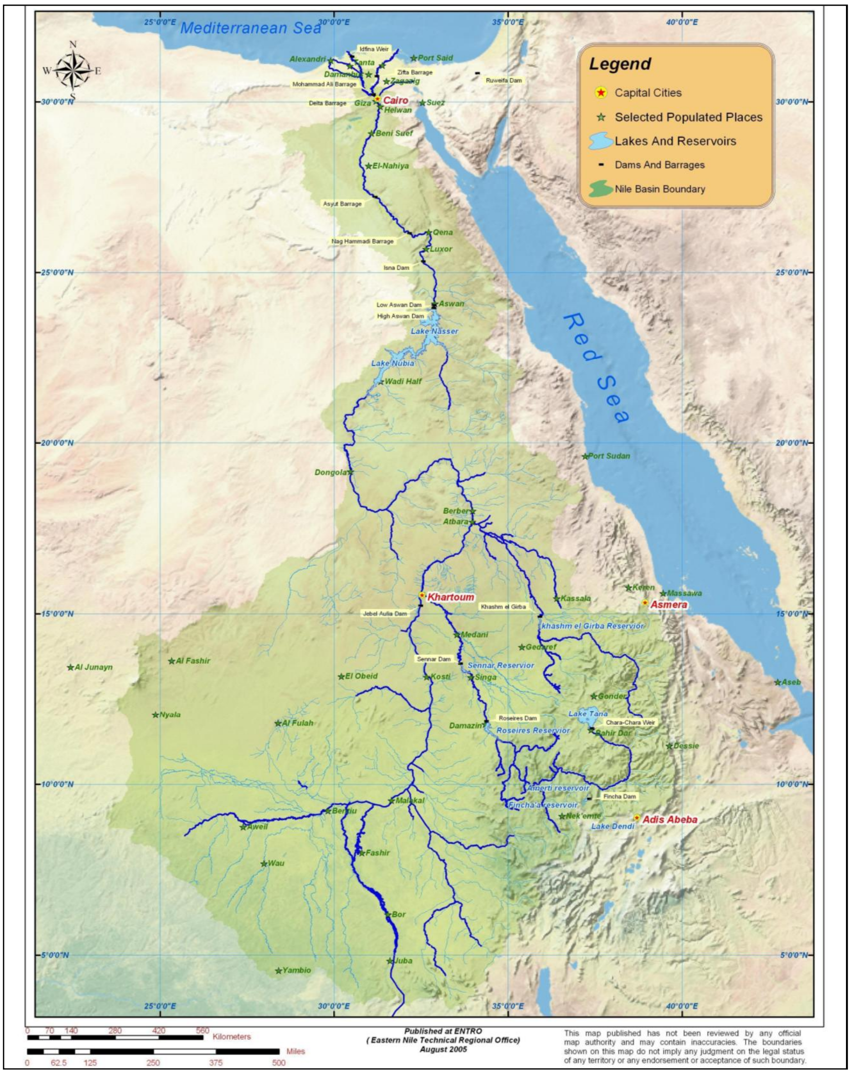

Figure 1.1 Layout of the Eastern Nile river system

2 Hydraulic infrastructure

2.1 River basins and hydraulic infrastructure

The Nile is about 6,700 km long and drains an area of approximately 3 million km2. It comprises the following sub-basins:

- White Nile Sub-basin, divided into:
- Equatorial Lakes Basin upstream of Mongalla; this part is not included in the ENWSM
- White Nile from Mongalla to Sobat mouth, here called the Bahr El Jebel, which is joined by the Bahr El Ghazal at Lake No; this part is included in the ENWSM
- Baro-Akobo-Sobat-White Nile Sub-basin, covering the basins of the Baro, Akobo and Sobat rivers and the White Nile from the mouth of the Sobat to Khartoum; this area is included in the ENWSM
- Abay-Blue Nile Sub-basin from Lake Tana to Khartoum, draining also the basins of the Dinder and the Rahad; this area is included in the ENWSM
- Tekeze-Setit-Atbara Sub-basin draining to the Main Nile at Atbara town; this area is included in the ENWSM
- Main Nile Sub-basin:
- Basin from Khartoum till Lake Nasser, which is included in the ENWSM
- Basin from Lake Nasser to the Mediterranean Sea at Alexandria, which is not included in the ENWSM.

The Eastern Nile Basin covers the following four sub-basins:

- Baro-Akobo-Sobat-White Nile Sub-basin — BASWN Sub-basin
- Abay-Blue Nile Sub-basin — ABN Sub-basin
- Tekeze-Setit-Atbara Sub-basin — TSA Sub-basin
- Main Nile Sub-basin — MN Sub-basin

The catchments of the Bahr El Jebel and Bahr El Ghazal between Mongalla and the Sobat mouth near Malakal, which drain the main swamp areas of the White Nile, are not part of the four Eastern Nile sub-basins. They are included in the ENWSM for modelling reasons only: the upper boundary of the model has been located at Mongalla.

2.2 The Equatorial Lakes basin

The Nile Basin between the source of the Kagera River in the south and Nimule just upstream of Mongalla in the north, covers land and lakes within the borders of Burundi, Rwanda, Tanzania, Kenya, Uganda, and the Democratic Republic of Congo. The Equatorial Lakes Basin constitutes some 13.4% of the entire Nile Basin. The hydraulic infrastructure of the White Nile in the Equatorial Lakes Basin comprises:

Figure 2.1 Nile Basin.

- The Kagera River with the Rusumo Falls, draining parts of Burundi and Rwanda to Lake Victoria,
- Lake Victoria, receiving its water from the net rainfall on the lake, from the Kagera River and a large number of smaller tributaries,

- Victoria Nile, with the Owen Falls, connecting Lake Victoria with Lake Kyoga,
- Lake Kyoga receiving its water from Lake Victoria and surrounding swamps,
- Kyoga Nile, with the Murchison Falls, connecting Lake Kyoga with Lake Albert,
- Lake George in south-western Uganda connected to Lake Edward,
- Semliki river, connecting Lake Edward with Lake Albert,
- Lake Albert, receiving water from the Kyoga Nile and the Semliki, Muzizi and Nkuzi Rivers, and
- Albert Nile from Lake Albert to Nimule, at the South Sudanese-Ugandan border, draining the Upper Nile waters, further increased with the runoff from the torrents between Pakwach and Mongalla, including Aswa River debouching at Nimule draining Northern Uganda.

The Equatorial Lakes basin, the upper part of the White Nile, has been excluded from the Eastern Nile Water Simulation Model. The flow at Mongalla in South Sudan has been taken as upstream boundary of the model.

2.3 White Nile from Mongalla to Sobat mouth

From Mongalla in South Sudan onward the White Nile, here called Bahr el Jebel, enters the Sudd swamps, which extend up to Lake No, west of Malakal. North of Mongalla the river passes Bor, where the entrance to the Sudd bypass the Jonglei Canal, is planned. Midway Bor and Lake No part of the river flow is conveyed via the Bahr el Zheraf, which joins the Nile again at Tonga. At Lake No the Bahr el Ghazal joins the Bahr el Jebel and between Tonga and Malakal, close to Hillet Doleib, the Sobat river confluences with the Nile. The planned outlet of the Jonglei Canal is near the mouth of Sobat River. Through the Sudd the Nile looses a lot of water to evaporation. Sutcliffe and Parks (1999) estimate the area of the Sudd seasonally varying from 7,000 to 13,000 km^2 prior to 1961 and from 17,000 to 29,000 km^2 as of 1961, when the inflow doubled.

The Bahr el Ghazal drains the steep divide between the basins of the Democratic Republic of Congo and the Nile in South-Western South Sudan around the city of Wau. The main contributors to the flow are the Lol, the Jur and the Tonj. From the west the Bahr el Ghazal is joined by the Bahr el Arab, draining Southern Darfur in Sudan Before the confluence of the Bahr el Ghazal with the Bahr el Jebel at Lake No it has lost almost all of its waters to evaporation in the swamps North-East of Wau, extending over an area ranging from 4,000 km^2 in the dry mid-eighties to approximately 17,000 km^2 in the wet early sixties of the last century, with large seasonal variations.

2.4 Baro-Akobo-Sobat0White Nile Sub-basin

The Baro drains a number of mountain streams from the Ethiopian Plateau in South-West Ethiopia upstream of Gambela. From its source the Baro is first joined by Genji River. Near Bure the Birbir River joins, which conveys also the runoff from the basins of the Geba, the Sor and the Gumero Rivers. Downstream of Gambela the river enters a marshy area and water is also lost to the Machar Swamps. Sutcliffe and Parks (1999) estimate the loss between Gambela and the mouth of the Baro at 2.8 BCM/year.

The Pibor drains the South Sudan States Eastern Equatoria and Jonglei (southern part), including the plains east of Bor upstream of Pibor Post via the Veveno, Lorilla and Kangen rivers.

Towards the confluence with the Baro the river is joined subsequently by the rivers Akobo, Gilo and Alwero. In the lower reaches of the Pibor and its tributaries the area is marshy and the rivers loose much of their flows to evaporation.

From the confluence of the Baro and the Pibor shortly upstream of Nasir, the river is called Sobat and enters the White Nile just downstream of Hillet Doleib, upstream of Malakal.

On Alwero the Abobo dam has been constructed, which is planned to supply irrigation water to a command area of 10,400 ha, most of which is currently being developed.

Downstream of Malakal the slope of the White Nile is very small: 1.5 cm/km. In the 730 km reach from the mouth of the Sobat to Khartoum inflows from tributaries are negligible; only Khor Adar debouching at Melut contributes. There is a net water loss due to evaporation from the river, further increased by the operation of Jebel Aulia dam and reservoir since 1937 which heads up the water table for irrigation and navigation purposes.

At present irrigation water is supplied from the White Nile in the Sudan to a total command area of 348,600 ha, including public and private pump schemes, Kenana Sugar, Kenana, Hagar Asalaya Sugar, Sondos and White Nile schemes.

2.4.1 Abay-Blue Nile Sub-basin

Lake Tana Basin

The headwaters of the Abay-Blue Nile are formed by the basins of the rivers draining to Lake Tana including Gigel Abay, Tana West, Gami Kure, Dirma, Megech, Gumero, Garno, Ribb, Gumara and Gelos.

In 1995-1996 the Chara Chara weir at the outlet of Lake Tana at Bahir Dar was put in operation for hydropower production (Tis-Abay HPP I & II with 77 MW installed capacity). The weir controls a volume of 9.1 BCM in the lake (= 2.4 x average annual outflow) between the levels 1784 and 1788 m + MSL. Currently, the weir is also used to divert water from the lake to the Tana-Beles system.

At present in the Gigel Abbay basin the Koga irrigation system exists, with a gross command area of 7,000 ha (net 5,100 ha).

Abay-Blue Nile tributaries d/s Lake Tana

Downstream of Lake Tana a number of tributaries discharge to the Blue Nile upstream of the border with Sudan, including a.o. Beshile, Welaka, Jemma, Muger, Guder, Birr, Finchaa, Diddessa (including Wama, Dabana River and Angar), Dabus and Beles. From the Sudanese-Etiopian border to the river mouth at Khartoum the river is joined by the Dinder and Rahad Rivers.

In Ethiopia at present in the Abay-Blue Nile Basin d/s of Lake Tana the following water use projects exists:

- Beles basin with Tana-Beles hydropower dam having an installed capacity of 460 MW and 2,000 ha irrigation project under development (not yet in operation),
- In Finchaa basin the Finchaa-Amerti dams with 134 MW installed capacity producing hydropower and supplying irrigation water to 6,205 ha under the Finchaa Sugar scheme.

On the Blue Nile in Sudan the Roseires (1966) and Sennar (1924) dams and reservoirs supply water for irrigation and generate hydropower. Their storage capacity at present is less than 3 Bm^3. The second and main filling of the reservoirs takes place in September and October as soon as the river flow at Deim has dropped to 350 Mm^3/day. Their emptying starts in November and lasts till April-May. To increase the capacity of Roseires reservoir to allow development of new irrigation schemes the dam is being raised. At present, the total irrigated area along the Blue Nile in Sudan, including Dinder and Rahad, amounts 1,304,940 ha. This comprises the schemes Gezira and Managil, Rahad, El Suki, Guneid Sugar, Sugar NW Sennar, Abu Naama, Seleit, Waha and public and privat pump schemes.

2.4.2 Tekeze-Setit-Atbara Sub-basin

The Atbara drains the Nile Basin north of Lake Tana. Its headwaters are formed by the Goang River, and leaves Ethiopia at Metema. On its course north, parallel to the Ethiopian-Sudanese border, it is joined by the Angereb. Further downstream, near Humera, the Setit or Tekeze, draining the Simien Mountains north-east of Gonder and also parts of Eritrea, joins the Atbara just upstream of Khasm El Girba reservoir (1964) in Sudan, which supplies water to the New Halfa scheme and generates hydropower. To the basin also the seasonal Mareb or Gash River belongs, which drains the South-Western part of Eritrea. It reaches Sudan near Kassala to dissipate in the Eastern Sudanese plains.

In Ethiopia at present no large-scale irrigation schemes exists in the Tekeze Basin, though a number of small scale irrigation farms exist. Recently, the Tekeze hydropower dam (TK5) in the upper Tekeze basin was put in operation.

In Sudan the Khasm El Girba Multipurpose Dam supplies water to the New Halfa schemes with a total irrigated area of 206,640 ha.

2.4.3 Main Nile Sub-basin

At Kartoum the Blue Nile joins the White Nile and the combined waters, increased with the runoff from Atbara, flow for 1430 km to Aswan. The river’s course consists of a series of mildly sloped placid reaches, separated by steep sloped turbulent rocky sections, called cataracts. From Khartoum onward the following cataracts are discerned: 6th cataract or Sabaluka cateract between Khartoum and Shendi, 5th cataract between Atbara and Abu Hamed, 4th cataract near Merowe, 3rd cataract at Kajbar, Dal cataract, 2nd cataract at Wadi Halfa and 1st cataract at Aswan.

A number of dams and barrages have been built in the Main Nile to generate hydropower and/or to head up/store water mainly for irrigation.

In 1903 at Aswan the first dam (now called Old Aswan Dam) in the Main Nile was constructed, followed in 1968 by the High Aswan Dam with Lake Nasser fully controlling the Nile regime in Egypt, whereas in 2009 the Merowe multipurpose dam for hydropower production and irrigation water supply in Sudan was inaugurated. At Lake Nasser, Nile water is diverted to the Toshka New Valley scheme. Further downstream the Esna, Nag Hammadi, Asyut and Delta (Damietta and Rosetta) barrages head up the water to divert virtually all Nile water released at Aswan mainly to irrigations areas along the river. Before entering the Mediterranean Sea the Damietta branch diverts water at Zifta barrage and ends up at Farascour dam and the Rosetta branch is controlled by Idfina barrage. The following sections in this reach are distinguished:

- Old Aswan dam to Esna barrage
- Esna barrage to Nag Hammadi barrage
- Nag Hammadi barrage to Asyut barrage
- Asyut barrage to Delta barrages
- Damietta branch, from Damietta, via Zifta barrage to Farascour dam
- Rosetta branch, from Rosetta to Idfina barrage.

The latter two branches ultimately discharge into the Mediterranean Sea.

At present, in Sudan along the Main Nile the total irrigation area amounts 150,620 ha, including 20,000 ha at Merowe. In Egypt the irrigated area along the Main Nile amounts currently 3.9 million ha.

2.5 Hydrological characteristics

2.5.1 Rainfall and evaporation

Since the course of the Nile extends from 4oS to 32oN it flows from highland regions in the tropical climate zone with abundant moisture to lowland plains under severe arid conditions, see Figure 2.2. The average annual rainfall over the basin is seen to decrease considerably from upstream to downstream. The highest rainfall region is around Lake Victoria, along the Nile-Congo divide (the hill torrents draining to the upper reaches of the Bahr el Ghazal basin) and south of Lake Tana (Blue Nile and Baro basins). North of the line Malakal-Roseires the annual amounts are seen to reduce drastically to fairly nil north of Dongola till Cairo to rise slightly toward the Mediterranean Sea.

The main controls on rainfall over the Nile Basin are localised convective heating, the passage of easterly wind westward over the Blue Nile and middle Nile catchments, and the extent and timing of the seasonal migration of the Inter Tropical Converge Zone (ITCZ). The effect of the migration of the ITCZ creates a bi-modal seasonal rainfall patterns in the Equatorial Lakes basin with rainfall maxima in April and between September and November. Northward, downstream Mongalla, see Figure 2.3, the months with maximum rainfall gradually shifts towards a single maximum in July-August. Also, the total amount reduces drastically towards the north.

Annual reference evapo-transpiration is seen to be highest between Khartoum and Lake Nasser with values in the order of 2,500 to 3,000 mm, gradually decreasing southward and northward. The seasonal variation is shown in Figure 2.4. Values are highest at the end of the dry season.

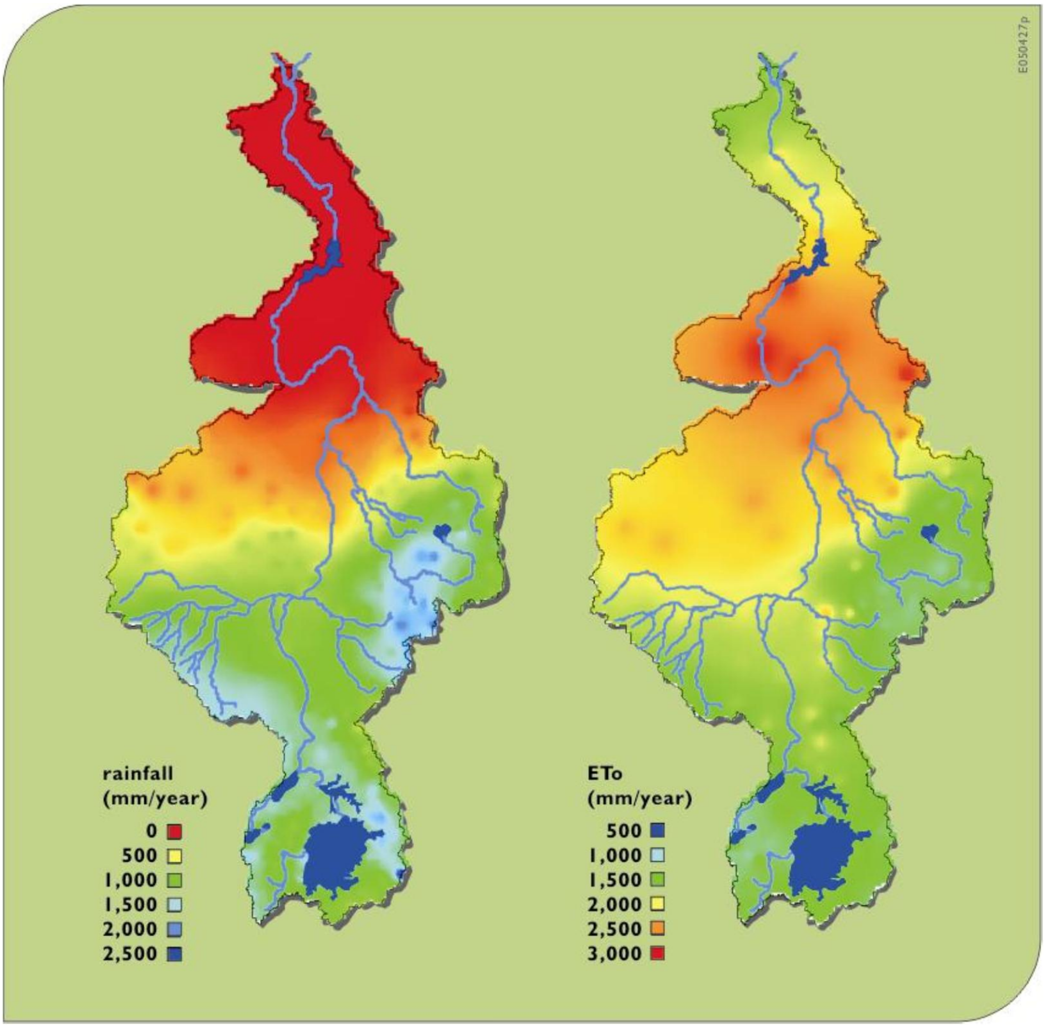

Figure 2.2 Average annual rainfall and reference evapo-transpiration in the Nile Basin

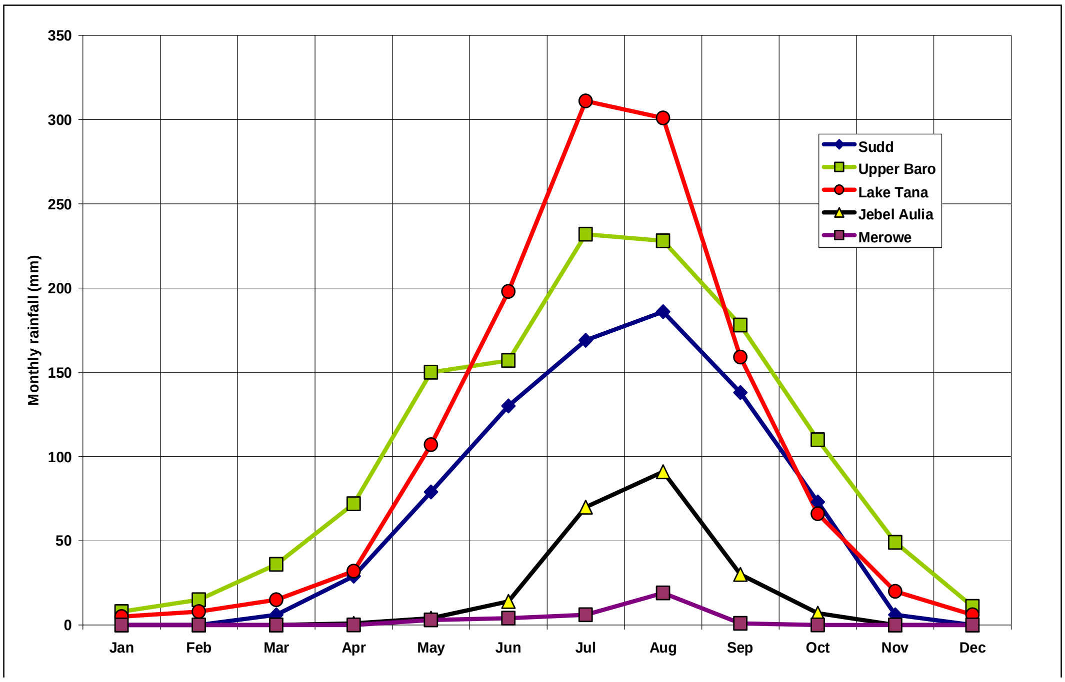

Figure 2.3 Average monthly rainfall pattern in model area

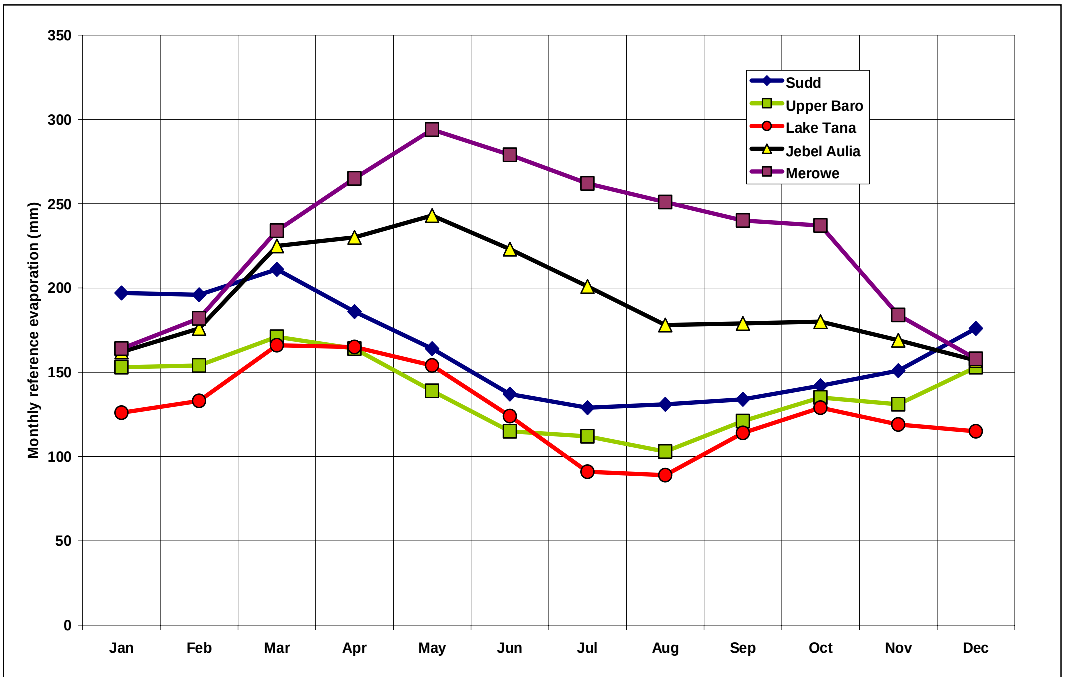

Figure 2.4 Average monthly reference evapo-transpiration in model area

2.5.2 River flows

Fluctuations in the Nile flows are primarily driven by the variation in rainfall over the Ethiopian Highlands. These highlands contribute on average about 83% of total Nile flow at Aswan, while the Equatorial Lakes Basin adds only some 17% to it, see Figure 2.6.
Although it is one of the world's major rivers, its flow is limited as the Nile loses a considerable amount of water to evaporation in the natural and man-made lakes, wetland areas and during

its 3000-kilometre course through the arid lands in The Sudan. Major losses take place in the Sudd in South Sudan as can be observed from Figure 2.7; whereas the average annual flow in the White Nile at Mongalla amounts about 40% of the flow at Aswan only 42% of it reaches Aswan.

The average monthly flows at key locations in the Nile Basin d/s of Mongalla are shown in Figure 2.8 to Figure 2.10. Figure 2.8 presents the attenuation of the Baro flow by the Machar marshes between Gambela and its mouth. Together with the delayed runoff from the Pibor by the extensive wetlands/swamps in the area, this results in a smoothened retarded hydrograph of the Sobat at its mouth near Hillet Doleib just upstream of Malakal. From Figure 2.9, which shows the inflows and outflow from the Sudd, it is observed that the Sudd completely flattens out the seasonal variation of the White Nile at Mongalla and the Bahr el Ghazal. As a result, the monthly average flow in the White Nile at Malakal varies like the Sobat at mouth plus a constant (i.e. the outflow from the Sudd).

The genesis of the average monthly flow in the Blue Nile is presented in Figure 2.9. The regime, wich generally peaks in August, clearly follows the rainfall pattern (see Figure 2.3) with highest amounts in July-August. Only the outflow from Lake Tana at Bahir Dar is attenuated by the lake and peaks generally in September-October. It is also observed that beyond the Ethiopian-Sudanese border very little is added to the Blue Nile flow in Sudan, keeping in mind that also part of the runoff from Dinder and Rahad originate from upstream of the border. All contributors to the natural flow in the Nile at Aswan are shown in Figure 2.10. The figure shows that the average monthly flow of the Atbara resembles the Blue Nile flow at Khartoum apart from a factor. Hence, the difference in shape between the Nile regime at Aswan and of the Blue Nile at Khartoum is caused by the White Nile, mainly by the swamps in South Sudan: it heads up the flow in the Main Nile in the lean season of the Blue Nile substantially and enlarges the duration of the flood period with an extra month. Though annually on average its contribution to the natural flow at Aswan is only some 30% its contribution from December till June is percentage wise much larger. Particularly this picture will alter substantially with the creation of artificial storage capacity in the Blue Nile in Ethiopia.

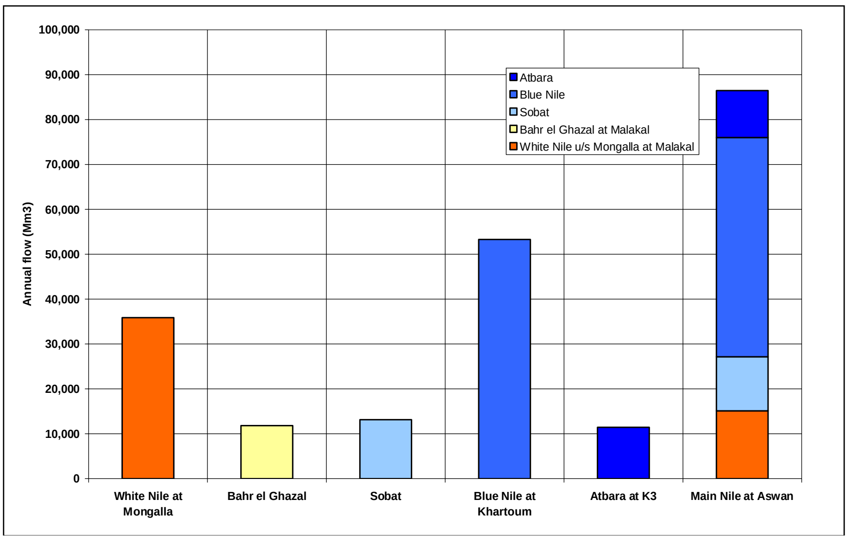

Figure 2.5 Average annual flows of Nile branches and their contributions to the flow at Aswan (in blue contributions from the Ethiopian Plateau)

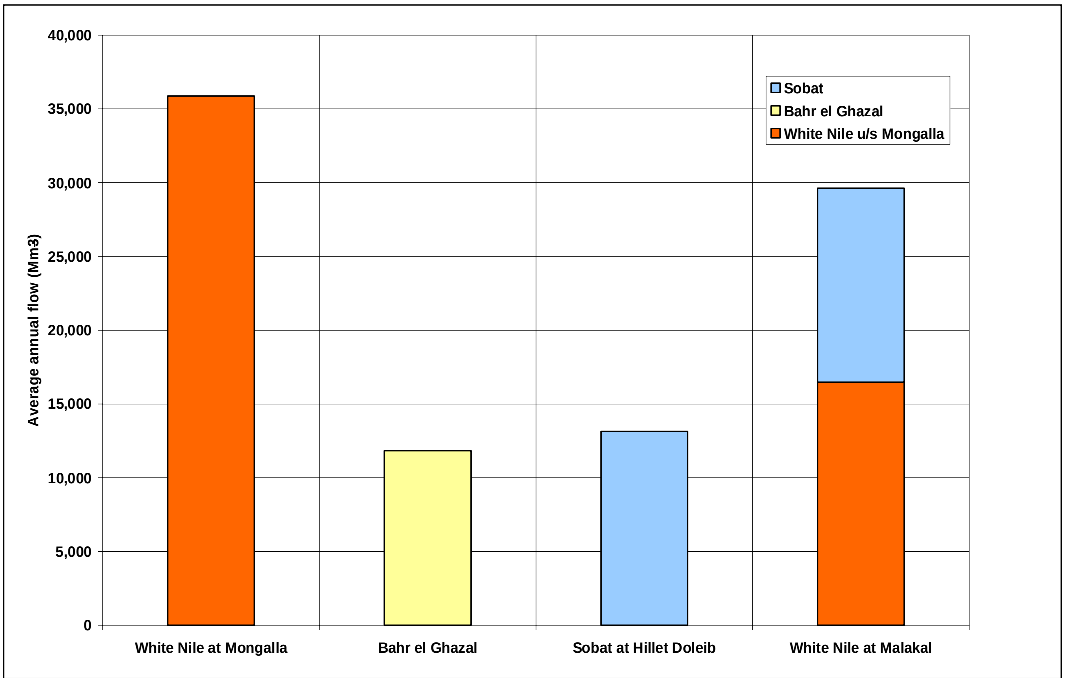

Figure 2.6 Inflows to the Sudd and their contributions to the White Nile at Malakal

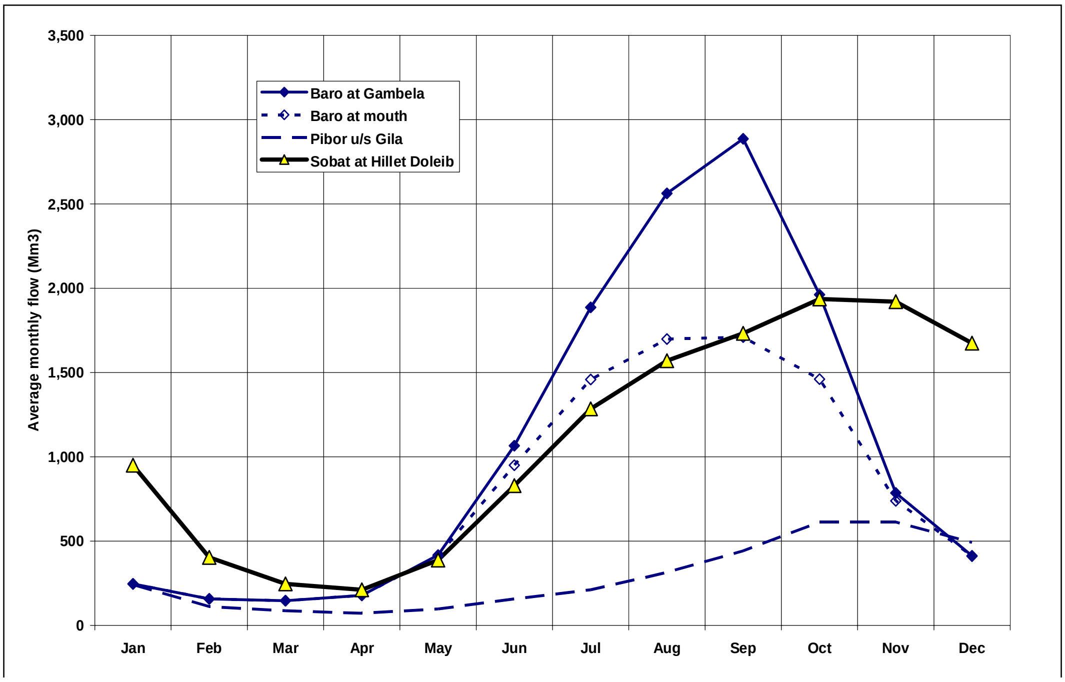

Figure 2.7 Average monthly flows in Baro, Pibor and Sobat

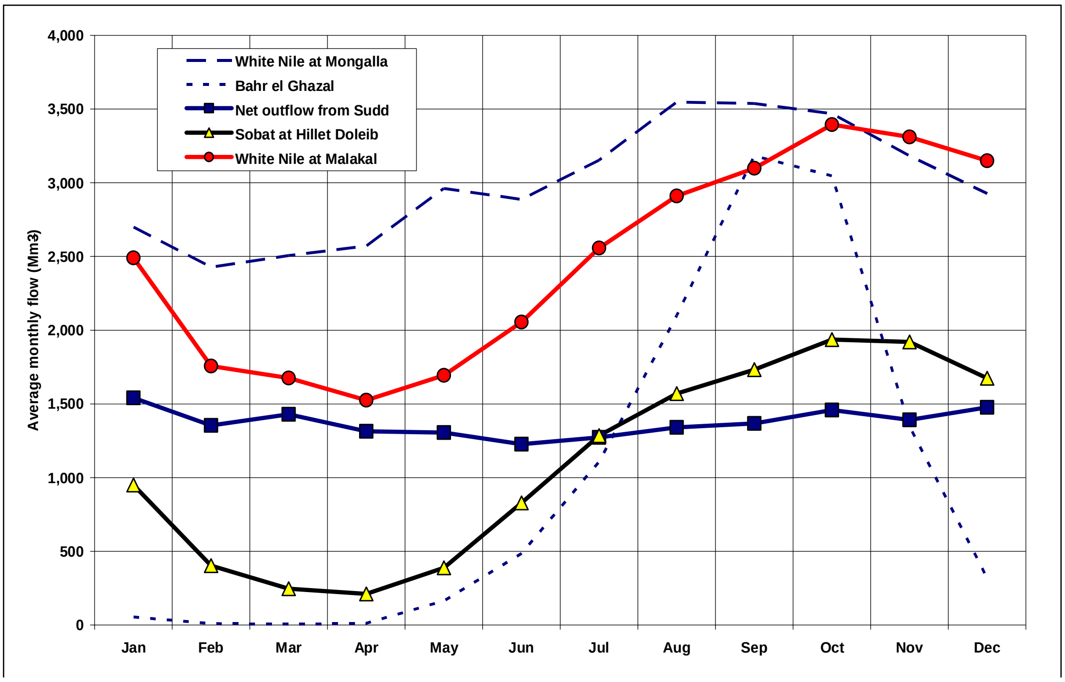

Figure 2.8 Average monthly flows in White Nile between Mongalla and Malakal

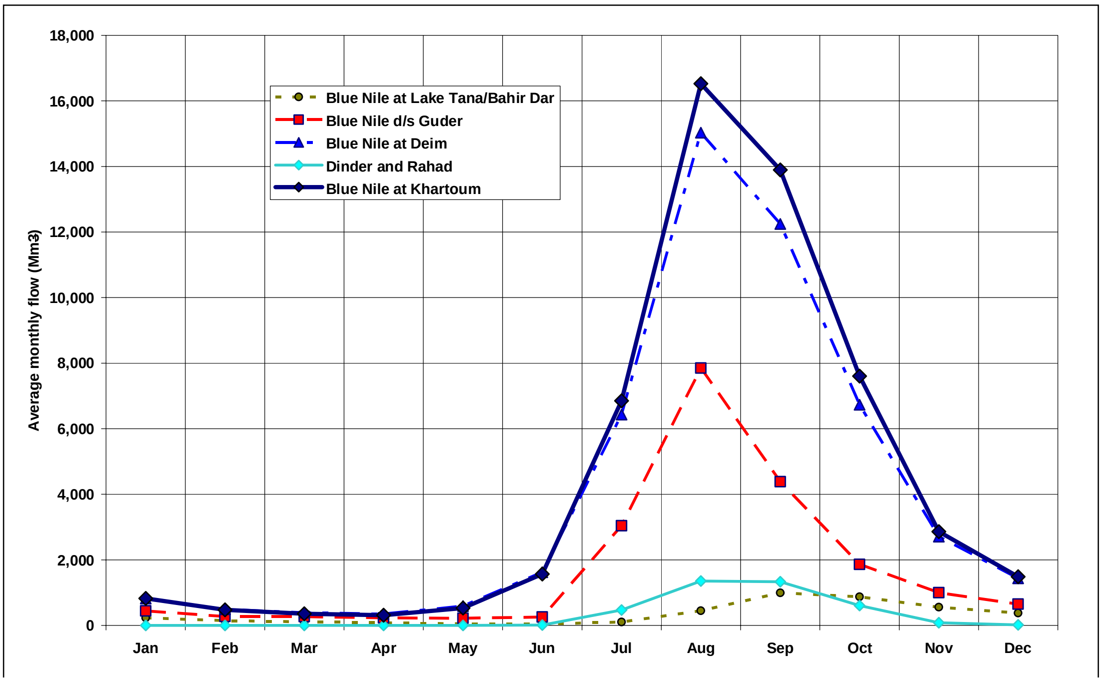

Figure 2.9 Average monthly flows in Blue Nile

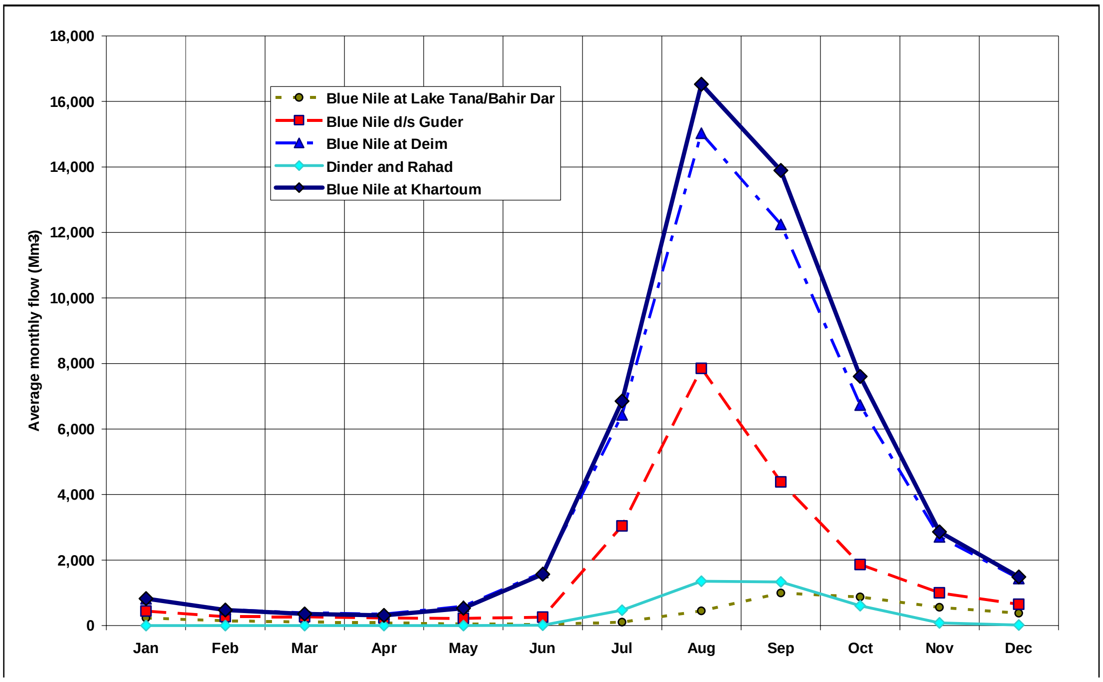

Figure 2.10 Average monthly flows in White Nile, Blue Nile, Atbara and Main Nile at Aswan

The statistics of the monthly natural flows of the Nile at Aswan are presented in Figure 2.11. It is observed that the deviations from the monthly means can be considerable, with a standard deviation up to 5,000 Mm^3.

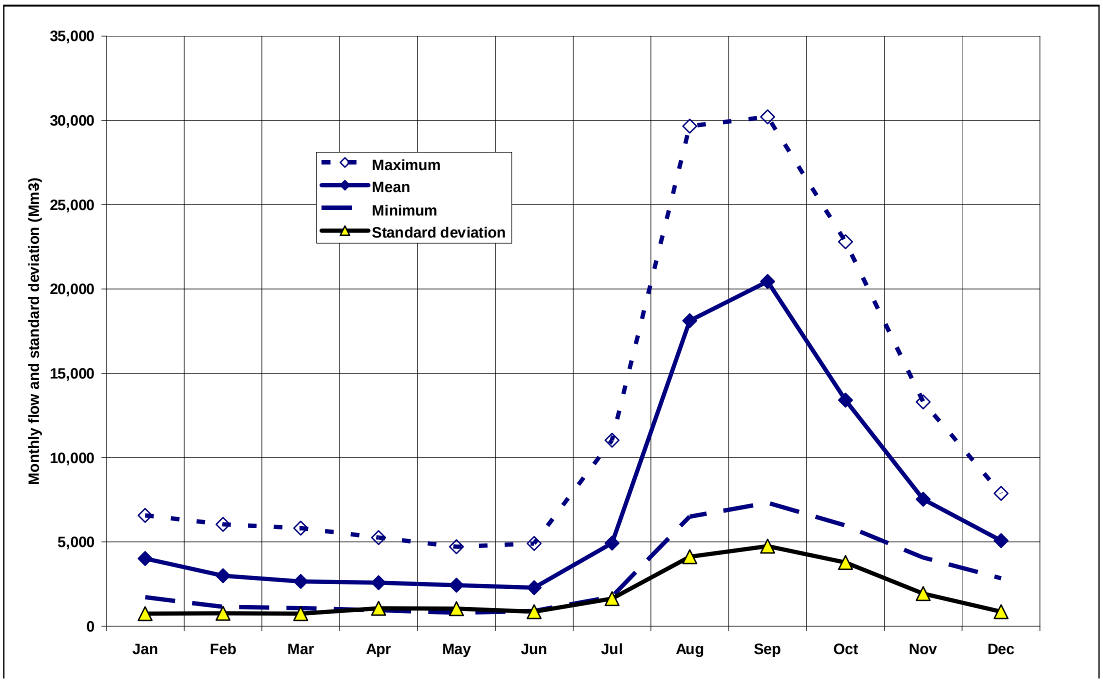

Figure 2.11 Monthly flow statistics of Nile at Aswan (natural flow), maximum, mean, minimum and standard deviation, Period 1900-2002

For water management, more important than deviations of flows of individual months from the mean are successions of prolonged dry and wet periods. In Figure 2.12 the annual flows (calendar years) of the Nile at Aswan are shown for two periods, 1872-1899 and 1900-2002. The figure shows that prior to 1900 the reported flows at Aswan have on average been considerably higher than thereafter (difference 21,000 Mm^3/year). Levels from Lake Victoria, available since 1895, indicate no anomalies in that period, which makes the White Nile as a source of this deviations unlikely (also because most of an increase would have evaporated in the Sudd). If true, then it should have come from the Blue Nile. This, however, is difficult to prove as measurements in the Blue Nile (at Khartoum) only started in 1900. In Volume IV of ‘The Nile Basin’ it is stated that ‘….the flood discharges prior to 1903 are probably about 8% too high.’… a conclusion based on a shift in the stage-relation curve between Wadi Halfa and Aswan. This shift was confirmed but appeared not due to a change in the Aswan gauge where the discharge rating applied to. It was concluded that these higher discharges at Aswan prior to 1900 are most likely true (Ogink, 2000). Nevertheless, in view of the large difference (see also Figure 2.13) the period prior to 1900 is considered less representative and hence is not considered, also because in the rest of the basin only at Lake Victoria measurements started prior to 1900. This makes reconstruction of historical series before 1900 impossible.

The accumulated deviations from the long term mean annual natural flow in the Nile at Aswan is presented in Figure 2.14. The graph shows sustained dry and wet periods in the flow series of the river. Most prominent is the below average period from 1978 up to and inclusive 1987, with a range of 140,400 Mm^3, when for 9 consecutive years the annual flow was on average 15,600 Mm^3 below the long term mean. This range exceeds the live, flood control and surcharge storage of Lake Nasser. The prolonged dry and wet periods in the river flow indicate that sufficiently long series have to be considered to cover the full characteristics of the flow variability for impact assessment. It is therefore suggested to use the flow series of the Nile and its tributaries as from 1900 onward, the longest series backward in time that can be derived for the key locations in the basin.

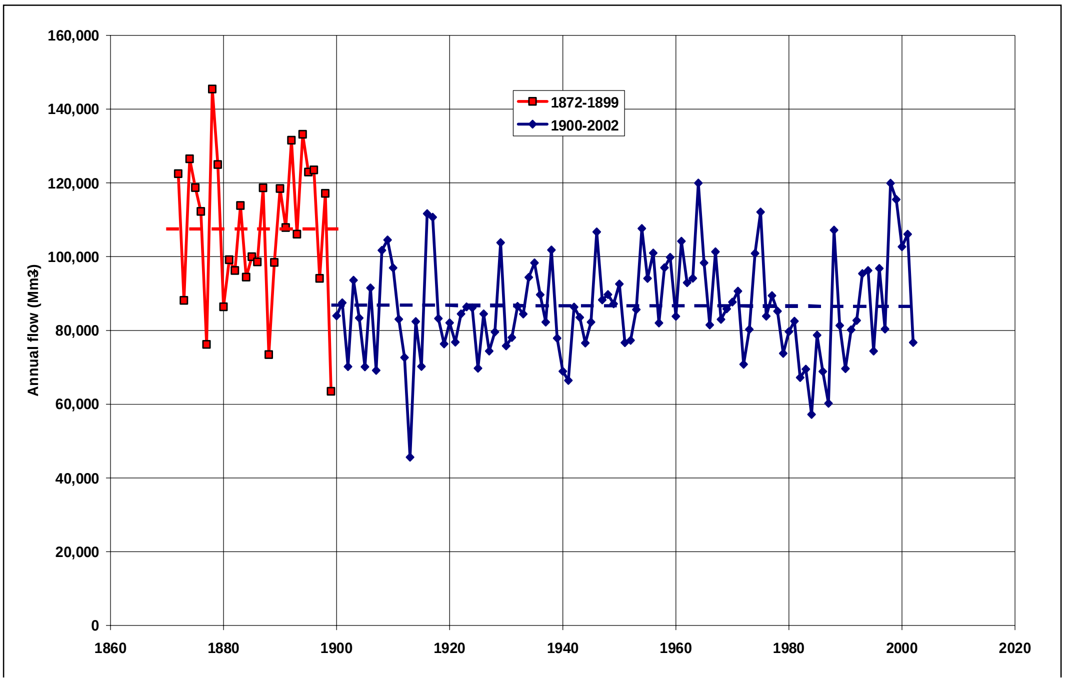

Figure 2.12 Natural annual flow of the Nile at Aswan, Periods 1872-1899 and 1900-2002

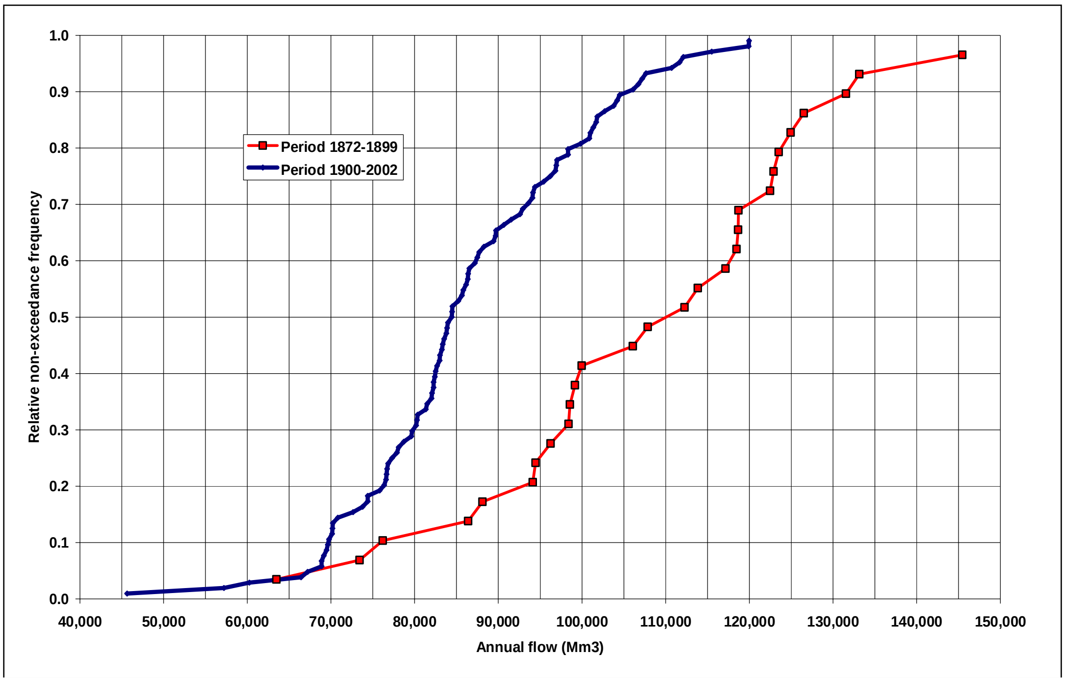

Figure 2.13 Frequency distributions of natural annual flow of the Nile at Aswan, Periods 1872-1899 and 1900-2002

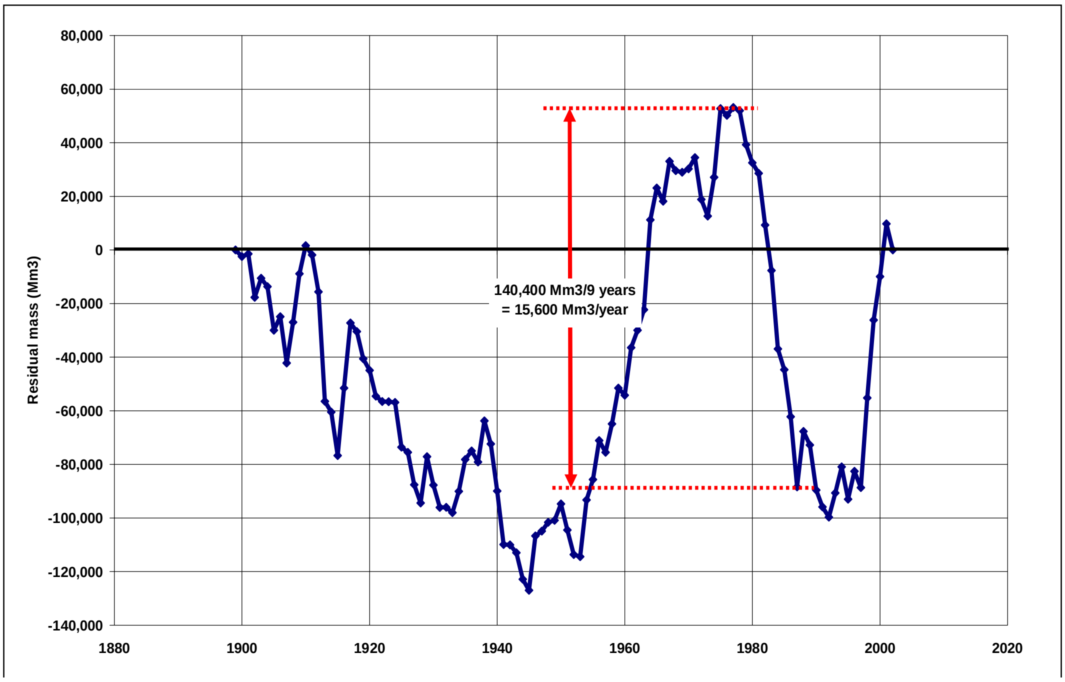

Figure 2.14 Accumulated departures from the mean (residual mass) of the Nile at Aswan, Period 1900-2002

2.5.3 Key hydrological stations

For the creation of representative flow series of sufficient length discharge data were made available for all key stations in the Nile Basin d/s and including Mongalla. The stations are listed below:

- White Nile from Mongalla to Malakal: major gauging stations in this reach of the White Nile are Mongalla, Buffalo Cape upstream of Lake No on the Bahr el Jebel, K3 on the Bahr el Zeraf near Fangak, and Tonga at the confluence of the Bahr el Jebel and Bahr el Zeraf.
- Bahr el Ghazal: major gauging stations are Nyamlel on the Lol, Wau on the Jur and Tonj on the Tonj.
- Baro, Akobo, Sobat basins: major gauging stations are Gambela on Baro, Us Gila on Pibor and Nasir and Hillet Doleib on Sobat.
- White Nile from Malakal to Blue Nile confluence: major discharge gauging stations in this reach are at Malakal and Mogren near to Khartoum, the latter being affected by backwater from the Blue Nile.
- Abay-Blue Nile: major gauging stations on the Abay-Blue Nile and tributaries are Bahir Dar at the outlet of Lake Tana, Kessie, Guder DS (planned Karadobi dam location), Bure (next to planned Beko Abo dam location), Shogole and at the Sudan-Ethiopian Border in Ethiopia, Deim, Roseires/Wad el Aies, Sennar DS, and Soba/Khartoum in the Sudan and Gwasi and Hawata on Dinder and Rahad in Sudan.
- Tekeze-Setit-Atbara: major gauging stations on the Atbara are at Kubur, Khashm el Girba and at K3. On Tekeze-Setit flow is gauged at Embamedre in Ethiopia and Wad el Heleiw in Sudan.
- Main Nile: major gauging stations on the Nile upstream of Aswan are Tamaniat, Hassanab and Dongola.

3 Database for ENWSM

3.1 General

The ENSWM of the Eastern Nile is used to simulate the behaviour of the system and to evaluate a variety of possible measures related to infra-structural and operational management. One of the key elements in the schematisation is a sound description of the hydrological and hydraulic behaviour of the system. In ENSWM this is done by defining a (large) number of nodes that represent the relevant elements of the system such as runoff from subbasins, reservoirs, irrigation demands, etc. (see van der Krogt, 2012 for an extensive description).

The effect of upstream developments should be investigated for historical and possible future flow conditions in the Nile basin, including sequences of wet and dry years. Flows, particularly on the White Nile, have shown large fluctuations and persistent behaviour. Such effects can only be included if sufficiently long flow series are used in the simulations. Based on the records of some key stations, which are available from the Nile Control Staff (2000, 2007), flows series as from 1900 onward till 2002 have been created at the inflow locations in the ENSWM of the Eastern Nile Basin. In Chapter 6 the procedures used for creating, validating and completing these series are discussed, preceded by the construction of rainfall and evapo-(transpi)ration series in the Chapters 4 and 5 .

3.2 Data availability

Rainfall
ERA40 30’ gridded daily rainfall series: 1961-2000 from ECMWF (European Centre for Medium range Weather Forecast).

Evaporation
Average monthly climatic and reference evapo-transpiration data: FAO East-Africa CLIMWAT databases for Ethiopia, Southern Sudan, Sudan and Egypt.

Water levels and flows
Monthly flow and some water level series at key stations that have been used in the creation of the ENSWM flow series are available for the periods as listed below.

- Main Nile at Aswan: 1925-2002: from NCS
- Natural river at Aswan: 1899-2002: from NCS
- Main Nile at Dongola: 1962-2002: from NCS
- Main Nile at Hudieba&Hassanab 1908-2002: from NCS
- Main Nile at Tamaniat&Shambat:1911-2002: from NCS
- Atbara at K3: 1903-2002, 1995 missing: from NCS
- Atbara at Khashm el Girba DS: 1987-2001: from NCS
- Tekeze at Embamadre: 1967-1976: from Howard Humphreys (1997)
- Blue Nile at Khartoum&Soba: 1900-2002: from NCS
- Dinder at mouth: 1907-1977: from NCS
- Rahad at mouth: 1912-1977: from NCS
- Blue Nile at Sennar dam DS :1912-2002: from NCS
- Blue Nile at Roseires&Wad el Aies:1912-1977, 1978-2002 flood period missing: NCS

• Blue Nile at Deim:	1966-2002: from NCS
• Abay at Sudan Border	1954-2003: series by NORPLAN
• Abay at Shogole	1954-2003: series by NORPLAN
• Abay at DS Guder mouth:	1954-2003: series by NORPLAN
• Abay at Kessie:	1954-2003: series by NORPLAN
• Abay at Bahir Dar:	1954-2003: series by NORPLAN
• Lake Tana:	1959-2005: wl from ENTRO
• Lake Tana inflows:	1960-2005: from ENTRO
• White Nile at Malakal:	1907-2002: from NCS
• Baro at Masha:	1967-2003: series by NORPLAN
• Genji at Gecha:	1967-2003: series by NORPLAN
• Baro at Baro dam:	1967-2003: series by NORPLAN
• Genji at Genji dam:	1967-2003: series by NORPLAN
• Geba at Supi:	1976-2004: many missing: from NCS
• Sor at Metu:	1980-2000: few missing: from NCS
• Baro at Bure/Baro Kella:	1967-2003: series by NORPLAN: from NCS
• Baro at Gambela:	1928-1959, 1967-2003, NCS and NORPLAN
• Baro at Gambela:	1905-1927, 1960-1972: wl from NCS
• Gila near Pugnido:	1977-1999: many missing: from NCS
• Pibor at US River Gila:	1929-1963, 1940 and 1945 missing: from NCS
• Sobat at Nasir:	1929-1970, 1971-1981 many missing: from NCS
• Sobat at Hillet Doleib:	1905-1983: from NCS
• White Nile at Abu Tong	1923-1983: many missing after 1964: from NCS
• Bahr el Zeraf at K3:	1908-1982: many missing after 1964: from NCS
• Bahr el Jebel at Buffalo Cape	1936-1983: some missing after 1963: from NCS
• Bahr el Jebel at Mongalla:	1905-1983: from NCS
• Torrents Lake Albert-Mongalla:	1907-1980: from NCS
• Lake Albert at its exit	1904-1981: from NCS

The list shows that a fairly complete record is available for a number of stations from the early twentieth century. Most data are available from the Nile Control Staff (NCS, 2000, 2007). Furthermore, for key locations on Blue Nile and Baro in Ethiopia data from 1954, respectively 1967 are available from (pre-)feasibility reports of Karadobi and Baro dams from NORPLAN. Finally, data series have been extracted from master plan studies, feasibility reports and databases available with ENTRO. Validation checks have been carried out on the data before use in the series creation.

3.3 Basin areas

The basin areas upstream of stream gauging stations and reservoirs as well as the areas of existing and potential irrigation areas have been determined from detailed topographical maps. In Table 3.1 an overview is given of the basin areas upstream of the major gauging stations and of tributaries, with the mean annual flow (MAF in Mm^3) and mean annual runoff (MAR in mm/year).

Table 3.1 Basin areas upstream of major stream gauging stations (ABN = Abay-Blue Nile, BASWN = Baro-Akobo-Sobat-White Nile, TSA = Tekeze-Setit-Atbara, MN = Main Nile) with annual average flows and runoff, Period 1900-2002

Basin	River	Location	Area	MAF (natural)	MAR (natural)
			(km^2)	(Mm^3)	(mm/yr)
ABN	various	Lake Tana inflow	11,994	5,432	453
ABN	Abay	Bahir Dar	15,091	4,009	266
ABN	Abay	Kessie	64,684	16,331	252
ABN	Abay	Guder DS	82,515	20,475	248
ABN	Abay	Beko Abo	95,069	23,731	250
ABN	Abay	Shogole	158,808	42,197	266
ABN	Blue Nile	Deim	183,356	48,842	266
ABN	Dinder	At mouth	32,385	2,795	86.3
ABN	Rahad	At mouth	43,933	1,067	24.3
ABN	Blue Nile	Khartoum	315,530	53,289	169
BASWN	Upper Baro	Baro-I	2,034	2,416	1,188
BASWN	Upper Baro	Baro-II	2,217	2,493	1,125
BASWN	Genji	At dam site	1,070	1,365	1,276
BASWN	Birbir	UB dams-Gambela	20,617	8,825	428
BASWN	Baro	Gambela	23,904	12,683	531
BASWN	Baro	At mouth	27,599	9,345	339
BASWN	Alwero	Abobo	2,853	595	208
BASWN	Gilo	Pugnido	9,290	3,297	355
BASWN	Pibor	Gilo US	125,858	2,343	18.6
BASWN	Sobat	Hillet Doleib	221,529	13,147	59.3
BASWN	Bahr el Jebel	Mongalla	481,577	35,805	74.3
BASWN	Bahr el Ghazal	U/s swamps	411,623	11,663	28.3
BASWN	Bahr el Jebel	D/s Sudd swamp	1,219,505	16,650	13.7
BASWN	White Nile	Malakal	1,441,034	29,626	20.6
TSA	Tekeze	Embamadre	45,611	5,252	115
TSA	Atbara	K3	231,245	11,506	49.8
MN	Main Nile	Aswan	2,771,271	86,449	31.2

4 Rainfall and effective rainfall

4.1 Data sources

For the ENWSM 30’ gridded daily rainfall data for the period 1961-2000 have been used from the ERA40 data series. This series is a product of weather forecast models used by the European Centre for Medium Range Weather Forecasts ECMWF and is composed of observations and satellite data, with a growing contribution of the latter in the course of time. This data set has previously been used by Tollenaar (2009) in the development of a rainfall-runoff model of the Nile basin. The daily data have been aggregated to monthly series for further use in ENWSM.

4.2 Extension of rainfall series

The ERA40 monthly rainfall series has been extended to the period 1900-2002 by resampling of years of the period 1961-2000 based on comparison of naturalized annual discharges of the two periods of representative stations in the distinguished basins. The following representative stations have been considered:

1. station Gambela representative for Baro-Akobo-Sobat-White Nile basin,
2. station Deim representative for the Abbay-Blue Nile basin,
3. station K3 representative for Tekeze-Setit-Atbara basin, and
4. station Aswan representative for the Main Nile basin.

The naturalized annual discharge series of the selected stations of the period 1961-2000 have been ranked. For each year of a particular station of the periods 1900-1960 and 2001-2002 the five years of the period 1961-2000 closest to the discharge of the year to be completed are considered, out of which one year is randomly selected. The rainfall of that selected year is considered representative for that particular year of the periods 1900-1960 and 2001-2002. In this way account is given to the physical relationship between rainfall and runoff, whereas all statistical properties of the shorter series are preserved in the extended series.

Using this procedure, based on the coordinates of the reservoirs and link storages in ENSWM relative to the 30’ rainfall grid for each reservoir and link storage monthly rainfall series for the period 1900-2002 have been created. The monthly averages have been presented in Table 4.2, Table 4.4, Table 4.6, and Table 4.8. As an example the monthly values for latitudinal regions in the Abay basin are shown in Figure 4.1. It is observed that duration of the rainy season reduced with increasing latitude. Highest rainfall generally occurs in the months July-August.

Similarly, monthly rainfall series for the period 1900-2002 have been prepared for all actual and potential irrigation schemes, to be used for the derivation of effective rainfall.

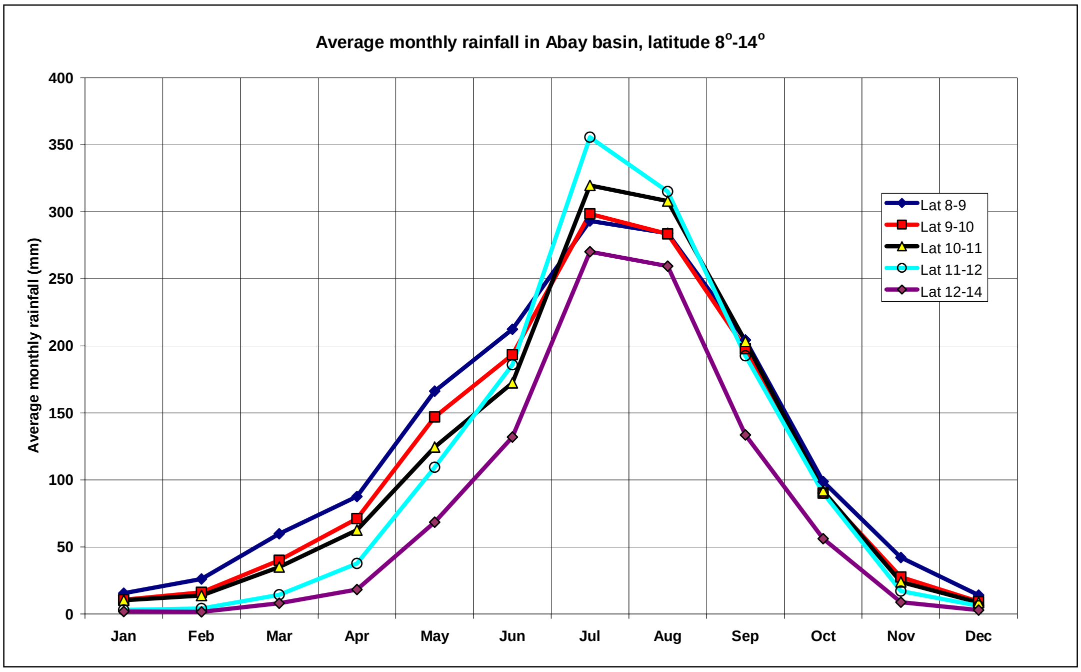

Figure 4.1 Average monthly rainfall in Abay basin, Period 1900-2002

4.3 Effective rainfall

For irrigated agriculture the water demand is determined by the consumptive use of the crop, which is determined from the reference evaporation times a crop factor and water use for field preparation, corrected for effective rainfall. The effective rainfall is the part of the rainfall that can be retained by the soil against gravity, and is computed here on a monthly basis using the following USBR formulae (Smith, 1988):

$$P_{eff} = P_m - 0.0016 P_m^2 \qquad for: \quad P_m \leq 250\ mm$$
$$P_{eff} = 125 + 0.1 P_m \qquad for: \quad P_m > 250\ mm \tag{4-1}$$

where: P_{eff} = effective rainfall [mm/month]

P_m = monthly rainfall [mm/month]

The relationship $P_{eff} = f\ (P_m)$ is displayed in Figure 4.2. It shows that the losses (runoff) increase linearly up to 40% at a monthly rainfall of 250 mm to grow gradually to 65% for a monthly rainfall of 500 mm. Note that in some application of this USBR formula instead of P_m $P_{75\%}$ or $P_{80\%}$ is used being the dependable rainfall that is exceeded during 75% or 80% of the time. In principle the effective rainfall depends on soil type, land use and evaporation as well. In the absence of detailed information on soil type and land use above simplified empirical equation is used. Note that from the available rainfall database any other relationship may be derived and applied in ENSWM if required.

Monthly average effective rainfall values have been derived for the modelled irrigation schemes derived from the gridded monthly rainfall series of the period 1900-2002. Series have been extracted from the gridded data set based on the coordinates of the schemes. The applied monthly values have been presented in Table 4.3, Table 4.5, Table 4.7 and Table 4.8.

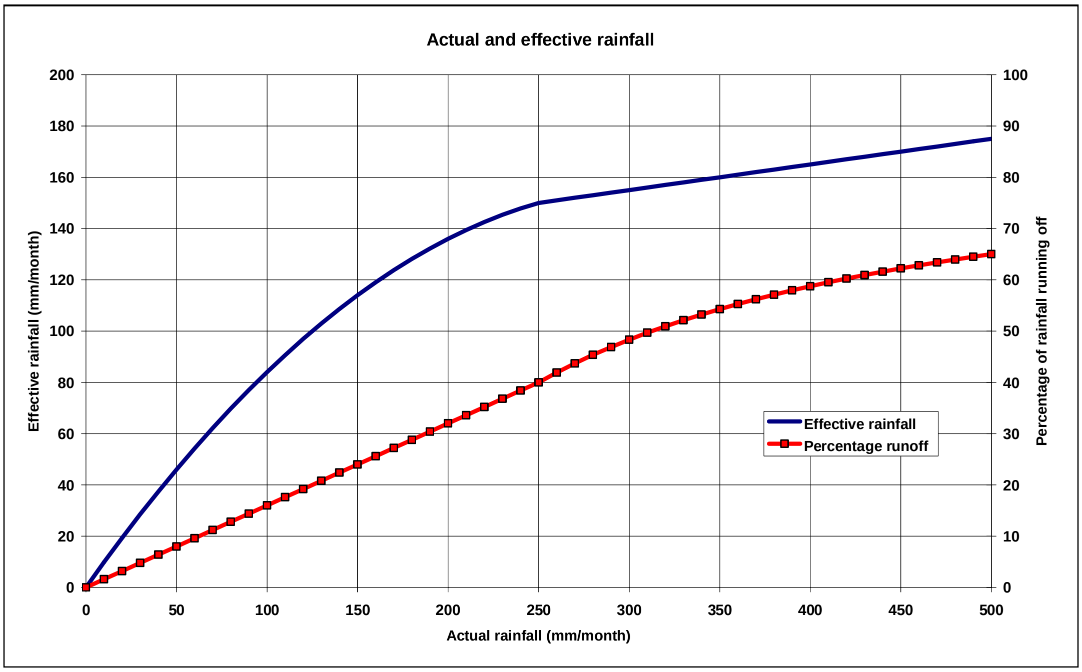

Figure 4.2 Actual and effective rainfall with percentage runoff according to USBR.

4.4 Overview of average monthly and annual rainfall and effective rainfall

An overview of the average monthly and annual rainfall of all reservoir and link storage nodes as well as the effective monthly and annual rainfall for all irrigation nodes is presented in Table 4.2 to Table 4.8.

Table 4.1 Average monthly and annual rainfall (mm) on Reservoir and Link Storage Nodes in the Baro-Akobo-Sobat White Nile basin

Location	ID	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Rsv_Et_AboboDam_Ir	14	2.2	4.4	21.0	47.1	126.8	139.7	208.8	185.2	127.4	97.4	39.3	7.7	1006.9
Rsv_Et_GebaADam_Hp(P)	24	28.7	36.8	87.1	118.8	182.3	233.5	278.0	276.8	227.6	119.2	82.9	24.3	1696.0
Rsv_Et_GambelaDam_Ir(P)	59	3.9	6.8	27.1	63.0	149.1	163.5	245.4	236.1	167.7	125.5	57.7	10.7	1256.5
Rsv_Et_DumbongDam_Ir(P)	61	5.8	7.9	33.3	64.6	150.2	149.3	209.0	195.9	140.6	115.9	46.0	11.0	1129.5
Rsv_Et_Gilo2Dam_Ir(P)	99	2.1	3.9	19.5	43.6	110.4	120.1	180.4	163.5	119.5	96.2	35.5	6.8	901.6
Rsv_Et_SorDam_Hp(P)	154	20.5	22.7	64.4	93.0	181.1	230.5	284.0	278.3	232.6	128.0	74.4	20.1	1629.5
Rsv_Et_SeseDam_Hp(P)	161	21.6	26.4	70.9	100.1	175.0	227.9	293.2	284.9	221.4	125.0	80.1	25.1	1651.7
Rsv_Et_GumeroDam_Hp(P)	199	18.0	20.5	60.1	88.2	174.9	211.6	265.3	260.3	214.2	122.0	70.0	18.5	1523.5
Rsv_Ss_SueDam_Hp(P)	265	0.1	0.8	10.2	44.4	112.1	156.7	203.9	210.3	159.7	78.1	1.8	0.0	978.0
Rsv_Et_GebaRDam_Hp(P)	360	15.7	20.4	55.9	83.6	161.2	196.3	262.9	255.7	196.9	115.2	64.5	20.6	1449.0
Rsv_Et_Baro1Dam_Hp(P)	370	34.2	35.8	85.2	121.4	214.0	268.8	295.7	285.9	269.1	151.2	96.5	30.4	1888.1
Rsv_Et_Baro2Dam_Hp(P)	375	27.6	29.3	76.8	106.8	184.7	217.4	269.7	272.3	226.7	137.1	86.7	27.1	1662.1
Rsv_Et_BirbirRDam_Hp(P)	507	10.7	15.3	47.0	76.5	153.7	186.3	250.6	243.9	186.9	107.9	54.7	15.6	1349.2
Rsv_Et_BirbirADam_Hp(P)	532	12.6	17.1	50.2	78.5	160.0	201.2	266.0	258.2	201.2	112.8	58.7	17.3	1433.8
Rsv_Et_ItangDam_Ir(P)	592	2.8	4.4	21.7	50.5	135.4	148.2	219.7	207.6	151.6	113.4	52.4	8.5	1116.3
Rsv_Et_Gilo3Dam_Ir(P)	600	1.8	3.4	18.2	41.8	111.7	124.1	186.4	171.0	123.1	97.2	34.7	6.1	919.6
Rsv_Et_Gilo1Dam_IrHp(P)	602	5.7	8.3	35.4	77.7	141.1	134.5	181.7	164.5	125.8	105.0	60.9	12.0	1052.7
Rsv_Ss_BeddenDam_Hp(P)	719	3.6	8.9	40.7	94.7	144.0	125.2	143.3	152.2	116.3	123.4	48.4	5.3	1006.1
Rsv_Ss_LakkiDam_Hp(P)	721	4.9	15.5	49.1	97.7	126.6	120.5	148.7	153.3	119.5	140.7	60.3	9.5	1046.4
Rsv_Ss_ShukoliDam_Hp(P)	722	4.6	14.6	46.1	94.3	120.8	117.4	140.4	151.2	117.9	143.3	62.7	8.9	1022.2
Rsv_Ss_FulaDam_Hp(P)	723	5.6	16.1	47.6	95.8	114.9	115.4	137.1	152.1	118.6	141.2	65.4	11.0	1020.8
Rsv_Et_SakuDam_Hp(P)	732	6.5	10.9	43.1	81.5	176.4	188.9	239.4	228.8	191.7	132.0	59.5	14.1	1372.8
Rsv_Et_TamsDam_Ir(P)	736	8.9	12.7	48.8	93.4	191.0	210.7	290.8	263.4	226.3	157.0	71.4	18.6	1593.1
Rsv_Et_ChiruDam_Ir(P)	741	6.3	10.3	36.8	74.1	158.8	174.2	241.1	231.8	173.4	144.5	64.4	14.1	1329.7
Rsv_Et_MeyDam_Ir(P)	749	5.7	7.7	33.2	64.9	156.6	157.4	218.3	203.5	146.6	117.4	45.4	10.8	1167.6
Rsv_Et_KashuDam_Hp(P)	783	38.5	43.9	99.0	153.7	215.6	214.9	226.5	217.1	211.7	147.6	100.2	35.2	1704.0
Rsv_Et_BekoDam_Hp(P)	784	23.0	28.3	65.0	100.7	160.3	170.9	199.9	193.1	167.0	111.1	77.7	22.4	1319.3
Rsv_Su_GebalAuliaDam_IrNvHp	1605	0.0	0.0	0.0	0.1	1.4	1.8	30.6	45.6	11.1	1.4	0.0	0.0	91.9
Lst_Su_EvapMalakalKhartoum	63	0.0	0.0	0.0	0.2	1.0	1.8	40.6	51.2	12.7	1.5	0.0	0.0	109.1
Lst_Ss_GhazalSwampBahrElGhazal	815	0.0	0.3	3.2	16.1	79.4	127.3	141.7	174.8	144.4	73.6	1.4	0.0	762.3
Lst_Ss_MacharSwamp	935	0.0	0.0	4.4	13.7	81.0	107.6	160.8	164.9	131.6	76.4	5.5	0.5	746.5
Lst_Ss_DelaySobatRiver	965	0.0	0.1	6.1	16.9	94.4	101.5	153.6	153.4	129.7	77.5	5.9	0.1	739.2
Lst_Ss_SuddSwampAlbertNile	1510	0.0	0.6	8.7	39.1	110.8	114.7	151.8	164.1	139.5	79.2	8.8	0.1	817.5
Lst_Ss_SuddSwamp	1525	0.1	0.1	5.9	25.5	92.8	116.4	150.2	166.9	142.8	73.3	3.4	0.0	777.5
Lst_Su_DelayMalakalKhartoum	1595	0.0	0.0	0.0	0.4	1.2	1.7	36.2	44.6	11.8	1.6	0.0	0.0	97.5

Table 4.2 Monthly and annual effective rainfall (mm) for Advanced Irrigation Nodes in the Baro-Akobo-Sobat White Nile basin

Location	ID	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Air_Ss_FengcoJonglei(P)	88	0.1	0.8	12.1	29.0	90.4	90.0	112.4	114.3	105.3	74.8	12.5	1.0	642.7
Air_Ss_MalakalRice(P)	683	0.0	0.0	4.7	15.4	68.8	81.9	112.4	114.2	100.8	62.5	5.2	0.0	565.9
Air_Su_KenanaSugarAndCrops	696	0.0	0.0	0.0	0.1	7.3	26.3	71.6	85.4	41.5	9.5	0.1	0.0	241.8
Air_Su_HagarAsalayaAndSondosAndWhiteNile	697	0.0	0.0	0.0	0.0	1.2	7.4	51.0	62.6	19.3	3.3	0.0	0.0	144.9
Air_Et_AlweroFrmChiru+Mey+DumbongDams(P)	756	4.4	7.3	26.7	55.2	106.8	114.5	143.6	138.8	115.1	102.7	51.4	11.1	877.5
Air_Et_BaroRightBankGravityFromItang(P)	817	2.4	3.7	18.8	41.7	97.7	104.0	134.8	130.8	110.1	90.2	42.5	7.3	784.0
Air_Et_BaroRightBankPumpFromItang(P)	818	2.0	3.3	17.8	40.9	97.9	105.4	135.6	131.2	110.6	89.5	40.8	6.8	781.6
Air_Et_BaroRightBnkFrmGmblGrvOrRvrPmp(P)	819	3.0	4.8	22.9	47.6	106.1	112.9	141.2	134.0	113.3	90.2	46.2	9.1	831.4
Air_Et_BaroLeftBankGravityFromItang(P)	824	2.4	3.7	18.8	41.7	97.7	104.0	134.8	130.8	110.1	90.2	42.5	7.3	784.0
Air_Et_BaroLeftBankPumpFromItang(P)	826	3.1	4.6	20.8	44.7	99.5	106.9	136.6	130.6	107.9	96.2	46.1	8.4	805.5
Air_Et_BaroLeftBankFrmGmblGrvOrRvrPmp(P)	831	3.5	5.4	22.8	47.7	103.3	110.3	139.6	132.2	108.5	96.2	49.2	9.6	828.2
Air_Et_LeftBankFromAbobo(P)	833	1.9	3.6	18.0	38.8	91.3	97.1	128.1	118.9	93.8	79.0	31.8	6.4	708.9
Air_Et_GiloRightBankFromGilo1Gravity(P)	836	2.5	4.7	20.9	42.4	94.3	98.0	128.0	118.0	93.1	78.8	34.5	8.0	723.2
Air_Et_GiloLeftBnkFrmGilo1GrvOrRvrPmp(P)	839	2.9	4.2	21.1	45.5	89.6	88.7	115.6	105.5	85.7	75.1	39.8	7.8	681.4
Air_Et_GiloRightBankFromGilo2Gravity(P)	842	1.8	3.3	17.1	37.0	86.9	92.4	123.7	115.4	92.1	78.7	30.3	5.9	684.7
Air_Et_GiloLeftBankFromGilo2Gravity(P)	843	2.0	3.7	18.2	38.5	86.5	90.4	121.6	112.7	90.2	78.2	31.0	6.6	679.5
Air_Ss_MongalaAndOtherSouth(P)	1480	1.4	6.5	30.2	69.2	102.4	92.2	99.4	105.2	89.9	85.6	35.1	3.2	720.3
Air_Su_PumpSchemesUpJebelAulia	1585	0.0	0.0	0.0	0.1	6.2	23.9	68.5	83.6	36.5	7.8	0.1	0.0	226.6
Air_Su_Kenana4(P)	1590	0.0	0.0	0.0	0.1	3.5	12.3	58.4	77.5	28.4	6.3	0.0	0.0	186.7

Table 4.3 Average monthly and annual rainfall (mm) on reservoir and link storage nodes in the Abbay-Blue Nile basin

Location	ID	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Rsv_Et_MendaiaUpDam_Hp(P)	38	0.9	2.7	14.4	47.7	148.4	212.5	279.9	272.5	196.0	107.1	23.3	3.5	1308.9
Rsv_Et_BekoAboDam_Hp(P)	39	6.5	8.2	27.2	49.1	126.8	188.8	316.7	296.7	189.1	92.5	22.2	6.1	1329.9
Rsv_Et_GumeraDam_Ir(P)	205	5.1	6.0	24.4	40.3	91.7	150.1	375.9	323.7	169.5	81.4	17.8	7.0	1292.8
Rsv_Et_RibbDam_Ir(P)	206	6.8	7.2	28.7	44.1	107.9	134.5	347.6	313.8	145.4	76.9	19.9	7.8	1240.6
Rsv_Et_MegechDam_Ir(P)	207	5.6	3.8	22.7	45.2	102.5	162.4	338.7	308.7	135.4	72.3	18.0	10.4	1225.8
Rsv_Et_GigelAbaiBDam_Ir(P)	208	6.9	5.7	21.4	54.5	123.9	207.1	424.6	358.8	211.8	102.6	21.8	10.8	1550.1
Rsv_Et_JemmaDam_Ir(P)	211	5.8	8.3	27.3	53.0	126.9	193.7	382.4	339.7	219.7	98.9	22.8	10.0	1488.6
Rsv_Et_KiltiDam_Ir(P)	212	2.1	3.7	10.8	37.7	119.0	199.8	383.8	335.0	203.6	101.7	19.1	5.7	1422.0
Rsv_Et_WeberiDam_Ir(P)	223	30.0	41.9	66.7	106.7	93.3	107.4	282.8	266.3	164.3	46.5	16.4	9.1	1231.3
Rsv_Et_RobiWeserbiDam_Ir(P)	229	22.7	35.0	60.3	93.7	87.1	102.0	290.5	279.2	167.7	45.3	15.8	9.0	1208.2
Rsv_Et_DuberDam_HpIr(P)	233	28.7	42.0	66.3	106.8	96.3	109.7	288.2	276.2	168.8	49.5	17.3	10.1	1259.8
Rsv_Et_RobiDam_HpIr(P)	235	27.4	36.6	68.7	102.6	124.6	156.9	315.1	301.6	199.8	66.1	19.0	13.3	1431.8
Rsv_Et_SelgiDam_Ir(P)	249	37.5	33.9	83.8	120.6	96.7	88.0	307.9	291.2	163.9	51.4	27.2	11.7	1313.8
Rsv_Et_MugaDam_Ir(P)	256	17.2	22.3	50.3	81.2	106.6	130.8	321.2	320.2	208.4	77.9	24.1	12.8	1373.1
Rsv_Et_GeltaDam_Ir(P)	262	19.5	28.3	56.4	89.8	126.1	144.8	323.5	333.9	222.1	92.7	32.7	15.3	1485.2
Rsv_Et_BogenaDam_Ir(P)	263	16.2	25.0	51.4	80.1	118.9	141.7	312.1	313.8	207.5	82.5	26.2	11.5	1387.1
Rsv_Et_UpperGuderDam_Ir(P)	276	21.8	28.6	64.9	88.1	158.4	208.4	319.8	306.4	216.5	82.5	22.2	10.3	1527.9
Rsv_Et_AnonuDam_Ir(P)	283	8.6	13.6	40.3	58.2	131.0	176.8	281.0	261.5	168.6	68.5	19.1	6.1	1233.2
Rsv_Et_KaleDam_Ir(P)	287	12.5	19.4	50.3	68.6	131.8	173.8	288.1	274.3	175.2	63.9	17.8	8.4	1284.1
Rsv_Et_ChemogaDam_Ir(P)	294	9.9	17.1	39.8	65.3	127.4	162.1	316.9	312.4	215.4	89.7	23.6	8.6	1388.3
Rsv_Et_NesheDam_IrHp(P)	297	9.6	14.5	40.0	65.1	158.6	208.9	324.5	304.4	211.8	90.5	22.0	9.2	1459.1
Rsv_Et_GulaDam_Ir(P)	309	9.1	16.1	38.6	63.6	118.4	167.2	335.9	314.6	210.2	91.8	21.9	10.4	1397.7
Rsv_Et_JedebDam_Ir(P)	310	13.0	21.1	45.9	75.3	130.3	162.8	323.1	330.6	231.7	101.4	30.0	12.9	1478.2
Rsv_Et_LahIrrDam_Ir(P)	331	9.6	14.4	37.2	64.3	128.7	184.8	374.0	349.8	227.9	103.5	25.7	12.8	1532.6
Rsv_Et_FettamDam_Ir(P)	336	5.5	6.6	23.7	45.1	121.1	185.8	324.5	303.8	189.4	94.0	21.7	5.3	1326.5
Rsv_Et_AyoDam_Ir(P)	344	5.9	8.1	25.6	52.3	140.0	211.9	356.3	332.8	222.3	106.6	26.0	9.0	1496.7
Rsv_Et_ZinginiDam_Ir(P)	346	3.8	5.3	19.6	42.7	135.5	206.6	326.7	306.4	207.0	99.0	23.2	5.3	1381.1
Rsv_Et_TimbiDam_Ir(P)	353	2.5	4.9	14.5	46.5	145.8	229.3	365.5	330.0	222.6	106.7	21.1	6.7	1496.0
Rsv_Et_GuchisDam_Ir(P)	357	2.5	4.9	14.5	46.5	145.8	229.3	365.5	330.0	222.6	106.7	21.1	6.7	1496.0
Rsv_Et_ArdiDam_Ir(P)	362	2.6	3.3	11.4	44.2	134.7	223.2	362.3	332.0	214.8	99.6	19.4	6.5	1454.0
Rsv_Et_NegesoDam_Ir(P)	391	9.8	21.6	52.8	77.7	171.3	221.5	301.5	284.7	199.8	97.1	38.5	12.5	1488.8
Rsv_Et_UpperDabanaDam_IrHp(P)	403	11.3	19.9	49.7	81.7	178.4	222.4	297.3	286.9	217.6	120.5	61.2	18.1	1564.9
Rsv_Et_UpperDidessaDam_Ir(P)	406	19.2	34.5	72.2	102.8	157.0	197.6	254.3	258.1	183.9	94.9	46.7	15.1	1436.3
Rsv_Et_AngerDam_Ir(P)	413	5.2	9.8	31.5	62.7	178.6	236.1	318.4	300.0	213.9	107.9	33.4	7.6	1505.1
Rsv_Et_NekemteDam_Ir(P)	414	4.1	7.7	30.6	59.5	160.9	207.1	281.3	270.9	185.1	90.7	30.3	7.3	1335.6
Rsv_Et_LekuUkeDams_Ir(P)	438	7.4	13.5	42.7	81.9	216.3	279.9	323.5	308.4	234.6	123.6	44.6	12.2	1688.8
Rsv_Et_BiyoGumbiDams_Ir(P)	442	3.7	6.9	28.7	58.0	158.4	204.0	277.5	269.9	187.9	92.8	31.1	7.1	1326.0
Rsv_Et_AleltuDam_Ir(P)	447	11.8	17.2	45.1	85.2	194.5	244.4	339.1	320.6	229.0	99.4	32.3	12.0	1630.5
Rsv_Et_WajaDam_Ir(P)	451	2.7	6.8	24.6	54.8	150.8	212.1	291.9	271.1	185.3	99.5	28.6	6.5	1334.5
Rsv_Et_GebregurachaDam_Ir(P)	453	2.5	6.0	22.8	53.0	157.5	222.2	298.4	284.7	204.5	105.4	28.5	6.9	1392.5
Rsv_Et_LowerDidessaDam_Ir(P)	455	2.7	5.2	21.1	54.7	156.6	216.7	299.8	284.6	210.3	114.8	34.9	8.5	1409.8
Rsv_Et_BarDam_Ir(P)	464	1.3	2.9	17.2	46.9	154.0	226.0	305.7	303.5	221.4	112.2	24.2	5.7	1421.0
Rsv_Et_GemberDam_Ir(P)	476	6.4	9.6	34.6	71.4	187.1	245.5	324.5	301.3	244.2	127.6	44.9	16.5	1613.6
Rsv_Et_FinchaaDam_HpIr	490	10.0	16.4	44.6	66.7	139.7	190.2	312.2	288.0	189.8	77.1	18.0	8.4	1361.2
Rsv_Et_DilaDam_Ir(P)	496	6.4	10.9	37.1	73.2	186.8	242.3	318.0	300.8	244.0	127.4	49.1	15.7	1611.6
Rsv_Et_MeniDam_Ir(P)	498	6.6	11.2	37.5	73.6	178.1	220.9	292.0	275.8	223.2	123.4	47.6	15.7	1505.7
Rsv_Et_LowerDabusDam_Hp(P)	501	2.2	3.2	19.3	54.8	145.4	204.3	267.4	259.7	204.9	127.3	34.4	8.8	1331.6
Rsv_Et_DaleBilutsuDams_Ir(P)	517	0.1	1.1	10.0	35.1	122.0	180.0	245.4	246.6	174.0	105.0	20.3	3.1	1142.7
Rsv_Et_UpperBelesDam_IrHp(P)	520	2.8	3.0	13.3	33.9	112.0	191.2	377.1	329.3	192.0	96.2	18.8	6.4	1376.0
Rsv_Et_GaleguDam_Ir(P)	522	0.1	0.1	0.6	8.8	62.3	162.1	289.4	281.5	162.3	59.6	4.4	0.3	1031.5
Rsv_Et_RahadDam_Ir(P)	525	0.1	0.0	0.4	5.1	59.2	140.6	277.9	266.2	140.7	50.1	5.3	0.2	945.8
Rsv_Et_LowerDinderDam_IrHp(P)	640	0.0	0.1	0.4	7.6	58.9	146.6	255.1	248.7	141.4	53.4	3.8	0.2	916.2
Rsv_Et_LakeTanaCharaCharaDam	700	1.6	1.6	9.2	23.1	89.8	165.8	364.2	318.3	161.9	80.2	13.6	3.8	1233.2
Rsv_Et_KogaDam_Ir	897	4.3	5.2	19.4	44.0	117.7	190.1	392.7	341.5	210.7	97.1	20.8	7.3	1450.7
Rsv_Et_LowerGuderProjectMottaDam_Hp(P)	992	8.6	13.6	40.3	58.2	131.0	176.8	281.0	261.5	168.6	68.5	19.1	6.1	1233.2
Rsv_Et_AmartiDam_Ir(P)	1005	9.6	14.5	40.0	65.1	158.6	208.9	324.5	304.4	211.8	90.5	22.0	9.2	1459.1
Rsv_Et_DidgaDam_Ir(P)	1062	5.0	9.7	35.8	66.9	171.3	217.2	292.0	279.6	195.2	100.4	35.2	10.1	1418.4
Rsv_Et_UpperDabusDam_Hp(P)	1091	2.9	3.0	20.6	62.2	159.3	231.4	288.8	283.2	231.8	134.1	36.6	6.3	1460.1
Rsv_Et_UpperBirrDam_Ir(P)	1113	9.3	15.6	38.5	63.6	117.2	168.4	353.3	329.6	214.2	95.4	23.3	11.3	1439.6
Rsv_Et_UpperDinderDam_Hp(P)	1118	0.3	0.1	2.8	16.3	80.9	160.2	291.1	273.2	154.9	69.0	10.1	1.6	1060.5
Rsv_Et_LahHppDam_Hp(P)	1187	5.2	7.7	25.7	48.3	136.0	193.3	336.4	313.1	217.8	94.5	21.3	5.9	1405.2
Rsv_Et_DebreGurachaDam_Ir(P)	1221	29.6	31.2	69.6	101.7	81.7	82.3	286.1	276.1	152.7	45.5	20.8	8.8	1186.1
Rsv_Et_RobiRikichaDam_Ir(P)	1236	28.7	39.6	64.6	101.6	87.9	99.2	282.8	266.2	160.2	45.0	15.9	9.0	1200.8
Rsv_Et_KaradobiDam_Hp(P)	1245	6.5	10.5	29.9	46.3	111.3	158.6	286.4	278.8	174.8	69.9	17.8	5.6	1196.3
Rsv_Et_HomechoDam_Ir(P)	1252	22.6	31.9	61.2	91.4	111.8	147.5	308.3	291.1	187.8	61.0	16.2	10.9	1341.8
Rsv_Et_MabilDam_Hp(P)	1265	2.9	4.2	15.3	35.0	124.7	194.0	296.8	289.1	186.8	94.6	20.7	3.5	1267.6
Rsv_Et_GigelAbaiADam_Ir(P)	1268	2.6	5.4	13.3	51.0	120.8	204.6	416.4	351.3	206.6	103.2	20.7	7.4	1503.4
Rsv_Et_MendaiaDownDam_Hp(P)	1285	0.8	2.4	13.2	47.0	142.8	205.1	270.1	265.1	190.1	107.2	22.3	3.3	1269.3
Rsv_Et_GrandRenaissanceDam_Hp(P)	1305	0.0	0.2	2.7	17.9	80.2	168.7	237.2	241.6	163.5	76.3	6.8	1.0	996.0
Rsv_Su_RoseiresDam_IrHp	1340	0.0	0.0	0.5	3.9	39.2	100.5	183.3	182.3	127.1	31.3	1.0	0.0	669.0
Rsv_Su_SennarDam_IrHp	1405	0.0	0.0	0.0	0.2	7.5	17.2	91.8	124.3	54.6	11.4	0.0	0.0	307.1
Lst_Su_DelayDinderRahadKhartoum	52	0.0	0.0	0.0	0.0	0.4	0.4	18.0	12.9	4.9	0.6	0.0	0.0	37.1
Lst_Su_DelayRoseiresSennar	54	0.0	0.0	0.0	0.2	18.5	43.8	110.1	157.3	74.1	16.1	0.1	0.0	420.3
Lst_Su_DelaySennarDinderRahad	58	0.0	0.0	0.0	0.1	7.5	16.8	85.7	109.1	45.9	10.5	0.1	0.0	275.7
Lst_Su_EvapDeimKhartoum	64	0.0	0.0	0.0	0.0	2.1	1.7	33.1	48.7	10.5	1.5	0.0	0.0	97.6
Lst_Su_DelayDeimRoseires	1320	0.0	0.0	0.8	9.4	60.6	126.2	193.5	200.8	139.7	57.8	3.5	0.0	792.3

Table 4.4 Monthly and annual effective rainfall (mm) for Advanced Irrigation Nodes in the Abbay-Blue Nile basin

Location	ID	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Air_Et_UpperDinder(P)	81	1.7	1.4	7.0	25.7	83.1	126.2	158.9	154.3	127.0	73.6	15.3	3.1	777.1
Air_Et_LowerBeles(P)	82	0.0	0.2	2.6	14.6	65.9	119.1	146.7	143.8	120.1	62.9	6.3	0.9	683.0
Air_Et_Hod+Jigna+Beks+Mene+Guram+AbaK(P)	84	3.0	3.0	13.6	27.7	73.2	107.8	161.4	154.8	114.3	65.4	14.4	4.2	742.9
Air_Su_Rahad	98	0.0	0.0	0.0	0.1	8.8	20.2	72.2	89.9	44.7	11.9	0.1	0.0	247.8
Air_Et_RibbRight+LeftBank(P)	203	3.8	4.0	16.3	30.2	81.6	110.1	161.0	155.8	113.4	66.8	15.8	4.6	763.3
Air_Et_Gura+Jar+Robit+Sera+Kola+Jiwan(P)	215	2.0	2.0	12.5	25.2	73.9	110.9	156.2	149.5	100.9	57.4	13.2	5.4	709.1
Air_Et_Durbet3(P)	216	2.5	5.0	12.3	42.1	90.2	131.0	166.6	159.7	135.1	82.2	18.9	6.9	852.6
Air_Et_DimbkPlain(P)	217	5.6	7.8	25.0	45.3	92.8	127.2	163.1	158.8	137.9	78.6	20.6	9.3	872.1
Air_Et_Jemma(P)	218	5.6	7.8	25.0	45.3	92.8	127.2	163.1	158.8	137.9	78.6	20.6	9.3	872.1
Air_Et_Chimba(P)	219	2.0	1.7	9.5	24.5	78.3	120.9	163.3	156.9	125.7	69.5	13.8	4.5	770.6
Air_Et_Wonda+Yemosht+Seba+Teneba+Bata(P)	220	4.5	5.5	20.7	35.4	77.9	111.5	164.5	158.4	126.7	73.1	17.1	5.9	801.2
Air_Et_Duber(P)	221	25.4	35.2	55.0	82.2	72.1	82.7	150.7	148.6	115.6	41.7	15.9	9.4	834.6
Air_Et_Wberi(P)	224	22.0	31.6	51.8	75.4	64.6	70.6	148.1	147.1	110.5	36.9	14.4	8.0	781.0
Air_Et_Weserbi(P)	225	20.6	30.7	51.1	74.8	66.4	76.2	149.6	148.4	113.9	38.9	14.6	8.5	793.8
Air_Et_Homecho(P)	236	20.6	28.3	51.6	73.7	82.5	104.7	154.9	152.0	123.9	50.0	15.0	10.2	867.4
Air_Et_Robi(P)	237	20.6	28.3	51.6	73.7	82.5	104.7	154.9	152.0	123.9	50.0	15.0	10.2	867.4
Air_Et_Selgi(P)	250	31.3	29.7	66.2	87.4	72.0	67.1	153.1	151.5	112.3	42.7	23.1	11.0	847.5
Air_Et_Yetmen(P)	257	16.0	20.6	44.3	66.5	79.1	92.8	155.5	155.4	129.2	60.4	21.3	12.1	853.3
Air_Et_GeltaLumame(P)	264	15.1	23.2	45.0	65.8	89.1	101.4	155.4	155.5	132.2	66.7	22.8	11.0	883.2
Air_Et_BogenaLumame(P)	266	15.1	23.2	45.0	65.8	89.1	101.4	155.4	155.5	132.2	66.7	22.8	11.0	883.2
Air_Et_HulukaDebis(P)	269	24.0	32.6	59.1	81.0	107.0	124.1	157.0	156.5	135.6	60.3	21.3	15.2	973.6
Air_Et_UpperGuder(P)	277	18.9	25.6	53.5	70.7	100.9	127.6	155.6	153.6	132.0	58.2	16.8	8.7	922.2
Air_Et_Anonu(P)	284	8.3	12.9	36.2	50.9	95.8	120.9	152.0	148.0	119.2	56.2	17.5	5.9	823.9
Air_Et_Kale(P)	288	8.9	14.4	37.5	50.9	90.0	115.7	151.4	148.0	117.3	52.0	15.4	6.2	807.7
Air_Et_ChemogaKola(P)	295	6.8	11.4	29.8	44.9	89.7	109.9	153.4	151.5	124.9	61.6	16.9	4.7	805.4
Air_Et_Neshe(P)	300	5.3	8.0	26.9	42.2	100.7	128.7	153.3	151.6	128.9	68.8	19.7	5.4	839.6
Air_Et_NediAmarti(P)	301	5.3	8.0	26.9	42.2	100.7	128.7	153.3	151.6	128.9	68.8	19.7	5.4	839.6
Air_Et_GulaDembech(P)	311	8.7	14.9	34.2	52.7	89.0	116.6	158.1	155.5	135.1	74.1	19.9	9.8	868.7
Air_Et_Jedeb(P)	312	11.3	19.2	35.2	56.2	90.7	116.6	158.0	157.2	135.1	75.1	22.7	11.5	888.8
Air_Et_MiddleB(P)	319	5.0	7.4	23.7	42.0	97.6	126.4	158.2	155.3	137.5	75.9	19.4	5.7	854.2
Air_Et_Lah(P)	332	6.7	10.2	28.3	46.5	92.3	122.7	160.4	157.3	137.8	77.5	20.1	8.2	867.9
Air_Et_Fettam(P)	337	5.2	6.3	21.9	39.5	93.1	126.2	157.2	154.3	129.0	75.7	19.9	5.2	833.5
Air_Et_AzemaAyo(P)	347	5.7	7.3	23.2	44.2	100.3	134.1	160.4	157.5	140.0	83.4	23.3	8.2	887.6
Air_Et_AzenaZingini(P)	348	3.7	5.0	18.2	37.3	98.4	132.5	157.2	154.3	135.5	78.9	21.1	5.0	847.2
Air_Et_Timbi(P)	354	2.4	4.5	13.2	39.4	101.9	137.2	161.4	157.3	140.1	84.2	19.3	6.3	867.2
Air_Et_Guchis(P)	358	2.4	4.5	13.2	39.4	101.9	137.2	161.4	157.3	140.1	84.2	19.3	6.3	867.2
Air_Et_Chagni(P)	363	2.4	4.2	17.8	36.6	97.2	131.9	159.5	155.9	136.0	80.2	19.4	7.9	848.9
Air_Et_ArjoDidessa(P)	381	17.1	28.5	57.4	79.0	113.2	133.3	148.3	146.3	128.2	76.2	41.3	13.8	982.7
Air_Et_ArjoDidessaPump(P)	383	8.4	16.7	41.7	60.8	115.4	134.3	150.5	148.5	128.2	75.2	32.9	10.1	922.8
Air_Et_Hida(P)	389	22.8	37.3	65.2	88.0	112.9	130.8	145.3	144.4	127.4	78.6	47.6	18.2	1018.5
Air_Et_Negeso(P)	394	10.3	17.3	43.2	66.2	113.2	134.5	150.1	146.6	120.9	67.2	31.3	9.5	910.4
Air_Et_Wama+Urgesa(P)	399	14.2	24.3	53.7	73.8	117.6	137.4	152.8	151.2	127.3	74.6	33.2	13.1	973.2
Air_Et_UpperDabana(P)	402	15.0	26.3	54.6	73.2	120.4	136.2	152.8	151.1	132.3	81.5	37.8	15.3	996.5
Air_Et_Dabana(P)	404	7.5	11.2	36.6	62.5	120.9	137.2	152.9	150.6	130.7	82.5	33.4	11.5	937.4
Air_Et_Dimtu(P)	410	7.5	11.2	36.6	62.5	120.9	137.2	152.9	150.6	130.7	82.5	33.4	11.5	937.4
Air_Et_Didga(P)	411	4.9	9.2	32.3	56.5	119.9	137.3	153.1	150.7	129.6	79.8	30.9	9.5	913.6
Air_Et_Anger(P)	419	4.7	8.9	28.7	55.2	120.1	143.0	155.4	152.9	134.8	85.2	31.8	7.3	927.8
Air_Et_Nekemte(P)	421	4.1	7.3	28.0	51.2	115.1	134.3	151.9	149.6	126.3	73.6	27.1	7.0	875.5
Air_Et_Dale(P)	433	5.9	9.8	31.9	60.2	124.0	144.2	154.8	152.6	135.5	79.3	30.7	7.7	936.6
Air_Et_LekuUke(P)	439	4.1	7.3	28.0	51.2	115.1	134.3	151.9	149.6	126.3	73.6	27.1	7.0	875.5
Air_Et_Biyo+Gumbi(P)	443	3.7	6.6	26.5	50.2	114.4	133.5	151.2	149.4	127.1	75.1	27.7	6.8	872.1
Air_Et_Dembigusu(P)	449	2.7	6.5	22.9	48.0	110.6	135.7	153.6	150.3	128.2	80.1	25.7	6.3	870.4
Air_Et_Chigsha(P)	454	2.5	5.8	21.3	46.7	113.5	138.3	154.3	152.2	134.7	83.6	25.6	6.6	885.2
Air_Et_Lugo(P)	459	1.2	2.8	15.3	41.6	109.4	138.4	153.1	151.7	134.8	85.2	22.3	3.6	859.5
Air_Et_Bar(P)	465	1.3	2.7	15.7	41.1	110.4	139.3	154.5	154.3	139.8	88.0	21.4	5.3	873.8
Air_Et_JemaAGanti(P)	477	3.0	5.0	19.9	48.2	114.4	135.7	153.1	149.6	134.6	90.2	32.4	9.0	895.1
Air_Et_LowerDuraPump(P)	486	0.2	1.4	10.2	31.7	100.2	130.0	148.0	147.7	128.1	82.6	19.4	2.9	802.3
Air_Et_UpperDila(P)	497	5.2	8.3	30.0	59.2	121.8	140.3	153.7	150.9	141.1	94.5	39.4	12.2	956.7
Air_Et_FelmtuDila(P)	499	6.4	10.1	33.6	61.6	123.1	138.8	152.9	149.7	138.7	94.6	41.2	14.2	964.9
Air_Et_Fincha	510	6.4	11.0	32.6	47.3	95.2	123.3	153.7	150.3	124.7	62.7	16.2	5.8	829.2
Air_Et_Dabus(P)	512	0.9	2.2	11.7	39.1	105.9	143.0	150.5	149.2	138.4	91.3	23.2	1.9	857.1
Air_Et_DaleBilutsu(P)	513	0.1	1.1	9.5	31.9	94.8	124.6	144.9	145.6	123.0	83.9	18.2	3.0	780.5
Air_Et_Galegu(P)	523	0.0	0.0	0.2	5.3	41.7	99.3	142.9	141.4	97.5	40.3	2.8	0.1	571.6
Air_Et_Rahad(P)	526	0.0	0.1	0.1	2.2	38.5	74.5	139.6	146.6	95.9	41.7	2.2	0.1	541.3
Air_Su_SennarSugarScheme	676	0.0	0.0	0.0	0.1	5.3	13.2	63.2	81.2	34.8	10.1	0.0	0.0	207.9
Air_Su_GuneidSugarExtension	678	0.0	0.0	0.0	0.0	2.7	1.9	30.3	50.8	12.2	2.4	0.0	0.0	100.5
Air_Su_GeziraManagil	679	0.0	0.0	0.0	0.0	1.6	2.7	32.4	45.7	13.1	1.7	0.0	0.0	97.2
Air_Su_BlueNilePumpSchemesDsSennar	682	0.0	0.0	0.0	0.0	2.1	1.9	29.7	40.4	10.4	1.6	0.0	0.0	86.1
Air_Su_Rahad2(P)	686	0.0	0.0	0.0	0.5	10.0	23.1	72.6	95.4	48.0	13.7	0.3	0.0	263.6
Air_Su_SouthDinder(P)	694	0.0	0.0	0.0	0.3	8.7	19.6	75.6	98.9	55.1	12.2	0.0	0.0	270.5
Air_Et_GubayMariam+Mitrha+Kirnya+Agid(P)	705	3.8	4.0	16.3	30.2	81.6	110.1	161.0	155.8	113.4	66.8	15.8	4.6	763.3
Air_Et_Koga	894	4.2	5.0	18.2	38.7	88.3	126.0	164.1	159.0	135.3	77.6	19.0	7.0	842.3
Air_Et_Ligome+Asinwara+Istumit+Kunzla(P)	907	1.8	1.5	9.1	23.4	76.4	119.0	161.6	155.3	120.5	66.0	13.3	4.4	752.2
Air_Et_AmriPlain(P)	923	6.3	5.1	19.0	44.3	94.3	131.2	167.5	160.7	135.0	81.5	20.1	9.9	874.8
Air_Et_AmboPlain(P)	933	2.5	5.0	12.3	42.1	90.2	131.0	166.6	159.7	135.1	82.2	18.9	6.9	852.6
Air_Et_GugAndInsewi+KongraDeblPlain(P)	934	5.3	3.4	14.7	38.0	88.9	128.6	166.5	159.3	129.7	77.5	18.0	7.7	837.6
Air_Et_Diyaleg+LijomRiste(P)	952	2.0	1.7	9.5	24.5	78.3	120.9	163.3	156.9	125.7	69.5	13.8	4.5	770.6
Air_Et_Delgi+BebehaAbo+Fentay+Gawrna(P)	958	1.7	1.6	10.5	23.8	75.5	115.3	158.8	152.6	111.1	63.5	13.3	4.4	732.2
Air_Et_LowerDinder(P)	1145	0.0	0.1	1.7	11.3	55.3	107.0	146.9	143.5	110.2	51.0	4.3	0.3	631.7
Air_Et_UpperBeles(P)	1175	2.0	2.3	10.5	27.1	88.0	127.1	159.7	155.2	129.3	76.0	16.4	4.4	798.1
Air_Et_DebreGuracha(P)	1222	26.1	26.7	57.1	79.0	62.9	63.0	149.3	148.6	106.1	38.6	18.5	8.4	784.2
Air_Et_RobiRikicha(P)	1237	25.5	33.8	54.1	79.0	67.2	74.5	148.3	146.3	111.2	38.6	14.7	8.5	801.5
Air_Su_AbuNaamaSeleitBlueNilePumpScheme	1350	0.1	0.0	0.1	2.4	26.9	70.6	115.5	121.8	88.5	27.4	0.6	0.0	453.8
Air_Su_Kenana2And3(P)	1355	0.0	0.0	0.0	0.6	20.7	47.1	102.9	121.2	76.2	23.4	0.4	0.0	392.6
Air_Su_ElSuki	1370	0.0	0.0	0.0	0.3	8.0	17.9	73.2	93.5	51.2	11.9	0.0	0.0	256.0

Table 4.5 Average monthly and annual rainfall (mm) on reservoir and link storage nodes in the Tekeze-Setit-Atbara basin

Location	ID	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Rsv_Et_TekezeDamTK5_Hp	47	2.0	3.9	13.4	15.7	29.8	63.8	200.0	200.7	54.5	15.6	7.4	3.0	609.8
Rsv_Et_MetemaDam_HpIr(P)	50	0.1	0.1	2.3	6.8	65.5	159.4	273.8	250.0	127.3	42.1	8.2	0.8	936.6
Rsv_Et_SmallScaleIrrDams_Ir	68	0.1	0.2	2.4	5.5	50.6	133.3	254.1	231.9	104.8	32.4	7.1	0.3	822.6
Rsv_Et_HumeraDam_IrHp(P)	565	0.1	0.0	0.7	2.9	22.1	65.6	162.8	164.2	65.9	15.2	2.7	0.1	502.3
Rsv_Su_RumelaDam_HpIr(P)	800	0.0	0.0	0.2	0.6	13.4	25.9	140.5	132.9	61.5	14.0	1.0	0.0	390.0
Rsv_Su_KhashmElGirbaDam_IrHp	875	0.0	0.0	0.0	0.7	6.4	9.8	88.4	95.3	23.5	7.8	0.9	0.0	232.8

Table 4.6 Monthly and annual effective rainfall (mm) for Advanced Irrigation Nodes in the Tekeze-Setit-Atbara basin

Location	ID	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Air_Et_Metema(P)	60	0.1	0.1	0.3	3.8	39.3	94.4	145.7	142.5	92.7	35.2	4.9	0.2	559.1
Air_Et_SmallScale	145	0.1	0.1	1.6	4.3	38.7	93.6	138.6	133.7	85.3	28.8	5.4	0.1	530.3
Air_Et_Humera(P)	575	0.2	0.0	0.2	1.4	12.6	52.3	104.9	104.3	62.5	16.9	1.3	0.0	356.5
Air_Su_UpperAtbara(P)	644	0.3	0.0	0.0	0.3	3.9	5.6	54.9	51.1	20.2	4.9	0.2	0.0	141.4
Air_Su_Rumela(P)	810	0.0	0.0	0.2	0.6	9.2	18.3	90.4	82.6	44.1	12.0	0.7	0.0	258.0
Air_Su_NewHalfa	890	0.0	0.0	0.1	0.2	3.6	2.3	44.0	29.3	6.2	1.9	0.1	0.0	87.7

Table 4.7 Average monthly and annual rainfall (mm) on reservoir and link storage nodes in the Main Nile basin

Location	ID	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Rsv_Su_ShereiqDam_Hp(P)	128	0.0	0.0	0.0	0.0	0.2	0.0	0.3	1.9	0.0	0.0	0.0	0.0	2.4
Rsv_Su_DalDam_Hp(P)	131	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Rsv_Su_SabalokaDam_IrHp(P)	1630	0.0	0.0	0.0	0.0	0.5	0.2	11.4	8.0	2.2	0.4	0.0	0.0	22.6
Rsv_Su_DagashDam_Hp(P)	1680	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.1
Rsv_Su_MogratDam_Hp(P)	1690	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
Rsv_Su_MeroweDam_IrHp	1700	0.0	0.0	0.0	0.0	0.0	0.0	0.1	1.8	0.0	0.0	0.0	0.0	1.9
Rsv_Su_KajbarDam_Hp(P)	1740	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Rsv_Eg_High AswanDam	1790	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Lst_Su_EvapKhartoumMerowe	66	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.2
Lst_Su_EvapMeroweNasser	67	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Lst_Su_DelayKhartoumAtbaraMouth	1670	0.0	0.0	0.0	0.1	0.1	0.0	0.7	1.9	0.1	0.1	0.0	0.0	2.9
Lst_Su_DelayAtbaraMouthMerowe	1695	0.0	0.0	0.0	0.0	0.0	0.0	0.1	1.5	0.0	0.0	0.0	0.0	1.6
Lst_Su_DelayMeroweDongala	1750	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Lst_Su_DelayDongalaNasser	1770	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 4.8 Monthly and annual effective rainfall (mm) for Advanced Irrigation Nodes in the Main Nile basin

Location	ID	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Air_Su_MainNileKhartoumAtbara	1640	0.0	0.0	0.0	0.0	0.4	0.2	12.1	8.9	1.6	0.7	0.0	0.0	23.9
Air_Su_MainNilePumpSchemes	1685	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.1
Air_Su_Merowe	1725	0.0	0.0	0.0	0.0	0.0	0.0	0.2	1.9	0.0	0.0	0.0	0.0	2.2
Air_Eg_ToshkaPumpScheme	1800	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

5 Evaporation

5.1 Reference evapotranspiration

The potential evapo-transpiration E_{pot} input used in RIBASIM for the Eastern Nile basin is based on monthly data of all meteorological stations in the basin available in the FAO East-Africa CLIMWAT databases for Ethiopia, South Sudan and Sudan. The potential evapo-transpiration E_{pot} of any surface follows from the reference evapo-transpiration ET_0 according to the Penman-Monteith equation times a vegetation factor or crop coefficient *k* (Allen, et al., 1998):

$$E_{pot} = k \times ET_0 \qquad (5\text{-}1a)$$

$$ET_0 = \frac{0.408\,\Delta\left(R_n - G\right) + \gamma\,\frac{900}{T+273}\,u_2\left(e_s - e_a\right)}{\Delta + \gamma\left(1 + 0.34\,u_2\right)} \quad [mm/day] \qquad (5\text{-}1b)$$

where:

E_{pot}	= potential evapo-transpiration [mm/day]
k	= vegetation factor [-]
ET_0	= reference evapo-transpiration [mm/day]
Δ	= slope of saturation vapour pressure versus temperature curve [kPa/^{o}C]
R_n	= net radiation [MJ/(m^{2}day)]
G	= soil heat flux [MJ/(m^{2}day)]
γ	= psychrometric constant [kPa/^{o}C]
T	= main daily air temperature at 2 m height [^{o}C]
u_2	= wind speed at 2 m height [m/s]
e_s	= saturation vapour pressure [kPa]
e_a	= actual vapour pressure [kPa]

The reference evapo-transpiration ET_0 is the evapo-transpiration from a hypothetical reference crop of height 0.12 m, a fixed surface resistance of 70 s/m and an albedo of 0.23, which closely resembles the evapo-transpiration from a green actively growing grass surface of uniform height with adequate water.

5.1.1 Penman-Montheith equation

The Penman-Monteith equation for evapotranspiration presented in (5-1b) follows form:

$$\lambda ET = \frac{\Delta\left(R_n - G\right) + \rho_a c_p \dfrac{\left(e_s - e_a\right)}{r_a}}{\Delta + \gamma\left(1 + \dfrac{r_s}{r_a}\right)} \qquad (5\text{-}2)$$

where:

ET = evapotranspiration [kg/(m^2.s] = [mm/s]
Λ = latent heat of vaporization [MJ/kg]
R_n = net radiation at crop surface [MJ/(m^2.s]
G = soil heat flux density [MJ/(m^2.s]
e_s = saturation vapour pressure [kPa]
e_a = actual vapour pressure [kPa]
e_s - e_a = saturation vapour pressure deficit [kPa]
Δ = slope of function e_s = f(T) [kPa/^{o}C]
γ = psychrometric constant [kPa/^{o}C]
ρ_a = mean air density at constant pressure [kg/m^3]
c_p = specific heat at constant pressure [MJ/(kg^{o}C)]
r_a = aerodynamic resistance [s/m]
r_s = (bulk) surface resistance [s/m]

Or equivalently:

$$ET = \frac{\dfrac{\Delta\left(R_n - G\right)}{\lambda} + \dfrac{\rho_a c_p}{\lambda}\dfrac{\left(e_s - e_a\right)}{r_a}}{\Delta + \gamma\left(1 + \dfrac{r_s}{r_a}\right)} \qquad (5\text{-}3)$$

ET becomes reference evapo-transpiration ET_0 by considering the evaporation from a hypothetical reference crop with a height of 0.12 m, a fixed surface resistance of 70 s/m and an albedo of 0.23 as stated above. The derivation is explained in the following.

5.1.2 Aerodynamic resistance r_a

The aerodynamic resistance r_a describes the resistance from the vegetation surface upward and involves friction from the air flowing over the vegetation. It determines the transfer of heat and water vapour from the evaporating surface into the air above the canopy using a logarithmic wind profile. It is determined by:

$$r_a = \frac{\ln\left(\dfrac{z_m - d}{z_{om}}\right)\ln\left(\dfrac{z_h - d}{z_{oh}}\right)}{\kappa^2 u_z} \quad [s/m] \qquad (5\text{-}4)$$

where:

r_a = aerodynamic resistance [s/m]
z_m = height of wind measurements [m]

z_h = height of humidity measurements [m]
d = zero plane displacement [m]
z_{om} = roughness length governing momentum transfer [m]
z_{oh} = roughness length governing transfer of heat and vapour [m]
κ = von Karman constant, 0.41 [-]
u_z = wind speed at height z [m/s]

Note that at $z_m = d$ (zero plane displacement) the wind function has its lower asymptote and the wind velocity is zero at $z_m = z_{om} + d$, i.e. the effective or nominal surface level. For the zero plane displacement and roughness lengths for a wide range of crops the following relations apply:

$$d = \frac{2}{3} h$$
$$z_{om} = 0.123\, h \qquad (5\text{-}5)$$
$$z_{oh} = 0.1\, z_{om}$$

with: h = crop height [m]

For the reference crop of height 0.12 m and when the wind and humidity measurements are carried out at 2 m above the surface, the aerodynamic resistance becomes:

$$r_a = \frac{\ln\left(\dfrac{2-\frac{2}{3}\,x\,0.12}{0.123\,x\,0.12}\right)\ln\left(\dfrac{2-\frac{2}{3}\,x\,0.12}{0.1\,x\,0.123\,x\,0.12}\right)}{(0.41)^2\,u_2} = \frac{208}{u_2} \quad [s/m] \qquad (5\text{-}6)$$

with: u_2 = wind speed at 2 m above the surface [m/s]

5.1.3 ‘Bulk’ surface resistance rs

The ‘bulk’ surface resistance describes the resistance of vapour flow through the transpiring crop and evaporating soil surface. For a dense full cover vegetation this resistance can be estimated by:

$$r_s = \frac{r_l}{LAI_{active}} \qquad (5\text{-}7)$$

where: LAI = leaf area index [-], i.e. the leaf area (upper side only) per unit of soil area
LAI_{active} = active (sunlit) leaf area index
r_l = stomatal resistance [s/m]

For a dense vegetation it is assumed that only the upper half of the vegetation contributes to heat and vapour transfer:

$$LAI_{active} = 0.5\, LAI \qquad (5\text{-}8)$$

For clipped grass, representing the hypothetical crop for reference evapotranspiartion, the following relation applies between the *LAI* and the crop height:

$$LAI = 24\, h \qquad (5\text{-}9)$$

The stomatal resistance r_l for a single leaf has a value of about 100 s/m under well watered conditions. Hence the reference bulk surface resistance becomes:

$$r_s = \frac{100}{0.5\ x\ 24\ x\ 0.12} \approx 70 \quad [s/m] \tag{5-10}$$

5.1.4 Coefficient of vapour term

The term in front of the saturation vapour deficit in equation (5-3) reads:

$$\frac{\rho_a c_p}{\lambda r_a} \quad with: \quad \rho_a = \frac{P}{T_{Kv} R} \quad and: \quad c_p = \frac{\gamma \varepsilon \lambda}{P} \tag{5-11}$$

Here R is the specific gas constant = 0.287×10^{-3} MJ/(kg.K) and ε is the ratio of the molecular weight of water vapour to dry air = 0.622. Replacing the virtual temperature T_{Kv} [K] by the air temperature T [^{o}C] according to:

$$T_{Kv} = 1.01(T + 273) \tag{5-12}$$

it follows:

$$\frac{\rho_a c_p}{\lambda r_a} = \frac{\gamma \varepsilon}{1.01(T+273) R r_a} \quad [kg/(m^2.s.^oC)] \tag{5-13}$$

Since 1 kg/(m^2.s) = 1 mm/s it follows for the reference crop conditions and expressed in mm/(day.^{o}C) for the above expression:

$$\frac{\rho_a c_p}{\lambda r_a} = 86400 \frac{\gamma\ x\ 0.622}{\{1.01(T+273)\}\ x\ \{0.287 x 10^{-3}\}} . \frac{u_2}{208} \approx \gamma \frac{900}{T+273} u_2 \quad [mm/(day.^oC)]$$

(5-14)

5.1.5 Net energy term

The net energy term $(R_n\text{-}G)/\lambda$ has dimension [MJ/(m^2.s).(kg/MJ] = [kg/(m^2.s]=[mm/s]
Or with R_n and G expressed in [MJ/(m^2.day)] and with λ = 2.45 [MJ/kg] the term $(R_n\text{-}G)/\lambda$ becomes: (5-15)

$$\frac{(R_n - G)}{\lambda} = \frac{1}{2.45}(R_n - G) = 0.408(R_n - G) \quad [mm/day] \quad with: \quad Rn, G\, [MJ/(m^2.day)]$$

The soil heat flux G for a vegetated surface is small compared to the net radiation term. In the computational procedure it is assumed that the soil temperature follows the air temperature:

$$G = c_s \frac{T_i - T_{i-1}}{\Delta t} \Delta z \tag{5-16}$$

where: G = soil heat flux [MJ/(m^2.day)]
c_s = soil heat capacity [MJ/(m^3.^{o}C)]
$T_{i,\, i\text{-}1}$ = air temperature at time i and i-1 [^{o}C]
Δt = length of time interval [day]
Δz = effective soil depth [m]

According to FAO, the soil heat flux for daily or ten-day periods beneath the grass reference surface is relatively small **and may be ignored**. When dealing with **monthly** periods the following relation is used assuming a constant soil heat capacity of 2.1 [MJ/(m^3.^{o}C)]:

if the temperature in the next month is known:

$$G_{month\ i} = 0.07\left(T_{month\ i+1} - T_{month\ i-1}\right) \tag{5-17}$$

if the temperature in the next month is not known:

$$G_{month\ i} = 0.14\left(T_{month\ i} - T_{month\ i-1}\right) \tag{5-18}$$

Summing up

With (5-6), (5-10), (5-14) and (5-15) substituted in equation (5-3) equation (5-1b) follows for the reference evapotranspiration ET_0 expressed in [mm/day].

Climatic data as provided by FAO contain the following data:

- station name, altitude, latitude and longitude
- monthly values of:
  - Tmax (^{o}C)
  - Tmin (^{o}C)
  - Relative Humidity (%)
  - Windspeed (km/day)
  - Sunshine duration (hrs)
  - Solar radiation (MJ/m^2/day)
  - ET_0 (mm/day)

To compute effect of temperature change:

- compute new net long wave radiation, saturation vapour pressure and new saturation deficit.
- assume that soil heat flux is zero.
- apply above Penman-Monteith formula.

5.2 ET0 in the basins

5.2.1 Baro-Akobo-Sobat-White Nile

The reference evapotranspiration in the Baro-Akobo-Sobat-White Nile basin as a function of elevation is shown in Figure 5.1. The function has the following form:

$$ET_0 = 3023.8\ (Elevation - 356.0)^{-0.1141} \tag{5-19}$$

where:

ET_0 = reference evapotranspiration (mm/year)

Elevation = altitude of station (m+MSL)

The function has been applied for all locations in the sub-basin in Ethiopia only. It is observed that for altitudes < 500 m+MSL the relation becomes inaccurate. Therefore, for locations in Sudan ET_0 has been derived from Figure 5.5, where a distinct relation is observed between latitude and ET0. The monthly variation for each location is based on the observed variation at the nearest climatological station in the FAO CLIMWAT database of East-Africa.

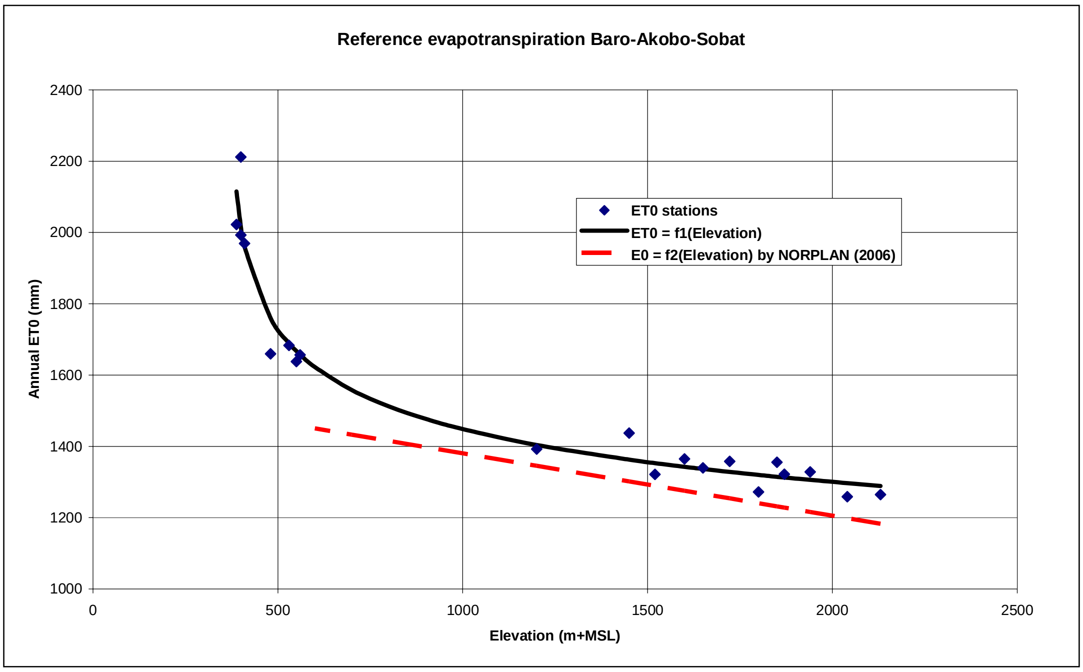

Figure 5.1 Reference evapotranspiration in Baro-Akobo-Sobat-White Nile basin as function of elevation

5.2.2 Abay-Blue Nile

The reference evapotranspiration in the Abay-Blue Nile basin as a function of elevation is shown in Figure 5.2. The figure shows that the overall fit is rather inaccurate for the elevations > 1000+MSL, i.e. the stations in Ethiopia. In Figure 5.3 the ET_0 values are presented as a function of elevation distinguished by latitude. A better fit to the data is observed from the graph. The following relations for locations in the Abay basin have therefore been applied:

$$\text{For latitude } 7^o\text{-}10^o\text{: } ET_0 \text{ (mm/year)} = 230.85 \ln(\text{Elevation}) + 3068 \quad (5\text{-}20)$$

$$\text{For latitude } 10^o\text{-}12^o\text{: } ET_0 \text{ (mm/year)} = 230.85 \ln(\text{Elevation}) + 3157 \quad (5\text{-}21)$$

$$\text{For latitude } 12^o\text{-}13^o\text{: } ET_0 \text{ (mm/year)} = 230.85 \ln(\text{Elevation}) + 3280 \quad (5\text{-}22)$$

With:

ET_0 = reference evapotranspiration (mm/year)

Elevation = altitude in m+MSL

For locations in the Sudan use has been made of Figure 5.5. The monthly variation for each location is based on the observed variation at the nearest climatological station in the FAO CLIMWAT database of East-Africa.

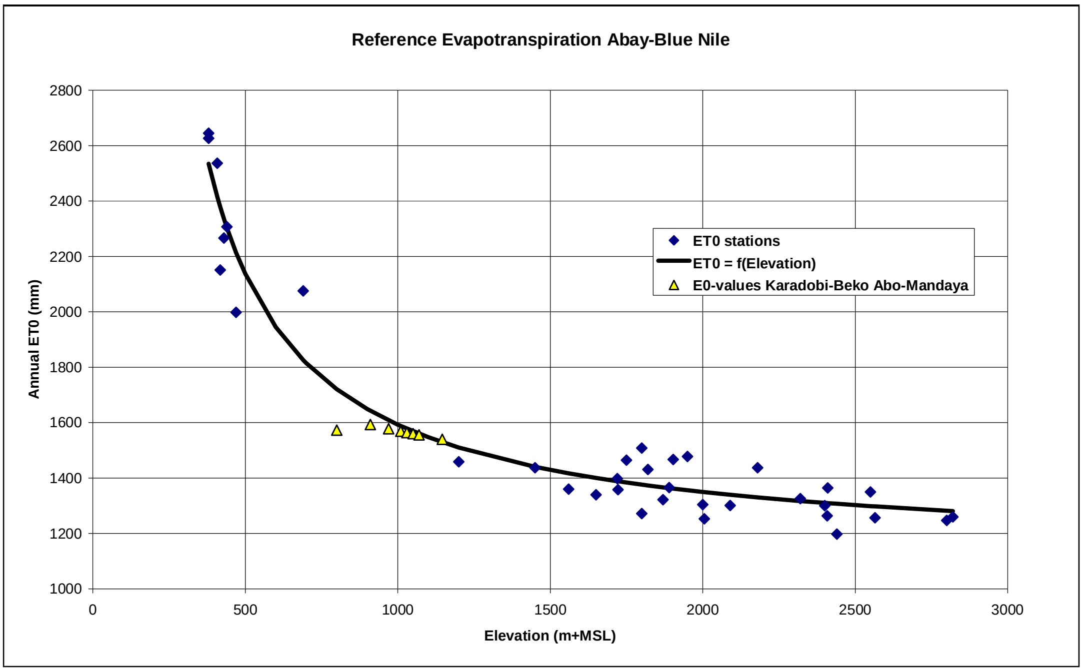

Figure 5.2 Reference evapotranspiration in Abay-Blue Nile basin as function of elevation

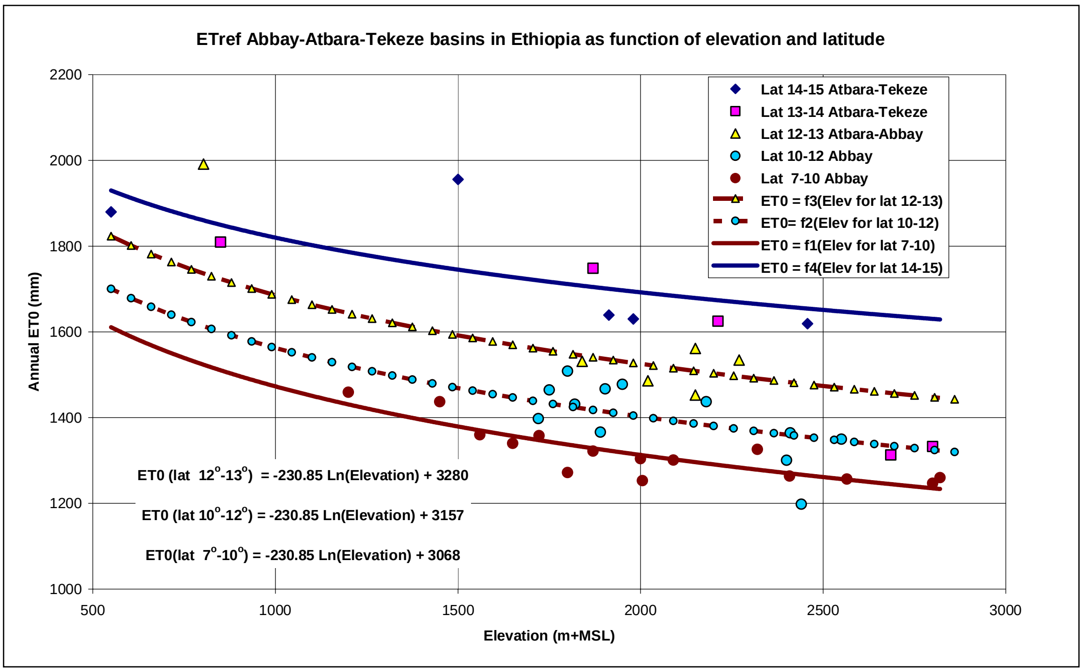

Figure 5.3 Reference evapotranspiration in Abay-Blue Nile basin as function of elevation and latitude

5.2.3 Tekeze-Setit-Atbara

The reference evapotranspiration ET_0 in the Tekeze-Setit-Atbara basin is presented in Figure 5.4. The presented relationship is described by the following equation:

$$ET_0 \text{ (mm/year)} = -466.2 \ln(\text{Elevation}) + 5127.4 \quad (5\text{-}23)$$

With:

ET_0 = reference evapotranspiration (mm/year)

Elevation = altitude of location in m+MSL

Above relation has been used for locations upstream of Tekeze Bridge only. In view of the poor fit, for all other locations in the basin ET_0 values derived for the nearest climatological stations have been used.

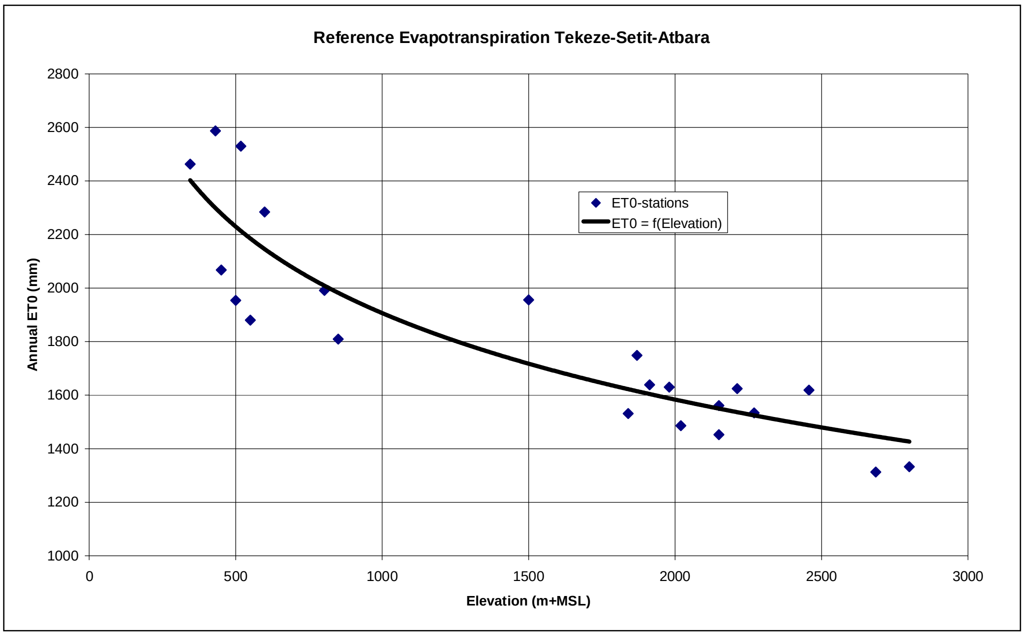

Figure 5.4 Reference evapotranspiration in Tekeze-Setit-Atbara basin as function of elevation

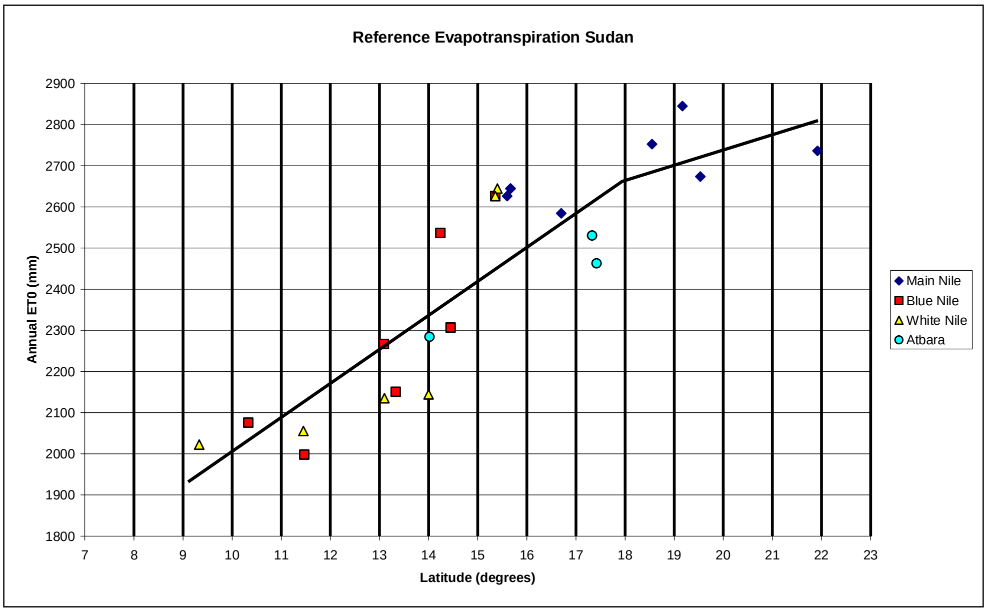

Figure 5.5 Reference evapotranspiration in Sudan as function of latitude

5.3 Open water evaporation

For open water FAO suggests 'crop' factors of 1.05 for shallow water surfaces and for deep water factors of 0.6525 for the mid growing season and 1.2525 for the end of the growing season in temperate climates. The difference for deep waters refers to reservoirs where in spring and early summer part of the incoming radiation is used for heating up the water in the reservoir, which energy is released in late summer and autumn. To assess the conditions in the Eastern Nile Basin for some 50 stations in Ethiopia, South Sudan, Sudan and Egypt in the CLIMWAT data base comparisons have been made between ET_0 and open water evaporation E0 according to the Penman formula and 2 adaptations to Penman formula correcting for wind fields over large water surfaces and difference between air and water temperature, see Section 5.3. The correction to be applied to ET_0 to arrive at E_0 reads:

For ET_0 < 1800 mm/year:	$E_0 = 1.15\ ET_0$	
For 1800 ≤ ET_0 ≤ 2600 mm/year:	$E_0 = (1 + 0.15\ (2600 - ET_0)/800)\ ET_0$	(5-24)
For ET_0 > 2600 mm/year:	$E_0 = 1.00\ ET_0$	

The 'crop'factor is diplayed in Figure 5.6. It follows that the open water evaporation is higher than the reference evapotranspiration for ET_0 < 2600 mm.

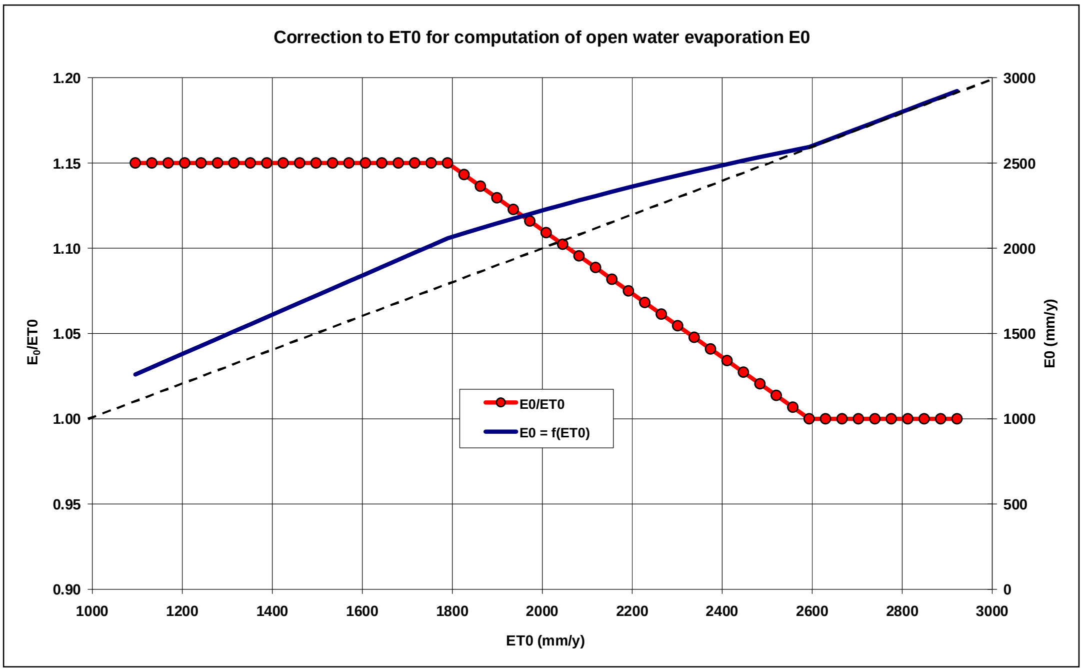

Figure 5.6 'Crop-factor k' to be applied to ET_0 *to compute open water evaporation E0*

A comparison with existing evaporation time series for Baro and Abay reservoirs has been presented in Figure 5.1 and Figure 5.2. Figure 5.1 shows that the adopted relations in the Baro I and II and Genji reservoirs feasibility studies (NORPLAN, 2006) even underestimate the reference evapotranspiration derived for the climatic stations in the basin. Compared to the open water evaporation applied in ENSWM the NORPLAN-values are 20% less. From Figure 5.2 it is observed that the assumed open water evaporation values used in the Karadobi, Beko Abo and Mandaya pre-feasibility studies closely follow the reference evapotranspiration values. The values adopted in ENSWM are about 200 mm/year higher. The feasibility studies for the dams around Laka Tana and TK5 onTekeze used 'crop'factors of 1.2 to 1.3 respectively to the reference evapotranspiration, which is 5-15 % higher than applied here.

5.4 Open water evaporation relative to the refrence evapotranspiration

To assess the ‘crop’ factors to be applied in the Eastern Nile basin for some 50 stations in Ethiopia, South Sudan, Sudan and Egypt in the CLIMWAT data base comparisons have been made between ET_0 and open water evaporation E_0 according to the following methods:

- E_0 calculated by the Penman method, presented by Shuttleworth in Maidment (1993), using the updated wind function given in Jensen (2010)
- E_0 calculated by the Penman method, presented in de Bruin and Kohsiek (1981), using the wind function by Sweers (1976) specially designed for reservoirs
- E_0 calculated by the Penman method taking into account the heat balance of the lake/reservoir according to Keijman (1973), elaborated and tested by McJannet et al (2008) in estimating open water evaporation for the Murray-Darling Basin in Australia.

The results of these comparions are presented in Figure 5.7 to Figure 5.9 and summarised in Figure 5.10.

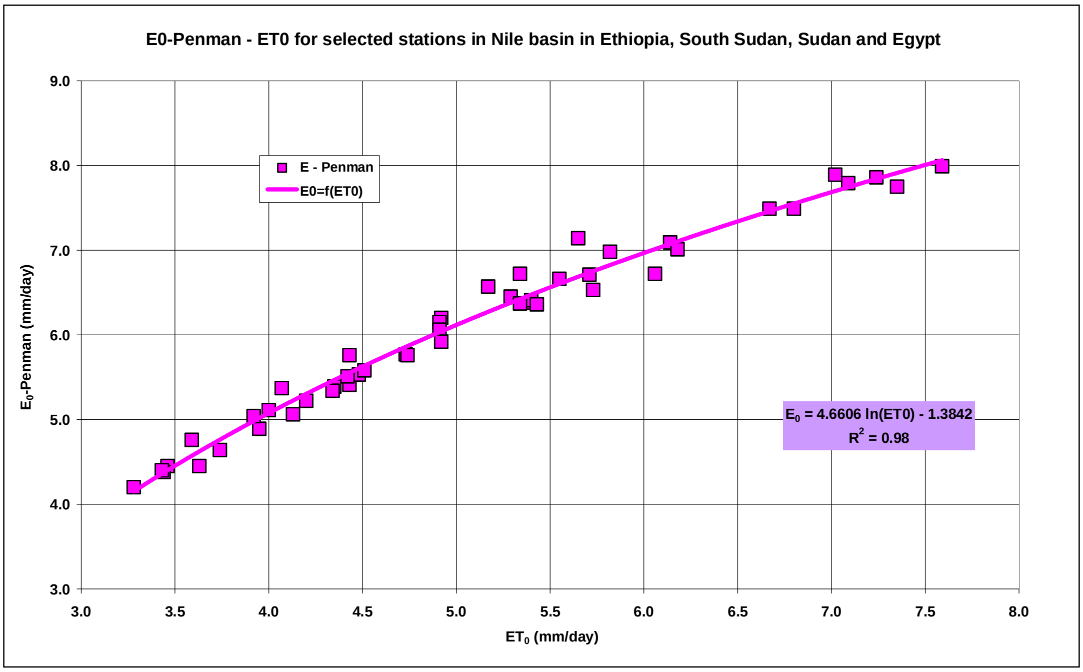

Figure 5.7 E_0*-Penman compared with* ET_0 *for stations in Ethiopia, South Sudan, Sudan and Egypt*

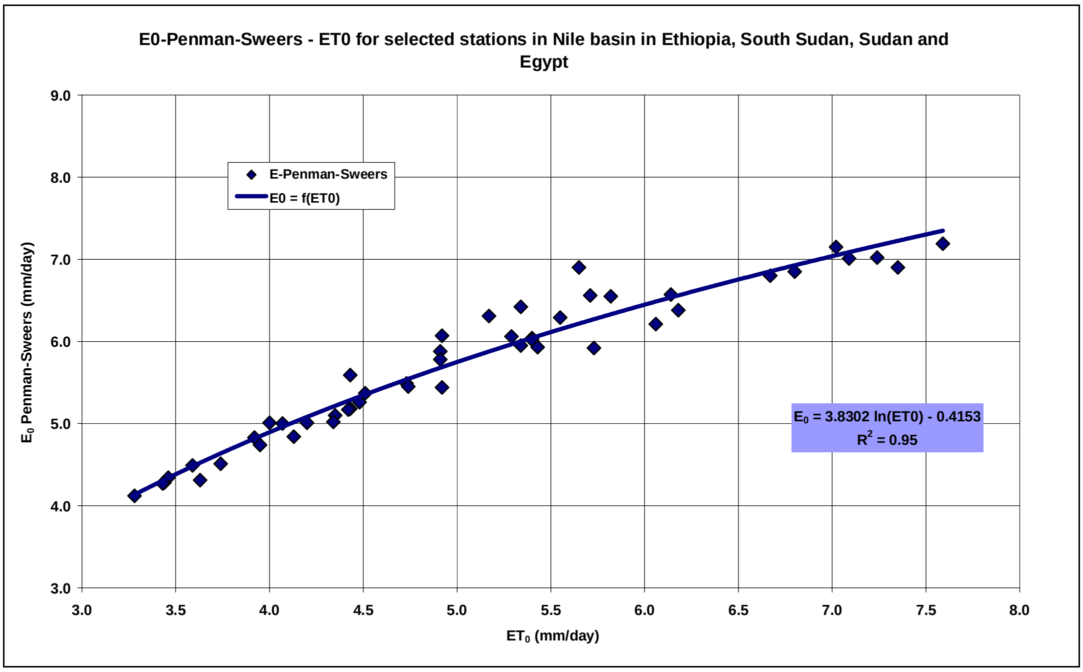

Figure 5.8 E_0*-Penman-Sweers compared with* ET_0 *for stations in Ethiopia, South Sudan, Sudan and Egypt*

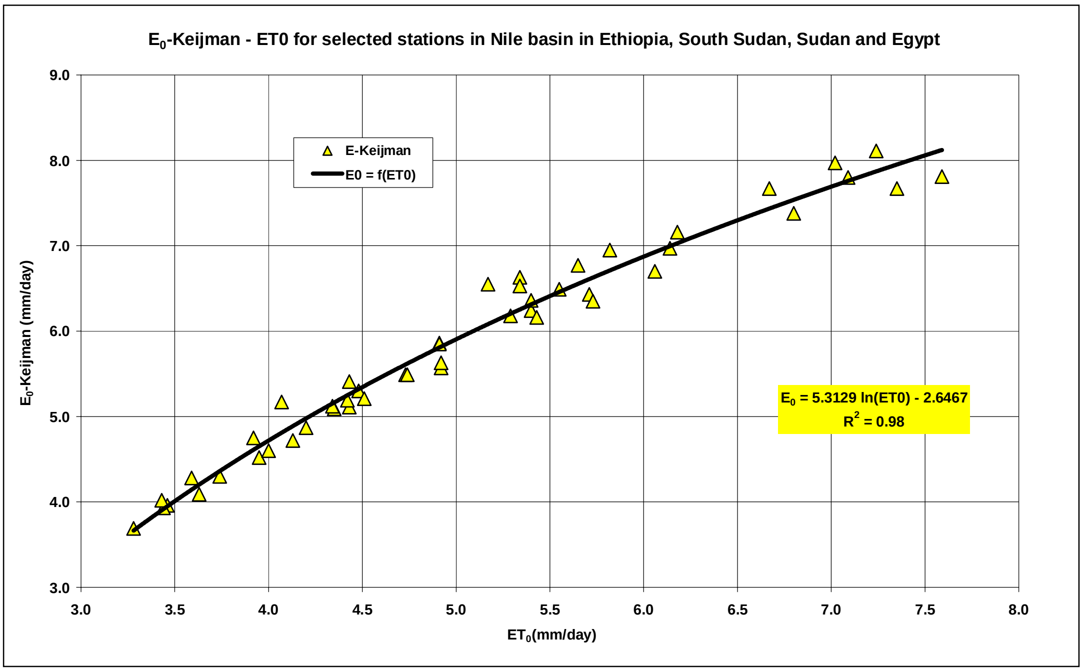

Figure 5.9 E_0*-Penman-Keijman compared with* ET_0 *for stations in Ethiopia, South Sudan, Sudan and Egypt*

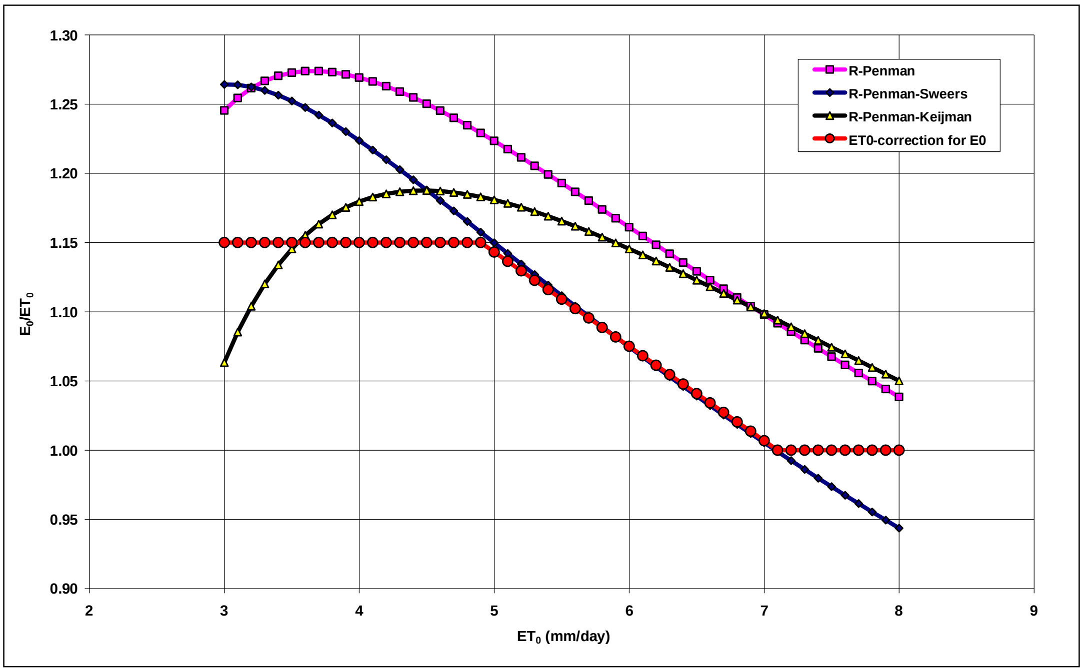

Figure 5.10 E_0/ET_0 *ratio's based on 50 stations in Nile basin d/s Mongalla*

The analysis shows that, generally, ET_0 will underestimate open water evaporation. A 'crop'factor of 1.05, as suggested by FAO for shallow lakes, is generally too low, except for locations with high evaporation rates. Shuttleworth in Maidment (1993) mentions that for larger evaporating surfaces the aerodynamic resistance is higher than assumed in the wind function applied in Penman's formula. Use of Penman's wind function would lead to systematic overestimations by 10 to 15 %.

It is observed from Figure 5.10 that such overestimations are also predicted by E_0-Penman-Sweers, which gives about 5-10% lower evaporation values. Similar percentages of overestimation by the Penman formula are reported by de Bruin (1987), who attributed the differences not only to the applied wind function but also to underestimation of the water surface temperature in comparison to that of the air 2 m above it, leading to an underestimation of the outgoing long wave radiation and hence an overestimation of the net radiation. This is consistent with the results of the Penman-Keijman model that included this feature; the model shows that in regions where ET_0 is small (i.e. regions with larger variations in temperature through the year) both Penman and Penman-Sweers overestimate open water evaporation. Jensen (2010) mentions in his review of open water evaporation that a 'crop'factor of 1.10 to ET_0 would be appropriate for reservoirs in the USA. Based on the comparison and additional literature surveys the 'crop'factors for open water as presented in the previous section will be applied, which is approximately a 10% reduction to the Penman open water evaporation estimate, see Figure 5.10.

5.5 Overview of applied evapo(transpi)ration values

The average monthly evaporation values as used in ENSWM are presented in the following tables, Table 5.1 to Table 5.8.

Table 5.1 Average monthly (mm/day) and annual (mm/year) ET_0*, Advanced Irrigation Nodes in Abay –Blue Nile basin*

ID	Name	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
81	Air_Et_UpperDinder(P)	4.39	5.03	5.27	5.27	5.03	4.23	3.59	3.03	3.75	4.47	4.31	3.91	1590.3
82	Air_Et_LowerBeles(P)	4.76	5.46	5.92	6.27	5.23	4.18	3.02	3.02	4.18	4.41	4.30	4.18	1668.6
84	Air_Et_Hod+Jigna+Beks+Mene+Guram+AbaK(P)	3.97	4.60	5.12	5.12	4.50	3.76	2.61	2.51	3.45	3.97	3.76	3.56	1426.7
98	Air_Su_Rahad	5.98	6.64	7.62	7.62	8.05	6.53	5.55	5.33	5.88	5.55	6.31	5.88	2340.0
203	Air_Et_RibbRight+LeftBank(P)	3.98	4.60	5.13	5.13	4.50	3.77	2.62	2.51	3.45	3.98	3.77	3.56	1427.3
215	Air_Et_Gura+Jar+Robit+Sera+Kola+Jiwan(P)	4.38	5.11	5.43	5.22	5.01	4.07	2.71	2.61	3.86	4.38	4.28	3.97	1550.6
216	Air_Et_Durbet3(P)	4.02	4.61	5.01	5.30	4.42	3.53	2.55	2.55	3.53	3.73	3.63	3.53	1410.3
217	Air_Et_DimbkPlain(P)	3.97	4.56	4.94	5.23	4.36	3.49	2.52	2.52	3.49	3.68	3.59	3.49	1392.9
218	Air_Et_Jemma(P)	3.99	4.58	4.97	5.26	4.38	3.51	2.53	2.53	3.51	3.70	3.60	3.51	1399.6
219	Air_Et_Chimba(P)	4.06	4.66	5.05	5.35	4.46	3.57	2.58	2.58	3.57	3.76	3.66	3.57	1423.3
220	Air_Et_Wonda+Yemosht+Seba+Teneba+Bata(P)	4.13	4.73	5.13	5.43	4.53	3.62	2.62	2.62	3.62	3.82	3.72	3.62	1446.2
221	Air_Et_Duber(P)	3.31	3.71	3.92	4.02	4.12	3.31	2.61	2.51	2.91	3.61	3.71	3.41	1252.0
224	Air_Et_Wberi(P)	3.33	3.73	3.94	4.04	4.14	3.33	2.62	2.52	2.93	3.63	3.73	3.43	1258.2
225	Air_Et_Weserbi(P)	3.33	3.73	3.93	4.03	4.13	3.33	2.62	2.52	2.92	3.63	3.73	3.43	1257.4
236	Air_Et_Homecho(P)	3.46	3.76	4.07	3.96	3.76	3.15	2.54	2.64	3.05	3.76	3.66	3.46	1255.4
237	Air_Et_Robi(P)	3.47	3.78	4.08	3.98	3.78	3.17	2.55	2.65	3.06	3.78	3.68	3.47	1260.8
250	Air_Et_Selgi(P)	3.17	3.54	3.91	4.01	4.66	4.94	3.82	3.63	3.45	3.54	3.17	3.07	1366.8
257	Air_Et_Yetmen(P)	3.82	4.28	4.28	4.97	4.05	3.35	2.66	2.54	3.35	3.93	3.70	3.70	1357.1
264	Air_Et_GeltaLumame(P)	3.84	4.30	4.30	5.00	4.07	3.37	2.68	2.56	3.37	3.95	3.72	3.72	1364.4
266	Air_Et_BogenaLumame(P)	3.83	4.30	4.30	4.99	4.06	3.37	2.67	2.55	3.37	3.95	3.72	3.72	1362.1
269	Air_Et_HulukaDebis(P)	3.76	4.05	4.14	4.53	3.86	3.18	2.41	2.41	3.08	3.76	3.76	3.57	1292.1
277	Air_Et_UpperGuder(P)	3.79	4.08	4.18	4.56	3.88	3.20	2.43	2.43	3.11	3.79	3.79	3.59	1301.5
284	Air_Et_Anonu(P)	4.09	4.40	4.51	4.92	4.19	3.46	2.62	2.62	3.35	4.09	4.09	3.88	1404.4
288	Air_Et_Kale(P)	4.08	4.39	4.50	4.92	4.18	3.45	2.62	2.62	3.35	4.08	4.08	3.87	1402.4
295	Air_Et_ChemogaKola(P)	4.29	4.81	4.81	5.59	4.55	3.77	2.99	2.86	3.77	4.42	4.16	4.16	1525.1
300	Air_Et_Neshe(P)	4.08	4.39	4.49	4.91	4.18	3.45	2.61	2.61	3.34	4.08	4.08	3.87	1400.7
301	Air_Et_NediAmarti(P)	4.05	4.36	4.47	4.88	4.16	3.43	2.60	2.60	3.32	4.05	4.05	3.84	1392.6
311	Air_Et_GulaDembech(P)	3.91	4.39	4.39	5.10	4.15	3.44	2.73	2.61	3.44	4.03	3.80	3.80	1391.3
312	Air_Et_Jedeb(P)	3.89	4.36	4.36	5.07	4.12	3.42	2.71	2.59	3.42	4.01	3.77	3.77	1381.9
319	Air_Et_MiddleB(P)	4.02	4.51	4.51	5.24	4.27	3.54	2.80	2.68	3.54	4.15	3.90	3.90	1430.5
332	Air_Et_Lah(P)	3.97	4.55	4.93	5.22	4.35	3.48	2.51	2.51	3.48	3.68	3.58	3.48	1389.9
337	Air_Et_Fettam(P)	4.30	4.82	4.82	5.61	4.56	3.78	3.00	2.87	3.78	4.43	4.17	4.17	1529.5
347	Air_Et_AzemaAyo(P)	4.12	4.53	4.94	5.56	4.43	3.60	2.68	2.68	3.60	3.81	3.81	3.60	1439.2
348	Air_Et_AzenaZingini(P)	4.17	4.58	5.00	5.63	4.48	3.65	2.71	2.71	3.65	3.85	3.85	3.65	1456.2
354	Air_Et_Timbi(P)	4.09	4.50	4.90	5.52	4.39	3.58	2.66	2.66	3.58	3.78	3.78	3.58	1428.3
358	Air_Et_Guchis(P)	4.08	4.49	4.90	5.51	4.39	3.57	2.66	2.66	3.57	3.78	3.78	3.57	1427.4
363	Air_Et_Chagni(P)	4.17	4.58	5.00	5.63	4.48	3.65	2.71	2.71	3.65	3.85	3.85	3.65	1456.2
381	Air_Et_ArjoDidessa(P)	4.20	4.54	4.65	4.88	3.74	3.18	2.95	2.84	3.40	3.97	3.97	3.97	1406.8
383	Air_Et_ArjoDidessaPump(P)	4.23	4.57	4.69	4.92	3.77	3.20	2.97	2.86	3.43	4.00	4.00	4.00	1417.6
389	Air_Et_Hida(P)	4.01	4.33	4.85	4.64	3.80	3.17	2.85	2.85	3.38	3.90	3.90	3.59	1376.4
394	Air_Et_Negeso(P)	4.13	4.47	4.58	4.80	3.68	3.13	2.90	2.79	3.35	3.91	3.91	3.91	1384.9
399	Air_Et_Wama+Urgesa(P)	4.20	4.54	4.65	4.88	3.74	3.18	2.95	2.83	3.40	3.97	3.97	3.97	1406.3
402	Air_Et_UpperDabana(P)	3.69	4.34	4.71	4.80	3.60	3.04	2.77	2.49	3.14	3.87	3.87	3.97	1346.0
404	Air_Et_Dabana(P)	3.88	4.56	4.95	5.04	3.78	3.20	2.91	2.62	3.30	4.07	4.07	4.17	1414.7
410	Air_Et_Dimtu(P)	3.90	4.58	4.97	5.06	3.80	3.21	2.92	2.63	3.31	4.09	4.09	4.19	1420.9
411	Air_Et_Didga(P)	4.19	4.76	5.10	4.99	3.85	3.17	2.83	2.83	3.17	3.85	3.85	3.85	1412.1
419	Air_Et_Anger(P)	4.17	4.74	5.07	4.96	3.83	3.16	2.82	2.82	3.16	3.83	3.83	3.83	1405.3
421	Air_Et_Nekemte(P)	4.21	4.78	5.12	5.00	3.87	3.18	2.84	2.84	3.18	3.87	3.87	3.87	1417.1
433	Air_Et_Dale(P)	4.16	4.73	5.06	4.95	3.83	3.15	2.81	2.81	3.15	3.83	3.83	3.83	1402.4
439	Air_Et_LekuUke(P)	4.13	4.69	5.02	4.91	3.79	3.13	2.79	2.79	3.13	3.79	3.79	3.79	1390.8
443	Air_Et_Biyo+Gumbi(P)	4.28	4.86	5.21	5.09	3.93	3.24	2.89	2.89	3.24	3.93	3.93	3.93	1441.9
449	Air_Et_Dembigusu(P)	4.39	4.98	5.34	5.22	4.03	3.32	2.96	2.96	3.32	4.03	4.03	4.03	1477.3
454	Air_Et_Chigsha(P)	4.46	5.14	4.23	5.49	3.31	3.31	3.09	2.74	3.77	4.11	4.00	4.23	1453.9
459	Air_Et_Lugo(P)	4.49	5.19	4.26	5.53	3.34	3.34	3.11	2.77	3.80	4.15	4.03	4.26	1466.1
465	Air_Et_Bar(P)	4.32	4.75	5.18	5.83	4.64	3.78	2.81	2.81	3.78	3.99	3.99	3.78	1508.8
477	Air_Et_JemaAGanti(P)	4.58	5.28	4.34	5.64	3.41	3.41	3.17	2.82	3.87	4.23	4.11	4.34	1493.6
486	Air_Et_LowerDuraPump(P)	4.75	5.22	5.70	6.41	5.10	4.15	3.09	3.09	4.15	4.39	4.39	4.15	1659.3
497	Air_Et_UpperDila(P)	4.23	4.88	4.01	5.20	3.14	3.14	2.93	2.60	3.58	3.90	3.79	4.01	1378.7
499	Air_Et_FelmtuDila(P)	4.24	4.90	4.03	5.22	3.16	3.16	2.94	2.61	3.59	3.92	3.81	4.03	1383.9
510	Air_Et_Fincha	4.00	4.31	4.41	4.82	4.11	3.39	2.57	2.57	3.29	4.00	4.00	3.80	1376.1
512	Air_Et_Dabus(P)	5.01	5.34	5.01	5.78	4.25	3.60	3.27	2.94	3.92	4.14	3.82	4.47	1566.8
513	Air_Et_DaleBilutsu(P)	4.92	5.53	5.53	6.02	4.43	3.81	3.44	3.07	4.18	4.43	4.30	4.55	1647.0
523	Air_Et_Galegu(P)	5.01	5.74	6.02	6.02	5.74	4.83	4.10	3.46	4.28	5.10	4.92	4.47	1815.1
526	Air_Et_Rahad(P)	5.01	5.74	6.01	6.01	5.74	4.83	4.10	3.46	4.28	5.10	4.92	4.46	1813.9
676	Air_Su_SennarSugarScheme	5.91	6.55	7.52	7.52	7.95	6.44	5.48	5.26	5.80	5.48	6.23	5.80	2310.0
678	Air_Su_GuneidSugarExtension	6.14	6.81	7.81	7.81	8.26	6.70	5.69	5.47	6.03	5.69	6.47	6.03	2400.0
679	Air_Su_GeziraManagil	6.14	6.81	7.81	7.81	8.26	6.70	5.69	5.47	6.03	5.69	6.47	6.03	2400.0
682	Air_Su_BlueNilePumpSchemesDsSennar	6.19	6.86	7.88	7.88	8.33	6.75	5.74	5.51	6.08	5.74	6.53	6.08	2420.0
686	Air_Su_Rahad2(P)	5.96	6.61	7.58	7.58	8.02	6.50	5.53	5.31	5.85	5.53	6.28	5.85	2330.0
694	Air_Su_SouthDinder(P)	5.86	6.50	7.45	7.45	7.88	6.39	5.43	5.22	5.75	5.43	6.18	5.75	2290.0
705	Air_Et_GubayMariam+Mitrha+Kirnya+Agid(P)	4.28	4.91	5.14	5.14	4.91	4.13	3.50	2.96	3.66	4.36	4.21	3.82	1550.8
894	Air_Et_Koga	4.02	4.61	5.00	5.29	4.41	3.53	2.55	2.55	3.53	3.73	3.63	3.53	1408.8
907	Air_Et_Ligome+Asinwara+Istumit+Kunzla(P)	3.80	4.40	5.00	5.14	4.64	3.86	2.74	2.68	3.55	3.89	3.71	3.47	1425.1
923	Air_Et_AmriPlain(P)	4.06	4.65	5.05	5.35	4.45	3.56	2.57	2.57	3.56	3.76	3.66	3.56	1422.6
933	Air_Et_AmboPlain(P)	4.04	4.63	5.02	5.32	4.43	3.54	2.56	2.56	3.54	3.74	3.64	3.54	1414.9
934	Air_Et_GugAndInsewi+KongraDeblPlain(P)	4.06	4.65	5.05	5.35	4.46	3.56	2.57	2.57	3.56	3.76	3.66	3.56	1422.8
952	Air_Et_Diyaleg+LijomRiste(P)	3.80	4.41	5.01	5.15	4.65	3.87	2.75	2.69	3.56	3.90	3.71	3.47	1427.4
958	Air_Et_Delgi+BebehaAbo+Fentay+Gawrna(P)	4.42	5.07	5.50	5.83	4.86	3.89	2.81	2.81	3.89	4.10	3.99	3.89	1550.9
1145	Air_Et_LowerDinder(P)	4.61	5.29	5.54	5.54	5.29	4.45	3.78	3.19	3.94	4.70	4.53	4.11	1670.5
1175	Air_Et_UpperBeles(P)	4.35	4.99	5.41	5.73	4.78	3.82	2.76	2.76	3.82	4.03	3.93	3.82	1524.9
1222	Air_Et_DebreGuracha(P)	3.73	4.27	4.18	4.18	4.45	3.45	2.64	2.45	2.91	4.00	4.09	3.82	1342.6
1237	Air_Et_RobiRikicha(P)	3.08	3.38	3.68	3.58	3.98	3.88	3.08	3.18	3.38	3.48	3.38	3.08	1253.2
1350	Air_Su_AbuNaamaSeleitBlueNilePumpSchem	5.63	6.24	7.16	7.16	7.57	6.14	5.22	5.01	5.52	5.22	5.93	5.52	2200.0
1355	Air_Su_Kenana2And3(P)	5.70	6.32	7.26	7.26	7.67	6.22	5.29	5.08	5.60	5.29	6.01	5.60	2230.0
1370	Air_Su_ElSuki	5.88	6.52	7.49	7.49	7.91	6.42	5.45	5.24	5.77	5.45	6.20	5.77	2300.0

Table 5.2 Average monthly (mm/day) and annual (mm/year) ET_0*, Advanced Irrigation Nodes in Baro-Akobo-Sobat-White Nile basin*

ID	Name	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
88	Air_Ss_FengcoJonglei(P)	4.47	5.47	6.26	6.42	6.49	6.23	5.56	4.88	5.02	4.77	4.86	4.47	1974.3
683	Air_Ss_MalakalRice(P)	4.64	5.68	6.51	6.67	6.75	6.47	5.78	5.07	5.22	4.96	5.06	4.64	2051.6
696	Air_Su_KenanaSugarAndCrops	4.83	5.92	6.78	6.95	7.03	6.74	6.02	5.28	5.44	5.16	5.27	4.83	2137.0
697	Air_Su_HagarAsalayaAndSondosAndWhiteNile	5.17	6.33	7.25	7.43	7.52	7.21	6.44	5.65	5.82	5.52	5.63	5.17	2286.2
756	Air_Et_AlweroFrmChiru+Mey+DumbongDams(P)	5.05	5.87	5.46	5.77	4.84	4.22	4.12	3.71	4.22	4.53	4.74	4.53	1733.8
817	Air_Et_BaroRightBankGravityFromItang(P)	5.63	6.32	6.09	6.20	5.05	4.48	4.25	3.79	4.59	4.94	5.17	5.40	1881.5
818	Air_Et_BaroRightBankPumpFromItang(P)	5.48	6.15	5.93	6.04	4.92	4.36	4.14	3.69	4.47	4.81	5.03	5.26	1831.6
819	Air_Et_BaroRightBnkFrmGmblGrvOrRvrPmp(P)	5.46	5.89	5.68	5.89	4.82	4.18	3.96	3.54	4.39	4.82	4.82	5.04	1778.1
824	Air_Et_BaroLeftBankGravityFromItang(P)	5.70	6.40	6.17	6.29	5.12	4.54	4.31	3.84	4.66	5.01	5.24	5.47	1906.6
826	Air_Et_BaroLeftBankPumpFromItang(P)	5.51	6.19	5.96	6.07	4.95	4.39	4.16	3.71	4.50	4.84	5.06	5.29	1842.2
831	Air_Et_BaroLeftBankFrmGmblGrvOrRvrPmp(P)	5.48	5.91	5.69	5.91	4.83	4.19	3.97	3.54	4.40	4.83	4.83	5.05	1782.0
833	Air_Et_LeftBankFromAbobo(P)	5.38	6.26	5.82	6.15	5.16	4.50	4.39	3.95	4.50	4.83	5.05	4.83	1847.8
836	Air_Et_GiloRightBankFromGilo1Gravity(P)	5.06	5.88	5.47	5.78	4.85	4.23	4.13	3.71	4.23	4.54	4.75	4.54	1736.8
839	Air_Et_GiloLeftBnkFrmGilo1GrvOrRvrPmp(P)	5.20	6.05	5.63	5.95	4.99	4.36	4.25	3.82	4.36	4.67	4.89	4.67	1788.1
842	Air_Et_GiloRightBankFromGilo2Gravity(P)	5.81	6.46	6.07	6.12	5.08	4.23	3.94	3.69	4.23	4.63	4.88	5.07	1829.0
843	Air_Et_GiloLeftBankFromGilo2Gravity(P)	5.83	6.48	6.08	6.14	5.09	4.24	3.95	3.70	4.24	4.64	4.89	5.08	1834.2
1480	Air_Ss_MongalaAndOtherSouth(P)	4.50	4.60	5.40	4.70	4.80	4.40	3.80	4.00	4.40	4.20	4.20	4.40	1625.1
1585	Air_Su_PumpSchemesUpJebelAulia	5.17	6.33	7.25	7.43	7.52	7.21	6.44	5.65	5.82	5.52	5.63	5.17	2286.2
1590	Air_Su_Kenana4(P)	4.95	6.06	6.95	7.12	7.20	6.91	6.17	5.41	5.57	5.29	5.39	4.95	2189.3

Table 5.3 Average monthly (mm/day) and annual (mm/year) ET_0*, Advanced Irrigation Nodes in Tekeze-Setit-Atbara basin*

ID	Name	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
60	Air_Et_Metema(P)	5.50	6.30	6.60	6.60	6.30	5.30	4.50	3.80	4.70	5.60	5.40	4.90	1991.2
145	Air_Et_SmallScale	4.94	5.69	6.09	6.35	6.15	5.75	4.85	4.10	4.75	5.20	5.10	4.65	1934.8
575	Air_Et_Humera(P)	4.40	5.10	5.60	6.10	6.00	6.20	5.20	4.40	4.80	4.80	4.80	4.40	1879.9
644	Air_Su_UpperAtbara(P)	4.98	5.58	6.48	7.08	7.14	7.30	6.16	5.51	5.86	5.24	5.03	5.03	2172.5
810	Air_Su_Rumela(P)	4.98	5.58	6.48	7.08	7.14	7.30	6.16	5.51	5.86	5.24	5.03	5.03	2172.5
890	Air_Su_NewHalfa	4.98	5.58	6.48	7.08	7.14	7.30	6.16	5.51	5.86	5.24	5.03	5.03	2172.5

Table 5.4 Average monthly (mm/day) and annual (mm/year) ET_0*, Advanced Irrigation Nodes in Main Nile basin*

ID	Name	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
1640	Air_Su_MainNileKhartoumAtbara	5.32	6.28	7.45	8.25	8.55	8.50	8.15	7.95	7.28	6.83	5.87	4.96	2599.9
1685	Air_Su_MainNilePumpSchemes	5.32	6.28	7.45	8.25	8.55	8.50	8.15	7.95	7.28	6.83	5.87	4.96	2599.9
1725	Air_Su_Merowe	5.30	6.50	7.70	8.70	9.40	9.10	8.40	8.00	7.90	7.70	6.30	5.40	2752.5
1800	Air_Eg_ToshkaPumpScheme	3.35	4.60	6.55	8.40	10.23	10.83	10.45	10.16	9.00	6.94	4.67	3.42	2701.0

Table 5.5 Average monthly (mm/day) and annual (mm/year) E_0 *in river sections and swamps*

ID	Name	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
63	Lst_Su_EvapMalakalKhartoum	5.87	6.63	7.39	7.50	7.18	7.18	6.09	5.22	5.76	5.54	6.09	5.87	2321.2
64	Lst_Su_EvapDeimKhartoum	5.96	6.61	7.59	7.59	8.02	6.51	5.53	5.31	5.85	5.53	6.29	5.85	2331.9
66	Lst_Su_EvapKhartoumMerowe	5.32	6.12	7.62	8.62	8.52	9.13	7.92	7.22	7.12	6.72	5.82	5.01	2592.0
67	Lst_Su_EvapMeroweNasser	5.10	5.90	6.30	8.70	9.70	10.00	9.00	9.20	9.20	8.60	6.50	5.20	2844.8
815	Lst_Ss_GhazalSwampBahrElGhazal	6.29	6.90	6.94	6.71	5.99	5.19	4.69	4.81	5.08	5.23	5.69	6.03	2113.7
935	Lst_Ss_MacharSwamp	6.67	7.82	8.26	7.66	6.86	5.99	5.11	4.73	5.27	5.60	5.98	6.36	2319.0
1510	Lst_Ss_SuddSwampAlbertNile	5.18	5.29	6.21	5.41	5.52	5.06	4.37	4.60	5.06	4.83	4.83	5.06	1868.8
1525	Lst_Ss_SuddSwamp	5.53	6.03	5.71	5.55	5.44	4.81	4.27	4.37	4.51	4.68	5.11	5.11	1857.8

Table 5.6 Average monthly (mm/day) and annual (mm/year) E_0 for Abay-Blue Nile reservoirs

ID	Name	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
38	Rsv_Et_MendaiaUpDam_Hp(P)	5.69	6.57	5.40	7.00	4.23	4.23	3.94	3.50	4.81	5.25	5.11	5.40	1855.9
39	Rsv_Et_BekoAboDam_Hp(P)	5.12	5.75	5.75	6.68	5.44	4.50	3.57	3.42	4.50	5.28	4.97	4.97	1821.7
39	Rsv_Et_BekoAboDam_Hp(P)	5.01	5.62	5.62	6.53	5.31	4.40	3.49	3.34	4.40	5.16	4.86	4.86	1780.7
205	Rsv_Et_GumeraDam_Ir(P)	4.50	5.21	5.80	5.80	5.09	4.26	2.96	2.84	3.91	4.50	4.26	4.03	1615.3
206	Rsv_Et_RibbDam_Ir(P)	4.91	5.68	6.33	6.33	5.55	4.65	3.23	3.10	4.26	4.91	4.65	4.39	1762.2
207	Rsv_Et_MegechDam_Ir(P)	4.97	5.80	6.16	5.92	5.68	4.62	3.08	2.96	4.38	4.97	4.86	4.50	1759.5
208	Rsv_Et_GigelAbaiBDam_Ir(P)	4.64	5.32	5.77	6.11	5.09	4.07	2.94	2.94	4.07	4.30	4.19	4.07	1626.3
211	Rsv_Et_JemmaDam_Ir(P)	4.54	5.21	5.65	5.98	4.99	3.99	2.88	2.88	3.99	4.21	4.10	3.99	1592.2
212	Rsv_Et_KiltiDam_Ir(P)	4.59	5.26	5.71	6.04	5.04	4.03	2.91	2.91	4.03	4.25	4.14	4.03	1608.6
223	Rsv_Et_WeberiDam_Ir(P)	3.82	4.28	4.51	4.63	4.74	3.82	3.01	2.89	3.35	4.16	4.28	3.93	1442.3
229	Rsv_Et_RobiWeserbiDam_Ir(P)	3.81	4.27	4.50	4.62	4.73	3.81	3.00	2.89	3.35	4.15	4.27	3.92	1439.1
233	Rsv_Et_DuberDam_HpIr(P)	3.81	4.27	4.50	4.61	4.73	3.81	3.00	2.88	3.35	4.15	4.27	3.92	1438.4
235	Rsv_Et_RobiDam_HpIr(P)	3.99	4.34	4.69	4.57	4.34	3.64	2.93	3.05	3.52	4.34	4.22	3.99	1448.3
249	Rsv_Et_SelgiDam_Ir(P)	3.55	3.97	4.38	4.49	5.22	5.53	4.28	4.07	3.86	3.97	3.55	3.44	1531.1
256	Rsv_Et_MugaDam_Ir(P)	4.38	4.92	4.92	5.71	4.65	3.85	3.06	2.92	3.85	4.52	4.25	4.25	1558.6
262	Rsv_Et_GeltaDam_Ir(P)	4.38	4.91	4.91	5.71	4.65	3.85	3.05	2.92	3.85	4.51	4.25	4.25	1557.5
263	Rsv_Et_BogenaDam_Ir(P)	4.37	4.90	4.90	5.69	4.63	3.84	3.05	2.91	3.84	4.50	4.24	4.24	1553.2
276	Rsv_Et_UpperGuderDam_Ir(P)	4.24	4.57	4.68	5.11	4.35	3.59	2.72	2.72	3.48	4.24	4.24	4.02	1457.5
283	Rsv_Et_AnonuDam_Ir(P)	4.68	5.04	5.16	5.64	4.80	3.96	3.00	3.00	3.84	4.68	4.68	4.44	1608.6
287	Rsv_Et_KaleDam_Ir(P)	4.66	5.01	5.13	5.61	4.78	3.94	2.99	2.99	3.82	4.66	4.66	4.42	1600.5
294	Rsv_Et_ChemogaDam_Ir(P)	4.44	4.98	4.98	5.78	4.71	3.90	3.09	2.96	3.90	4.57	4.30	4.30	1577.9
297	Rsv_Et_NesheDam_IrHp(P)	4.30	4.63	4.74	5.19	4.41	3.64	2.76	2.76	3.53	4.30	4.30	4.08	1479.1
309	Rsv_Et_GulaDam_Ir(P)	4.49	5.04	5.04	5.86	4.77	3.95	3.13	3.00	3.95	4.63	4.36	4.36	1597.5
310	Rsv_Et_JedebDam_Ir(P)	4.46	5.00	5.00	5.81	4.73	3.92	3.11	2.97	3.92	4.60	4.33	4.33	1585.8
331	Rsv_Et_LahIrrDam_Ir(P)	4.75	5.45	5.91	6.26	5.21	4.17	3.01	3.01	4.17	4.40	4.29	4.17	1665.0
336	Rsv_Et_FettamDam_Ir(P)	4.54	5.09	5.09	5.92	4.82	3.99	3.17	3.03	3.99	4.68	4.41	4.41	1615.3
344	Rsv_Et_AyoDam_Ir(P)	4.71	5.18	5.65	6.35	5.06	4.12	3.06	3.06	4.12	4.35	4.35	4.12	1644.4
346	Rsv_Et_ZinginiDam_Ir(P)	4.76	5.23	5.71	6.42	5.11	4.16	3.09	3.09	4.16	4.40	4.40	4.16	1661.7
353	Rsv_Et_TimbiDam_Ir(P)	4.68	5.15	5.62	6.32	5.03	4.10	3.04	3.04	4.10	4.33	4.33	4.10	1635.8
357	Rsv_Et_GuchisDam_Ir(P)	4.69	5.16	5.62	6.33	5.04	4.10	3.05	3.05	4.10	4.34	4.34	4.10	1637.7
362	Rsv_Et_ArdiDam_Ir(P)	4.77	5.25	5.73	6.45	5.13	4.18	3.10	3.10	4.18	4.42	4.42	4.18	1668.5
391	Rsv_Et_NegesoDam_Ir(P)	4.51	4.87	4.99	5.24	4.02	3.41	3.17	3.04	3.65	4.26	4.26	4.26	1510.3
403	Rsv_Et_UpperDabanaDam_IrHp(P)	4.41	5.18	5.62	5.73	4.30	3.64	3.31	2.98	3.75	4.63	4.63	4.74	1608.8
406	Rsv_Et_UpperDidessaDam_Ir(P)	4.65	5.02	5.63	5.39	4.41	3.67	3.31	3.31	3.92	4.53	4.53	4.16	1597.5
413	Rsv_Et_AngerDam_Ir(P)	4.72	5.36	5.74	5.62	4.34	3.57	3.19	3.19	3.57	4.34	4.34	4.34	1590.3
414	Rsv_Et_NekemteDam_Ir(P)	4.80	5.45	5.84	5.71	4.41	3.63	3.24	3.24	3.63	4.41	4.41	4.41	1616.6
438	Rsv_Et_LekuUkeDams_Ir(P)	4.75	5.39	5.77	5.64	4.36	3.59	3.21	3.21	3.59	4.36	4.36	4.36	1598.1
442	Rsv_Et_BiyoGumbiDams_Ir(P)	4.88	5.54	5.94	5.80	4.48	3.69	3.30	3.30	3.69	4.48	4.48	4.48	1643.5
447	Rsv_Et_AleltuDam_Ir(P)	4.28	4.86	5.21	5.09	3.94	3.24	2.89	2.89	3.24	3.94	3.94	3.94	1442.2
451	Rsv_Et_WajaDam_Ir(P)	5.03	5.71	6.11	5.98	4.62	3.80	3.40	3.40	3.80	4.62	4.62	4.62	1693.0
453	Rsv_Et_GebregurachaDam_Ir(P)	5.08	5.86	4.82	6.25	3.78	3.78	3.52	3.13	4.30	4.69	4.56	4.82	1657.2
455	Rsv_Et_LowerDidessaDam_Ir(P)	5.18	5.98	4.91	6.37	3.85	3.85	3.59	3.19	4.38	4.78	4.65	4.91	1689.1
464	Rsv_Et_BarDam_Ir(P)	4.97	5.47	5.96	6.71	5.34	4.35	3.23	3.23	4.35	4.60	4.60	4.35	1736.4
476	Rsv_Et_GemberDam_Ir(P)	5.19	5.98	4.92	6.38	3.86	3.86	3.59	3.19	4.39	4.79	4.65	4.92	1691.7
490	Rsv_Et_FinchaaDam_HpIr	4.31	4.64	4.75	5.20	4.42	3.65	2.76	2.76	3.54	4.31	4.31	4.09	1482.3
496	Rsv_Et_DilaDam_Ir(P)	4.87	5.62	4.62	5.99	3.62	3.62	3.37	3.00	4.12	4.50	4.37	4.62	1588.3
498	Rsv_Et_MeniDam_Ir(P)	4.88	5.63	4.63	6.01	3.63	3.63	3.38	3.00	4.13	4.51	4.38	4.63	1592.4
501	Rsv_Et_LowerDabusDam_Hp(P)	5.17	5.51	5.17	5.95	4.38	3.71	3.37	3.03	4.04	4.27	3.93	4.61	1614.7
517	Rsv_Et_DaleBilutsuDams_Ir(P)	5.57	6.27	6.27	6.82	5.01	4.32	3.90	3.48	4.74	5.01	4.87	5.15	1866.1
520	Rsv_Et_UpperBelesDam_IrHp(P)	4.69	5.37	5.83	6.17	5.14	4.11	2.97	2.97	4.11	4.34	4.23	4.11	1642.6
522	Rsv_Et_GaleguDam_Ir(P)	5.52	6.32	6.62	6.62	6.32	5.32	4.51	3.81	4.71	5.62	5.42	4.92	1997.4
525	Rsv_Et_RahadDam_Ir(P)	5.45	6.24	6.54	6.54	6.24	5.25	4.46	3.77	4.66	5.55	5.35	4.86	1973.6
640	Rsv_Et_LowerDinderDam_IrHp(P)	5.55	6.35	6.65	6.65	6.35	5.34	4.54	3.83	4.74	5.65	5.44	4.94	2007.5
700	Rsv_Et_LakeTanaCharaCharaDam	4.67	5.41	6.16	6.33	5.71	4.75	3.38	3.30	4.37	4.79	4.56	4.27	1753.8
897	Rsv_Et_KogaDam_Ir	4.59	5.27	5.71	6.05	5.04	4.03	2.91	2.91	4.03	4.26	4.15	4.03	1610.0
992	Rsv_Et_LowerGuderProjectMottaDam_H	4.66	5.02	5.14	5.61	4.78	3.94	2.99	2.99	3.82	4.66	4.66	4.42	1601.3
1005	Rsv_Et_AmartiDam_Ir(P)	4.47	4.81	4.93	5.39	4.58	3.78	2.86	2.86	3.67	4.47	4.47	4.24	1536.1
1062	Rsv_Et_DidgaDam_Ir(P)	4.39	5.16	5.60	5.71	4.28	3.62	3.29	2.96	3.73	4.61	4.61	4.72	1601.3
1091	Rsv_Et_UpperDabusDam_Hp(P)	4.80	5.40	5.40	5.88	4.32	3.72	3.36	3.00	4.08	4.32	4.20	4.44	1607.9
1113	Rsv_Et_UpperBirrDam_Ir(P)	4.57	5.13	5.13	5.96	4.85	4.02	3.19	3.05	4.02	4.71	4.44	4.44	1626.3
1118	Rsv_Et_UpperDinderDam_Hp(P)	5.35	6.13	6.42	6.42	6.13	5.16	4.38	3.70	4.57	5.45	5.26	4.77	1938.1
1221	Rsv_Et_DebreGurachaDam_Ir(P)	4.27	4.90	4.80	4.80	5.11	3.96	3.02	2.81	3.34	4.59	4.69	4.38	1540.5
1236	Rsv_Et_RobiRikichaDam_Ir(P)	3.54	3.88	4.22	4.11	4.56	4.45	3.54	3.65	3.88	3.99	3.88	3.54	1436.8
1245	Rsv_Et_KaradobiDam_Hp(P)	4.82	5.19	5.31	5.80	4.94	4.07	3.09	3.09	3.95	4.82	4.82	4.57	1654.9
1252	Rsv_Et_HomechoDam_Ir(P)	3.99	4.34	4.69	4.57	4.34	3.64	2.93	3.05	3.52	4.34	4.22	3.99	1448.3
1265	Rsv_Et_MabilDam_Hp(P)	5.22	5.74	6.27	7.05	5.61	4.57	3.39	3.39	4.57	4.83	4.83	4.57	1824.7
1268	Rsv_Et_GigelAbaiADam_Ir(P)	4.63	5.31	5.76	6.10	5.08	4.07	2.94	2.94	4.07	4.29	4.18	4.07	1623.0
1285	Rsv_Et_MendaiaDownDam_Hp(P)	5.54	6.23	6.23	6.79	4.99	4.29	3.88	3.46	4.71	4.99	4.85	5.13	1855.9
1305	Rsv_Et_GrandRenaissanceDam_Hp(P)	6.02	6.54	6.02	7.06	5.36	4.32	4.05	3.53	4.71	4.97	4.97	5.49	1915.2
1305	Rsv_Et_GrandRenaissanceDam_Hp(P)	6.04	6.57	6.04	7.09	5.39	4.33	4.07	3.55	4.73	4.99	4.99	5.52	1923.6
1340	Rsv_Su_RoseiresDam_IrHp	6.01	6.68	7.34	7.57	7.46	6.57	5.01	4.56	4.90	5.34	5.68	6.01	2223.5
1405	Rsv_Su_SennarDam_IrHp	5.96	6.61	7.59	7.59	8.02	6.51	5.53	5.31	5.85	5.53	6.29	5.85	2331.9

Table 5.7 Average monthly (mm/day) and annual (mm/year) E_0 for Baro-Akobo-Sobat-White Nile reservoirs

ID	Name	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
14	Rsv_Et_AboboDam_Ir	6.05	7.04	6.54	6.91	5.80	5.06	4.94	4.44	5.06	5.43	5.68	5.43	2077.9
24	Rsv_Et_GebaADam_Hp(P)	4.45	4.89	5.12	5.00	4.00	3.45	3.11	2.89	3.56	4.00	4.00	4.11	1477.1
59	Rsv_Et_GambelaDam_Ir(P)	6.01	6.48	6.25	6.48	5.30	4.60	4.36	3.89	4.83	5.30	5.30	5.54	1955.9
61	Rsv_Et_DumbongDam_Ir(P)	5.78	6.73	6.26	6.61	5.55	4.84	4.72	4.25	4.84	5.19	5.43	5.19	1987.0
99	Rsv_Et_Gilo2Dam_Ir(P)	6.46	7.18	6.74	6.80	5.64	4.70	4.37	4.09	4.70	5.14	5.42	5.63	2031.9
154	Rsv_Et_SoreDam_Hp(P)	4.67	5.14	5.38	5.26	4.21	3.62	3.27	3.04	3.74	4.21	4.21	4.32	1552.3
161	Rsv_Et_SeseDam_Hp(P)	4.55	5.01	5.24	5.12	4.10	3.53	3.19	2.96	3.64	4.10	4.10	4.21	1511.6
199	Rsv_Et_GumeroDam_Hp(P)	4.64	5.10	5.34	5.22	4.18	3.60	3.25	3.02	3.71	4.18	4.18	4.29	1540.6
265	Rsv_Ss_SueDam_Hp(P)	6.88	7.45	7.68	6.99	5.62	4.81	4.01	3.78	4.01	4.70	6.19	6.53	2086.0
360	Rsv_Et_GebaRDam_Hp(P)	4.92	5.41	5.65	5.53	4.43	3.81	3.44	3.20	3.93	4.43	4.43	4.55	1632.6
370	Rsv_Et_Baro1Dam_Hp(P)	4.67	5.16	5.41	5.16	4.06	3.57	3.20	3.07	3.69	4.55	4.30	4.30	1554.5
375	Rsv_Et_Baro2Dam_Hp(P)	4.77	5.28	5.53	5.28	4.15	3.64	3.27	3.14	3.77	4.65	4.40	4.40	1588.5
507	Rsv_Et_BirbirRDam_Hp(P)	4.89	5.38	5.62	5.50	4.40	3.79	3.42	3.18	3.91	4.40	4.40	4.52	1623.0
532	Rsv_Et_BirbirADam_Hp(P)	4.72	5.19	5.43	5.31	4.25	3.66	3.31	3.07	3.78	4.25	4.25	4.37	1568.1
592	Rsv_Et_ItangDam_Ir(P)	6.34	7.12	6.86	6.99	5.69	5.05	4.79	4.27	5.18	5.57	5.82	6.08	2120.0
600	Rsv_Et_Gilo3Dam_Ir(P)	6.56	7.29	6.84	6.90	5.73	4.77	4.44	4.16	4.77	5.22	5.50	5.72	2063.4
602	Rsv_Et_Gilo1Dam_IrHp(P)	5.40	6.29	5.84	6.18	5.18	4.52	4.41	3.97	4.52	4.85	5.07	4.85	1856.4
719	Rsv_Ss_BeddenDam_Hp(P)	5.18	5.29	6.21	5.41	5.52	5.06	4.37	4.60	5.06	4.83	4.83	5.06	1868.8
721	Rsv_Ss_LakkiDam_Hp(P)	5.18	5.29	6.21	5.41	5.52	5.06	4.37	4.60	5.06	4.83	4.83	5.06	1868.8
722	Rsv_Ss_ShukoliDam_Hp(P)	5.18	5.29	6.21	5.41	5.52	5.06	4.37	4.60	5.06	4.83	4.83	5.06	1868.8
723	Rsv_Ss_FulaDam_Hp(P)	5.18	5.29	6.21	5.41	5.52	5.06	4.37	4.60	5.06	4.83	4.83	5.06	1868.8
732	Rsv_Et_SakuDam_Hp(P)	4.92	5.40	5.40	5.40	4.32	3.84	3.48	3.12	4.20	4.44	4.44	4.56	1625.4
736	Rsv_Et_TamsDam_Ir(P)	5.41	5.80	5.93	5.93	4.64	4.12	3.74	3.35	4.38	4.77	4.77	5.02	1757.9
741	Rsv_Et_ChiruDam_Ir(P)	5.67	6.60	6.14	6.48	5.44	4.75	4.63	4.17	4.75	5.09	5.33	5.09	1948.9
749	Rsv_Et_MeyDam_Ir(P)	5.69	6.62	6.16	6.51	5.46	4.76	4.65	4.18	4.76	5.11	5.34	5.11	1955.9
783	Rsv_Et_KashuDam_Hp(P)	4.67	4.89	5.22	5.11	4.11	3.78	3.56	3.00	3.89	4.11	4.22	4.34	1547.8
784	Rsv_Et_BekoDam_Hp(P)	4.92	5.15	5.50	5.39	4.33	3.98	3.75	3.16	4.10	4.33	4.45	4.57	1630.7
1605	Rsv_Su_GebalAuliaDam_IrNvHp	5.48	6.70	7.68	7.87	7.96	7.64	6.82	5.98	6.16	5.85	5.96	5.48	2420.7

Table 5.8 Average monthly (mm/day) and annual (mm/year) E_0 for Tekeze-Setit-Atbara reservoirs

ID	Name	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
47	Rsv_Et_TekezeDamTK5_Hp	4.81	5.35	6.31	6.84	6.52	6.20	4.17	3.53	5.02	5.45	4.92	4.49	1934.2
50	Rsv_Et_MetemaDam_HpIr(P)	6.13	7.02	7.35	7.35	7.02	5.91	5.01	4.23	5.24	6.24	6.02	5.46	2218.5
68	Rsv_Et_SmallScaleIrrDams_Ir	5.56	6.40	6.85	7.14	6.91	6.47	5.46	4.61	5.34	5.84	5.73	5.23	2176.1
565	Rsv_Et_HumeraDam_IrHp(P)	4.99	5.79	6.36	6.92	6.81	7.04	5.90	4.99	5.45	5.45	5.45	4.99	2133.7
800	Rsv_Su_RumelaAndBurdanaDams_HpI	5.38	6.03	7.00	7.65	7.71	7.88	6.65	5.95	6.32	5.66	5.44	5.44	2346.7
875	Rsv_Su_KhashmElGirbaDam_IrHp	5.38	6.03	7.00	7.65	7.71	7.88	6.65	5.95	6.32	5.66	5.44	5.44	2346.7

Table 5.9 Average monthly (mm/day) and annual (mm/year) E_0 for Main Nile reservoirs

ID	Name	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
128	Rsv_Su_ShereiqDam_Hp(P)	5.32	6.28	7.45	8.25	8.55	8.50	8.15	7.95	7.28	6.83	5.87	4.96	2599.9
131	Rsv_Su_DalDam_Hp(P)	4.90	5.70	6.80	8.70	9.75	9.80	9.25	9.00	8.90	8.05	6.05	4.70	2790.5
1630	Rsv_Su_SabalokaDam_IrHp(P)	5.32	6.12	7.62	8.62	8.52	9.13	7.92	7.22	7.12	6.72	5.82	5.01	2592.0
1690	Rsv_Su_MogratDam_Hp(P)	5.00	6.10	7.30	8.40	9.10	8.90	8.60	8.20	8.10	7.30	5.90	4.90	2673.7
1700	Rsv_Su_MeroweDam_IrHp	5.30	6.50	7.70	8.70	9.40	9.10	8.40	8.00	7.90	7.70	6.30	5.40	2752.5
1740	Rsv_Su_KajbarDam_Hp(P)	5.10	5.90	6.30	8.70	9.70	10.00	9.00	9.20	9.20	8.60	6.50	5.20	2844.8
1790	Rsv_Eg_HighAswanDam_Hp(E)	3.35	4.60	6.55	8.40	10.23	10.83	10.45	10.16	9.00	6.94	4.67	3.42	2701.0

6 River flows

6.1 General

In this chapter the river flows derived for the distinguished variable inflow nodes (Vif's) in ENSWM are discussed. All flows are based on the natural flows at a selected number of key stations, mentioned in Section 3.2, for the period 1900-2002.

6.2 Baro-Akobo-Sobat-White Nile sub-basin

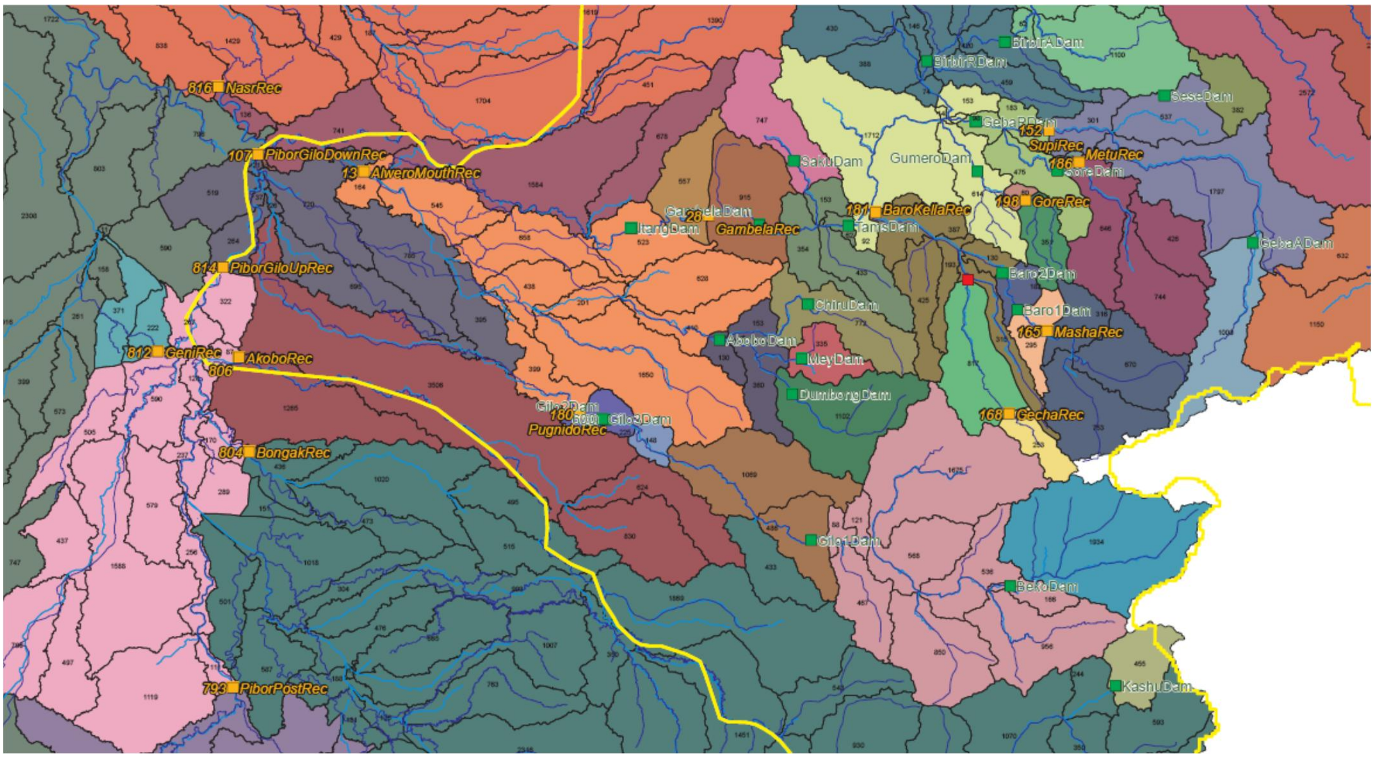

Figure 6.1 Hydrometric stations in Baro-Akobo Sub-basin

6.2.1 Baro at Gambela

The key station on Baro is Gambela. The water level is gauged about 1 km downstream of the bridge at Gambela, whereas the flow measurements are taken from the bridge, see Figure 6.2. It is observed that the bridge is located just downstream of a bend in the Baro river, which makes the location less suitable for flow measurements.

Gambela's monthly flow record for the period 1900-2003 has been created as follows:

- For the period 1900-1904 annual flows have been determined based on regression with the Blue Nile at Deim and the Sobat at Hillet Doleib:

$$Q_{Gambela} = 5843 + 0.1076 Q_{Deim} + 0.122 Q_{Hillet\ Doleib} \quad (Mm^3) \qquad (6\text{-}1)$$

- The monthly values have subsequently been determined according to the average monthly percentage of the annual value.

- For the period 1905-1927 and 1960-1972 from observed water levels at Gambela. Analysis of flow measurements in the period 1928-1959 revealed that the station control has been very stable in the entire period. Therefore, the rating curve fitted to all discharge measurements was used to transform the water levels prior to and after the period with a discharge record. The following rating curve has been applied:

$$Q = 5.32\left(h_{Gambela} - 8.54\right)^{1.79} \quad (Mm^3/day) \qquad \text{(6-2)}$$

- For the period 1928-1959 monthly flows as published by the Nile Control Staff have been used.
- For the period 1973-2003 the monthly flows published by NORPLAN (2006) in their Baro I&II and Genji Hydropower Project Feasibility Report have been applied. Note that the Gambela flow data for the years 1967 - 1972 as published by NORPLAN have not been used as these data appeared inconsistent with the data derived in step 2 based on observed water levels published by the Nile Control Staff. This inconsistency was confirmed by double mass analysis of the published flows for the dam sites Baro-I and II, derived from the extended series of station Masha on Baro.

The monthly and annual flow statististics and annual series are shown in Table 6.1 and Figure 6.3 to Figure 6.5. From Figure 6.3 it is observed that the annual flows do not show any distinct trend, but prolonged dry spells occurred between 1905 and 1915 (excl. 1909, 1910) and 1975 and 1987 (excl. 1978), particularly visualised by the 11-year moving average. It shows that care is needed to select sufficiently long periods representative for the flow statistics of the Baro at Gambela. The frequency distribution of annual flows is presented in in Figure 6.4. It shows only marginal differences between the first and second part of the series.

Figure 6.2 Gambela gauging station on Baro: discharge measured at bridge site and water level gauged 1 km downstream of bridge

Table 6.1 Monthly and annual flow statistics (Mm^3) of Baro at Gambela, Period 1900-2002

Malakal	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Average	2490.6	1772.4	1675.3	1525.1	1694.2	2055.4	2558.3	2911.1	3098.6	3384.2	3310.8	3150.2	29,626.1
Stdev	822.6	598.0	507.7	342.6	316.6	307.4	321.3	353.3	423.9	529.0	542.1	701.7	4,928.8
Cvar	0.33	0.34	0.30	0.22	0.19	0.15	0.13	0.12	0.14	0.16	0.16	0.22	0.17
Min	1400.0	1040.0	963.0	860.0	1040.0	1560.0	1978.7	2251.9	2396.5	2180.0	2220.0	1630.0	22,593.0
Max	6060.0	4620.0	4840.0	3070.0	2800.0	2910.0	3500.0	4150.0	5200.0	6090.0	6210.0	6420.0	48,750.7

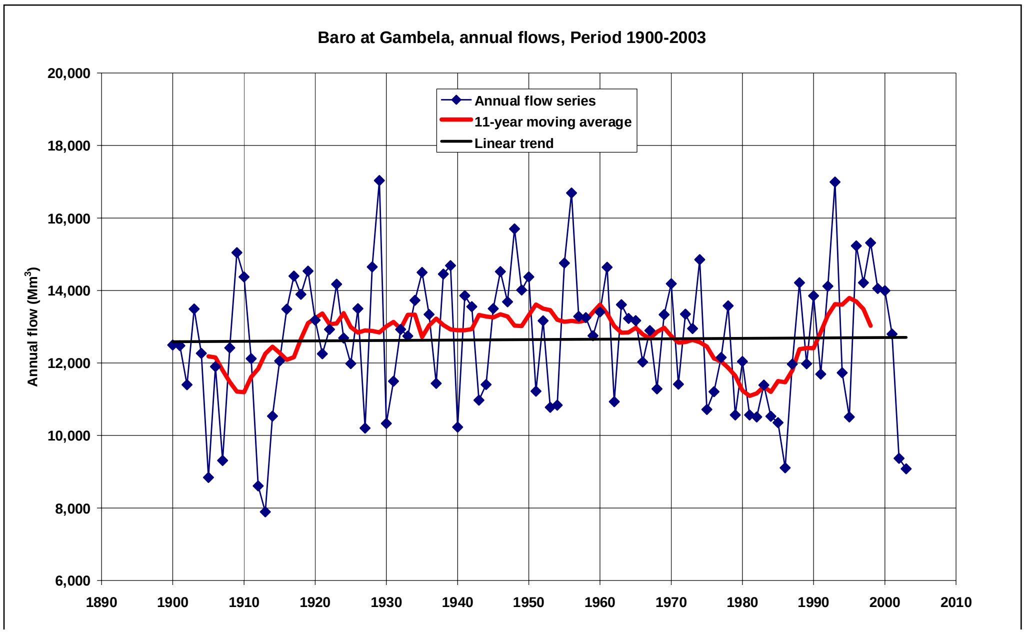

Figure 6.3 Annual flow series of Baro at Gambela, Period 1900-2003

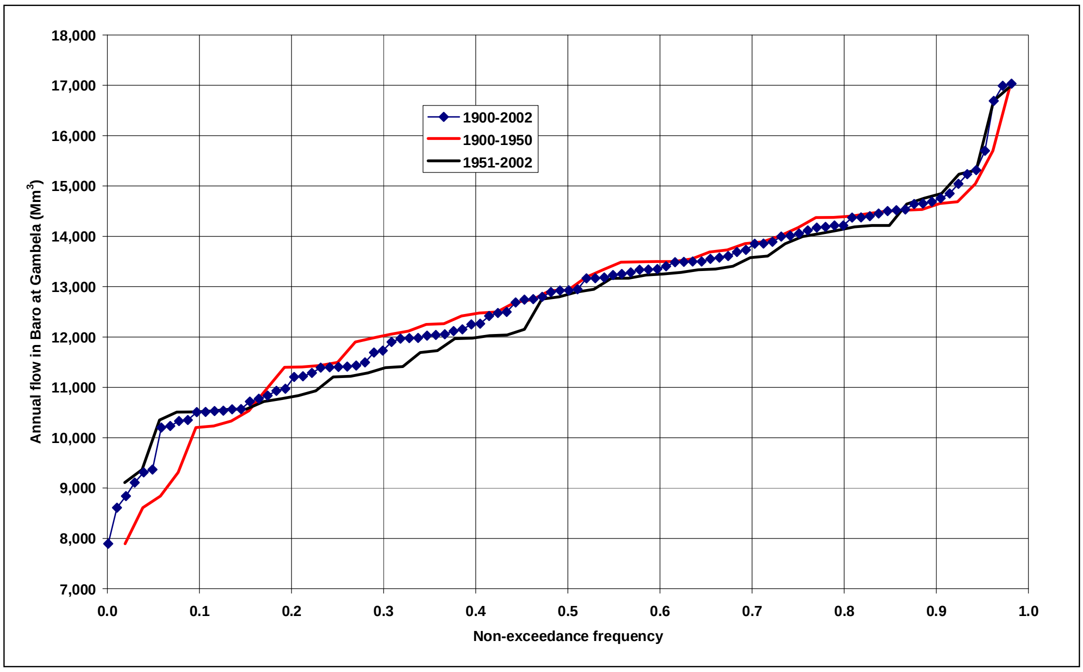

Figure 6.4 Frequency distribution of annual flow in Baro at Gambela, Period 1900-2002

Figure 6.19 shows that the wet season extends from June to October with the highest monthly flows generally in August-September. The coefficients of variation of the monthly flows in the wet season are low, which means stable high flows also reflected in a low variation of annual flows. The variation in flow volumes is seen to be highest in April-May.

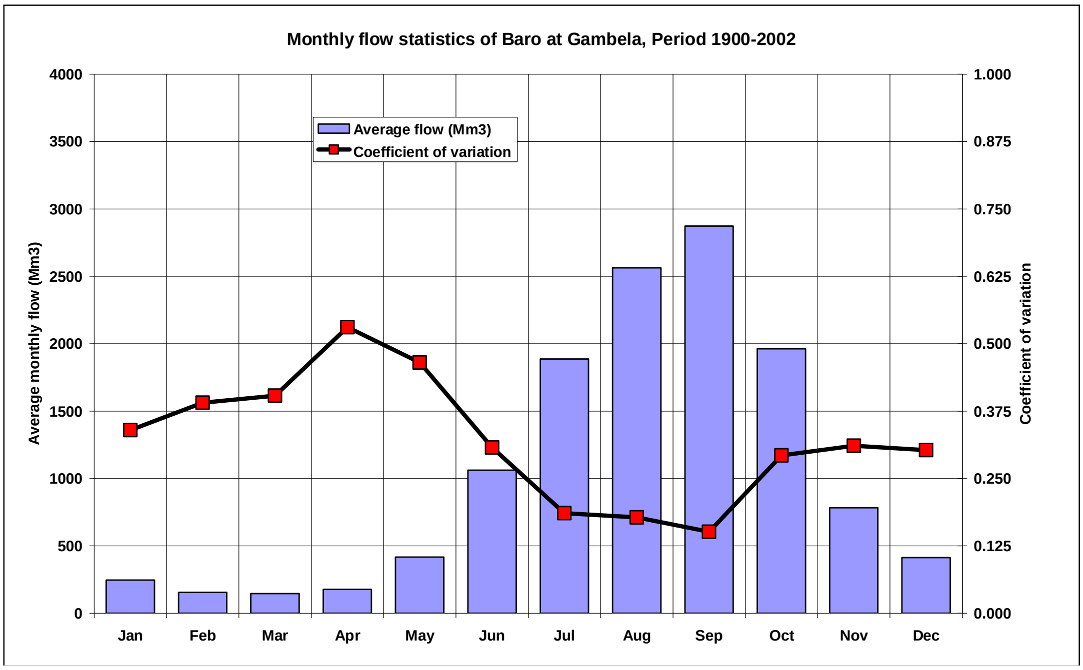

Figure 6.5 Monthly flow statistics of Baro at Gambela, Period 1900-2002

6.2.2 Baro upstream of Gambela

Upstream of Gambela monthly flows are partially available for the stations Masha on Baro, Gecha on Genji, Supi on Geba, Metu on Sor and Baro Kella near Bure on Baro from ENTRO (2006) and NORPLAN (2006). NORPLAN (2006) extended/completed the series of above stations by multiple correlation to the period 1967-2003 and published the monthly flows of Masha, Gecha and Baro Kella and additionally the monthly mean values of Metu and Supi. It used the series of Masha to derive the series for reservoir inflows of Baro-I, Bari-II and Genji reservoirs by applying transposition factors accounting for catchment area ratio at the respective sites and areal rainfall ratio upstream of the sites, further adjusting the Genji flows for the proportional mean monthly flow ratios of the Gecha and Masha stations. Comparison of the summed flows at Baro-II and Genji with Gambela revealed inconsistencies; in 9% of the months of the low flow periods of the years 1967-2003 the water balance for Baro upstream of Gambela would lead to negative Birbir flows. The published flows of Baro-II and Genji which appeared to be inconsistent with Gambela were subsequently replaced by the flow at Gambela multiplied with the average monthly flow ratios of the resulting and source series. Larger inconsistencies were observed in water balance analyses with the Baro Kella series. Also in view of the short observation record and some extreme outliers in the extended series of this station that series was disregarded.

According to NORPLAN (2006) annual rainfall and reference evapotransipration in the region upstream of Gambela is well correlated with elevation according to the following relations:

$$P_{annual}\,(mm) = 828.3\,\exp(0.00046\,Elev(m)) \quad (6\text{-}3)$$

$$ET(mm) = -\,0.175\,Elev(m) + 1555.5 \quad (6\text{-}4)$$

where:

P_{annual} = annual rainfall (mm)

ET = annual reference evapotranspiration according to Penman-Monteith (mm)

$Elev$ = elevation in m+MSL

These relations were used by NORPLAN in transferring station data to other locations. Equation (6-3) was used to derive the transposition factors for Baro and Genji reservoir inflows and both equations were applied to derive the reservoir rainfall and evaporation values in the feasibility study. In Chapter 5 it has been shown that equation (6-4) underestimates reservoir evaporation. In ENWSM equation (5-19) in combination with (5-24) is applied in stead of (6-4), which leads to considerably higher open water evaporation amounts.

The regimes of the upper Baro and Birbir and tributaries differ: the rise, fall and maximum flows in the upper Baro are generally ahead of those in Birbir, which can be observed from average monthly flows of the two branches shown in Figure 6.6.

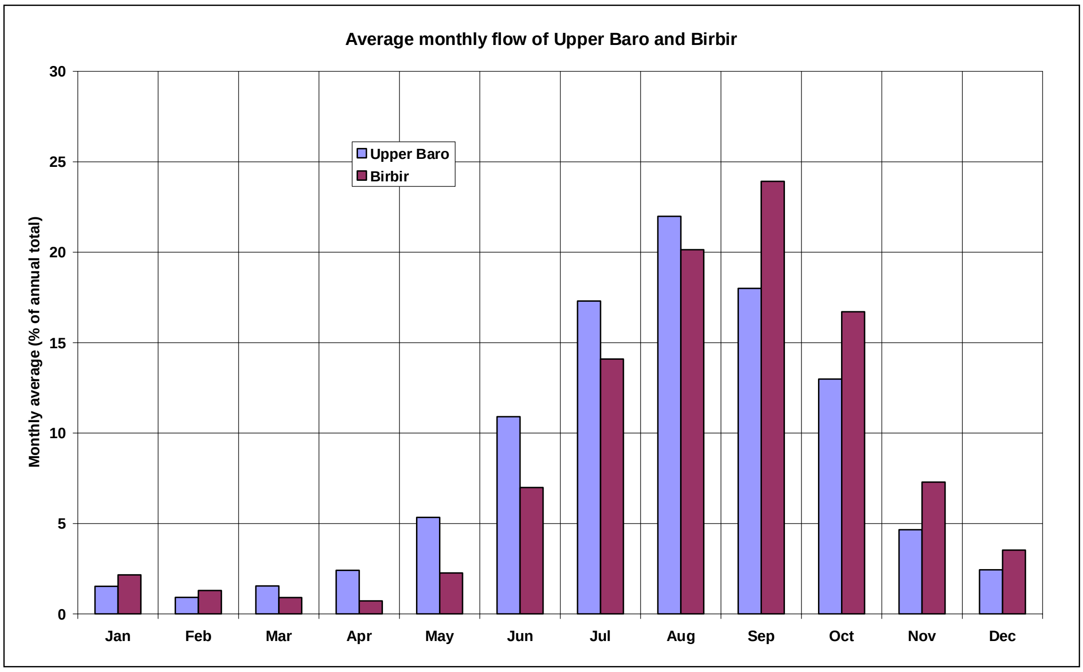

Figure 6.6 Average monthly flow in upper Baro and Birbir, Period 1967-2003

6.2.2.1 *Partitioning based on Gambela flows weighted by average monthly flow ratios*

One option to create flow series for locations upstream of Gambela is partitioning according to monthly flow at Gambela times the ratio of monthly average at the location to the monthly average at Gambela:

$$Q_{Li,j} = \frac{Qa_{Li}}{Qa_{Gi}} Q_{Gi,j} \quad (6\text{-}5)$$

Where:

$Q_{Li,j}$ = flow at location L in month i of year j

$Q_{Gi,j}$ = flow at Gambela in month i of year j
Qa_{Li} = average monthly flow at location L in month i
Qa_{Gi} = average monthly flow at Gambela in month i

The ratios Qa_{Li} /Qa_{Gi} as percentages for selected locations upstream of Gambela are presented in Table 6.2. The applied percentages are based on the monthly flow data of the period 1967-2003. Application of this procedure to the flow series of Gambela of the period 1900-2002 leads to the monthly average flows series presented in Table 6.3.

Table 6.2 Average monthly flow at stations on Baro and tributaries as percentage of average monthly flow at Gambela (data derived from NORPLAN, 2006)

Procedure % of flow at Gambela														
Station	**Area (km^2)**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual**
Baro at Masha	1,653	10.45	10.48	19.29	25.89	23.81	20.13	17.22	15.77	11.68	11.66	9.77	10.30	14.49
Genji at Gecha	115	1.04	1.02	1.81	2.68	2.03	1.46	1.27	1.20	0.98	1.05	0.94	1.01	1.18
Baro-I	2,231	13.73	13.77	25.35	34.02	31.28	26.45	22.63	20.72	15.34	15.32	12.83	13.54	19.04
Baro-II	2,333	14.16	14.21	26.16	35.10	32.28	27.29	23.35	21.38	15.83	15.81	13.24	13.97	19.65
Genji	1,341	9.48	9.30	16.42	24.34	18.47	13.24	11.56	10.91	8.91	9.53	8.58	9.22	10.76
Sor at Metu	1,622	7.37	7.35	7.46	8.82	9.54	12.16	14.21	14.42	14.20	12.39	9.16	8.26	12.78
Geba at Supi	3,894	9.23	11.86	12.57	14.25	12.65	8.57	14.21	15.99	15.05	15.95	10.45	8.94	13.97
Birbir d/s stations	14,271	59.76	57.28	37.38	17.48	27.06	38.73	36.66	37.29	46.01	46.31	58.57	59.62	42.85
Baro at Gambela	23,461	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

Table 6.3 Average monthly and annual flows in Mm^3 and annual runoff in mm/year at selected locations on Baro and tributaries upstream of Gambela, Period 1900-2002

Average flows 1900-2002 in Mm^3														
Station	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual**	**Runoff**
	(Mm^3)	**(Mm^3)**	**(Mm^3)**	**(Mm^3)**	**(Mm^3)**	**(Mm^3)**	**(Mm^3)**	**(Mm^3)**	**(Mm^3)**	**(Mm^3)**	**(Mm^3)**	**(Mm^3)**	**(Mm^3)**	**(mm/yr)**
Masha	25.7	16.2	28.1	46.0	99.3	213.8	324.8	404.1	335.6	228.8	76.4	42.6	1,837.7	1,111.7
Gecha	2.6	1.6	2.6	4.8	8.5	15.5	24.0	30.8	28.2	20.6	7.4	4.2	150.2	1,306.4
Baro-I	33.8	21.3	36.9	60.4	130.4	280.9	426.8	531.0	440.9	300.6	100.4	55.9	2,414.7	1,082.3
Baro-II	34.9	22.0	38.1	62.4	134.6	289.9	440.4	548.0	455.0	310.2	103.6	57.7	2,491.9	1,068.1
Genji	23.4	14.4	23.9	43.2	77.0	140.6	218.0	279.7	255.9	187.0	67.2	38.1	1,364.4	1,017.4
Metu	18.1	11.4	10.9	15.7	39.8	129.1	268.1	369.6	408.0	243.1	71.7	34.1	1,620.6	999.1
Supi	22.8	18.3	18.3	25.3	52.7	91.1	268.1	409.8	432.4	312.9	81.8	36.9	1,771.7	455.0
Birbir d/s	147.2	88.6	54.5	31.0	112.8	411.4	691.4	955.6	1,322.2	908.5	458.3	246.3	5,434.7	380.8
Gambela	246.4	154.7	145.7	177.6	416.9	1,062.1	1,886.1	2,562.7	2,873.5	1,961.7	782.6	413.2	12,683.3	540.6

This procedure leads to flow data that are consistent with the flow at Gambela and which do preserve the monthly and annual mean. However, the variation and serial correlation coefficients will be affected. From Figure 6.7 it is observed that extension based on Gambela will lead to smoothening of the series' variation for both Upper Baro (= flow at Baro-II and Genji damsites) and Birbir. With respect to the serial correlation, as shown in Figure 6.7, the extension procedure based on Gambela will alter the historical pattern of Upper Baro, but has no effect on Birbir.

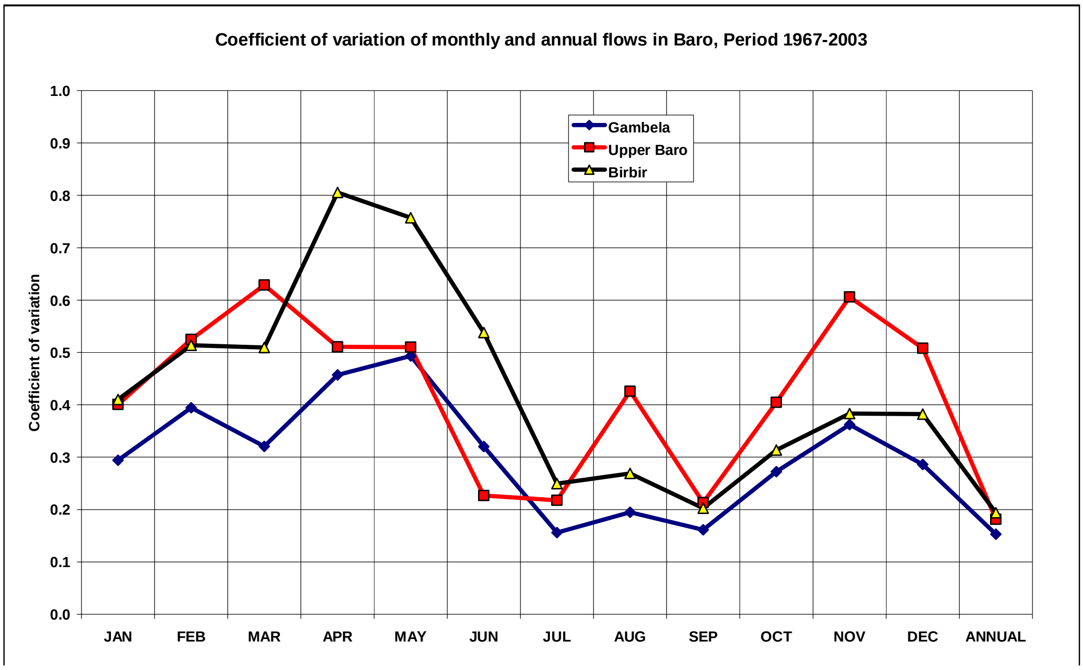

Figure 6.7 Coefficient of variation of monthly and annual flows in Baro, Period 1967-2003

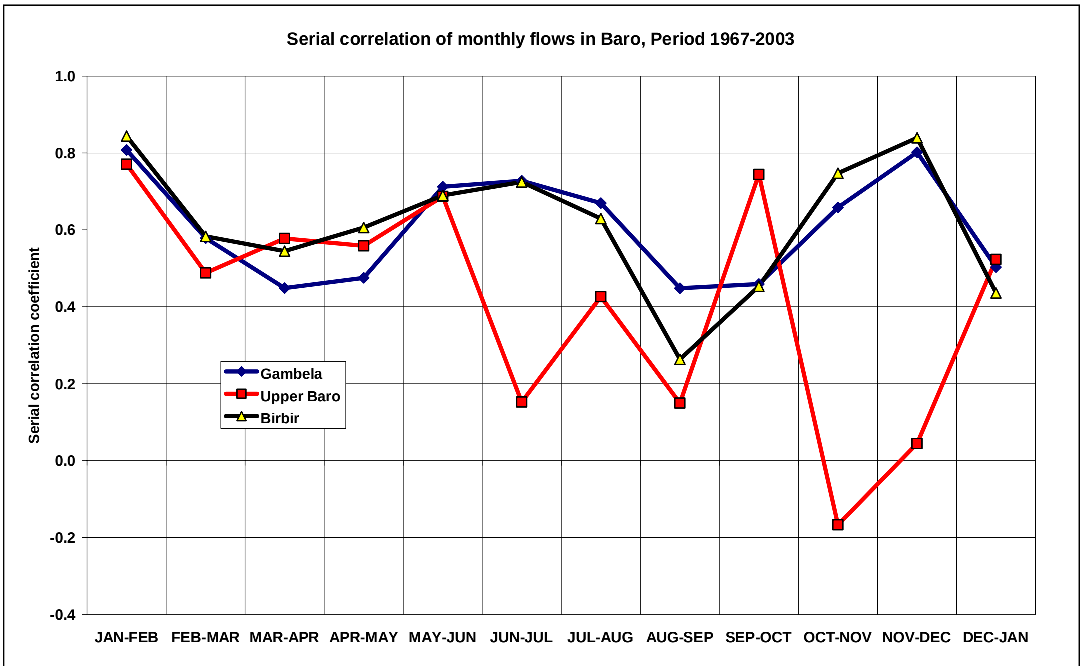

Figure 6.8 Serial correlation of monthly flows in Baro, Period 1967-2003

6.2.2.2 *Partitioning based on nearest neighbour resampling*

To preserve both the first and second order moments of the series at locations upstream of Gambela an alternative extension procedure is presented using resampling of hydrological years (April-March) of Upper Baro based on the historical flows (hydrological years) at Gambela. The hydrological year series of Gambela of the period 1967-2003 is ranked according to the flow value with its associated year number. For each flow value the five year numbers with flows nearest to that ranked flow value are listed.

In the extension procedure for the years 1900-1966 the historical flow value for Gambela of a particular year is compared with the flows of 1967-2003 and the one nearest to the historical value with its associated five year numbers is selected. Hence, for each year between 1900 and 1966 five years out of the period 1967-2003 is available. Next, out of these five one year is selected at random for each year between 1900 and 1966. The randomly selected year has an associated flow record of Upper Baro out of the period 1967-2003 with it. So, for each year between 1900 and 1966 a nearest neighbour to the flow at Gambela for Upper Baro is selected. Since historical sequences of monthly flows for Upper Baro are introduced, in this way the serial correlation is also automatically preserved. The Birbir flow is obtained as the difference between the monthly flows at Gambela and Upper Baro. Water balance checks have been carried out as for the period 1967-2003 discussed above and the same correction procedure has been applied to eliminate inconsistencies.

The results of the extension are presented in Figure 6.9 to Figure 6.15. Figure 6.9 and Figure 6.10 show the correlation between the annual flows at Gambela and Upper Baro and Birbir respectively for the source and extended series. It can be observed that the noise in the relationships is properly preserved. The double mass analysis in Figure 6.11 shows that the extended Upper Baro series is consistent with the flow at Gambela.

The extended annual flow series of Upper Baro and Birbir are given with trend line and 11-year moving averages in Figure 6.12 and Figure 6.13. In comparison with Figure 6.3 it is observed that similar trends exist in the generated series, commensurate with the correlation patterns presented in Figure 6.9 and Figure 6.10.

The monthly flow characteristics of Upper Baro and Birbir as computed for the period 1967-2003 are seen in Figure 6.14 and Figure 6.15 to be well preserved in the extended series for all months.

For the partitioning of the flows for Upper Baro the percentages based on average monthly flow ratios are presented in Table 6.4. No partitioning has been applied sofar for Birbir, though the values presented in Table 6.3 could have been used. However, the runoff percentages deviate considerably from the annual isohyets available. Flow data available indicate e.g. that the runoff from Sor at Metu in mm is about twice as large as the runoff of Geba at Supi, which is inconsistent with the presented rainfall pattern. Hence, when developments on Birbir have to be analysed it is necessary that first the rainfall and discharge series of the relevant stations are critically reviewed, including the development of the discharge series from observed water levels, stage-discharge data and discharge ratings. In Table 6.5 the average monthly flows for the period 1900-2002 are presented as assumed for the Upper Baro up to the dam sites Baro-II and Genji and of the remaining area between Upper Baro and Gambela, indicated as Birbir.

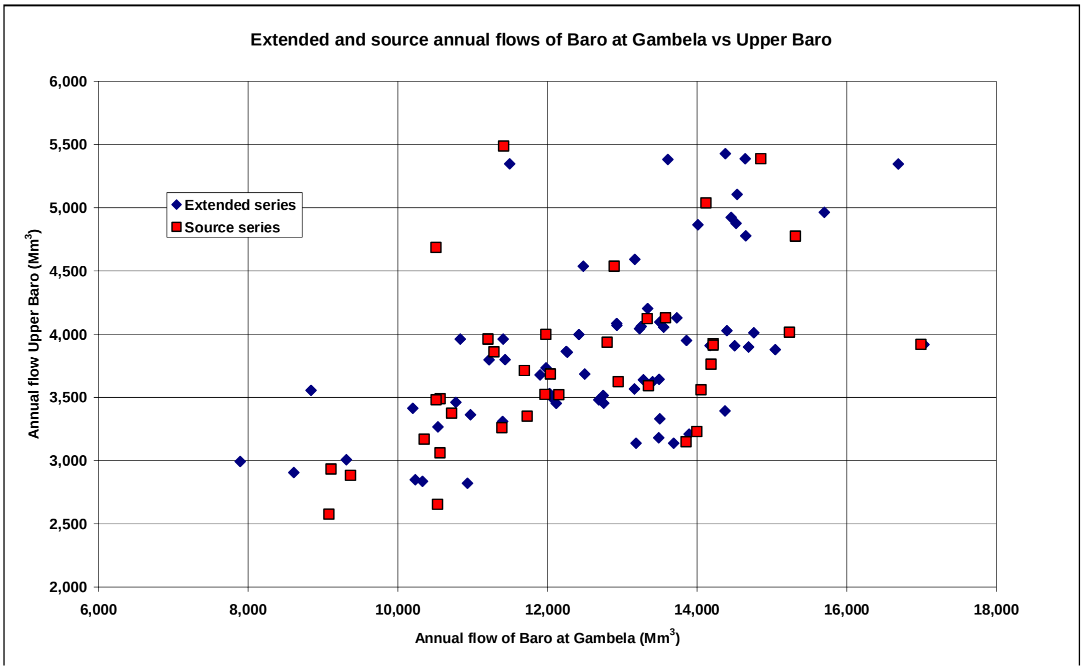

Figure 6.9 Extended and source annual flows of Baro at Gambela and Upper Baro

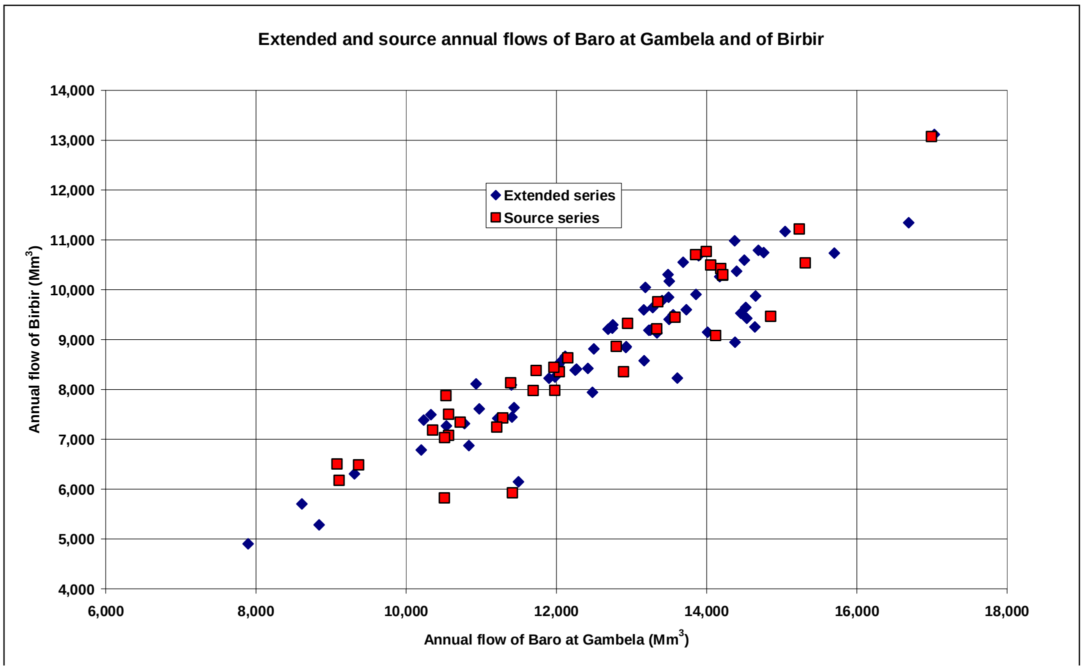

Figure 6.10 Extended and source annual flows of Baro at Gambela and Birbir

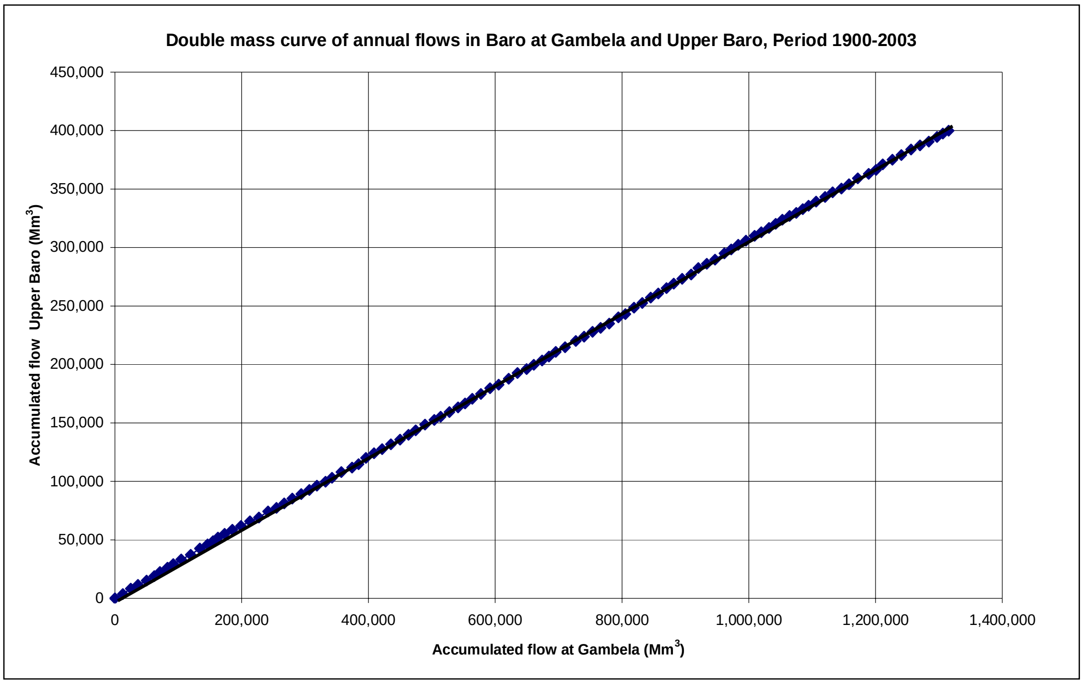

Figure 6.11 Double mass curve of annual flow of Upper Baro and Baro at Gambela, Period 1900-2003

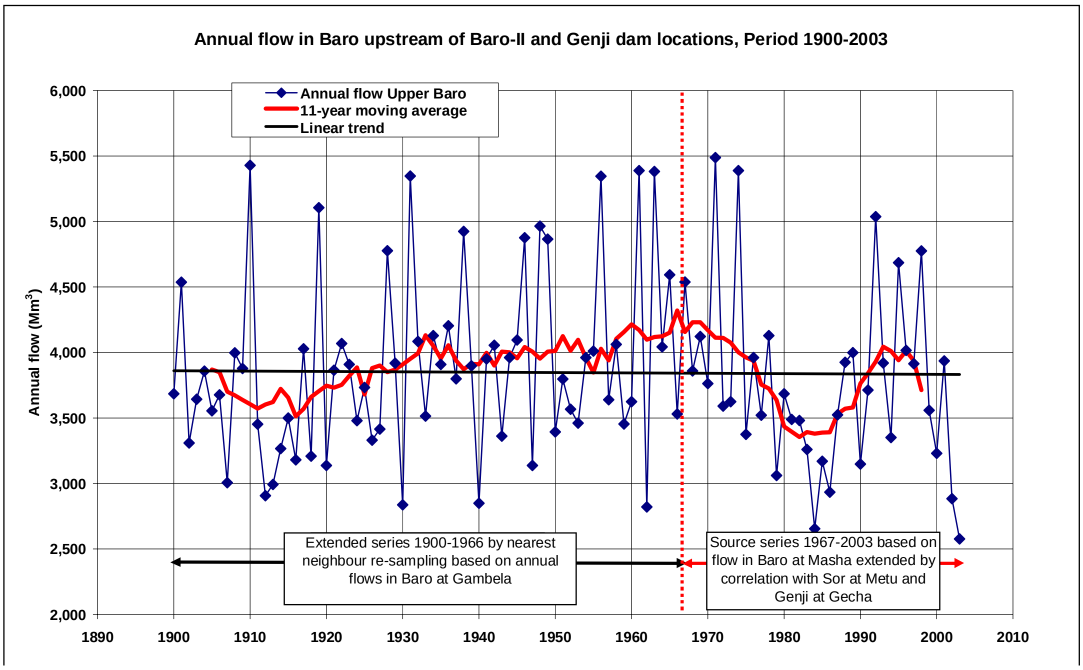

Figure 6.12 Annual flow in Upper Baro (= upstream of Baro-II and Genji dam sites), Period 1900-2003

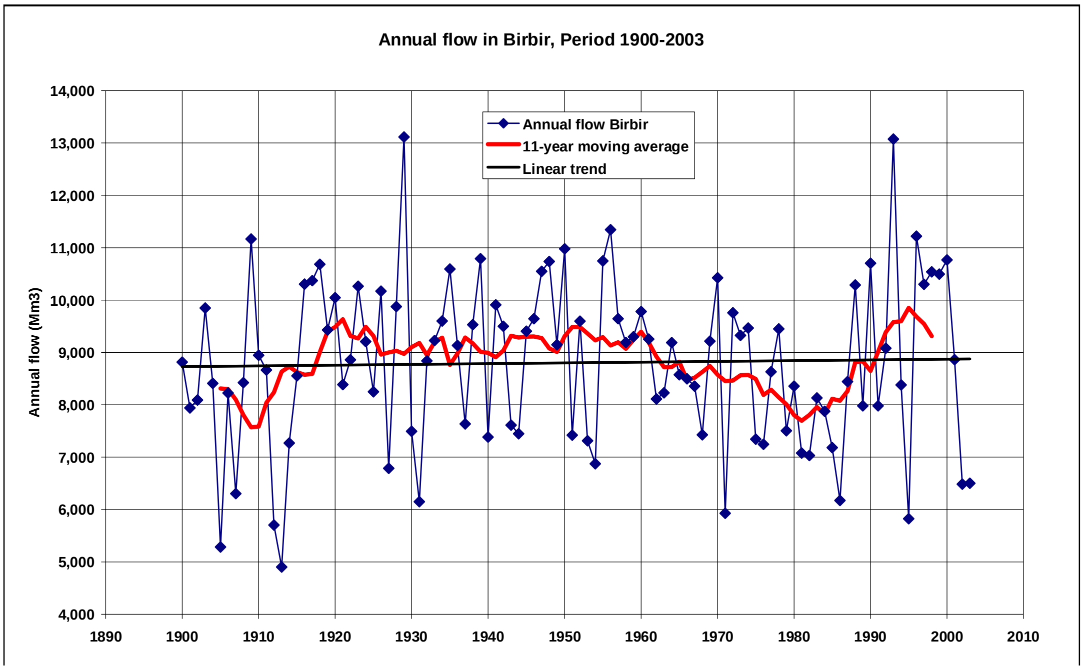

Figure 6.13 Annual flow in Birbir, Period 1900-2003

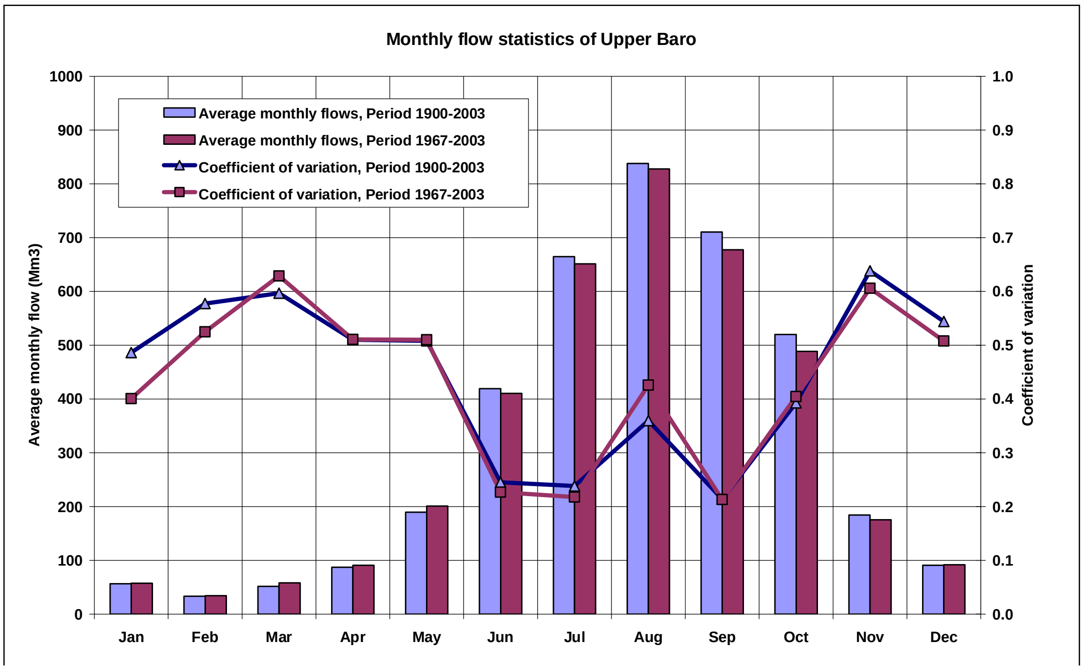

Figure 6.14 Monthly flow statistics of Upper Baro, Periods 1900-2003 and 1967-2003

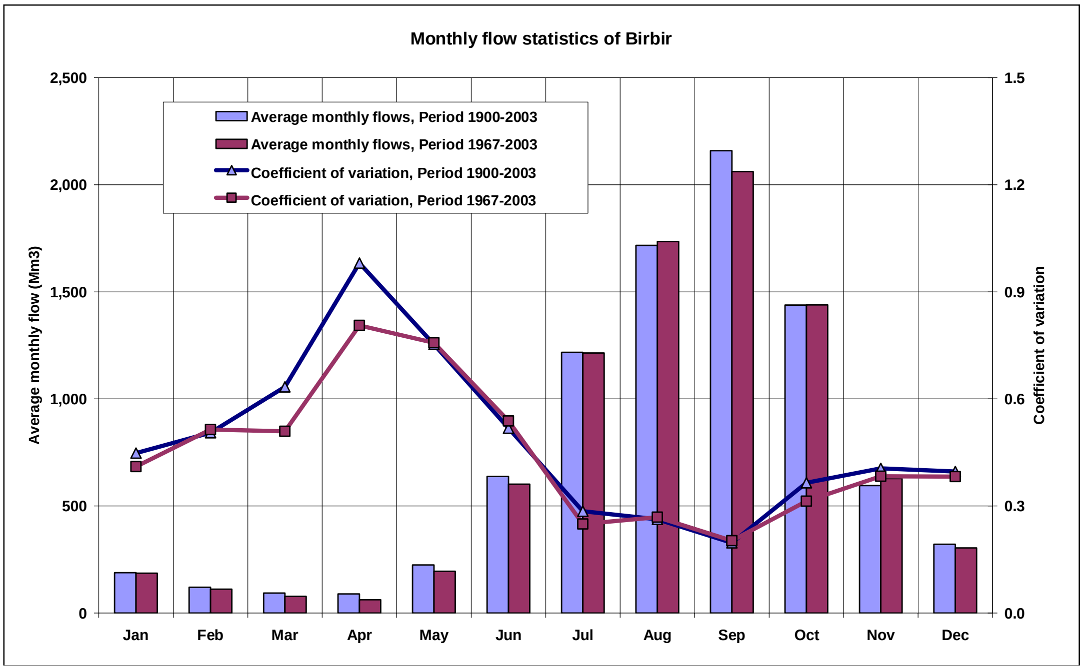

Figure 6.15 Monthly flow statistics of Birbir, Periods 1900-2003 and 1967-2003

Table 6.4 Used percentages in extension of flows 1900-1966 based on generated series of Upper Baro and Birbir

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Masha	44.18	44.57	45.31	43.55	46.91	49.66	49.33	48.83	47.20	46.00	44.75	44.43	47.65
Gecha	4.41	4.36	4.25	4.51	4.01	3.60	3.65	3.72	3.96	4.14	4.33	4.38	3.90
Baro-I	58.05	58.56	59.54	57.22	61.64	65.25	64.82	64.16	62.02	60.45	58.80	58.38	62.62
Baro-II	59.91	60.43	61.44	59.05	63.61	67.33	66.89	66.21	64.00	62.38	60.68	60.25	64.62
Genji	40.09	39.57	38.56	40.95	36.39	32.67	33.11	33.79	36.00	37.62	39.32	39.75	35.38
Upper Baro	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

Table 6.5 Average monthly and annual flows (Mm^3) in Upper Baro and Birbir, Period 1900-2002

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Baro-I	32.9	19.6	30.9	50.4	117.6	274.9	431.6	540.1	440.8	315.4	108.7	53.0	2416.0
Baro-II	33.9	20.2	31.9	52.0	121.4	283.7	445.4	557.4	454.9	325.5	112.2	54.7	2493.2
Genji	22.7	13.2	20.0	36.0	69.4	137.7	220.5	284.4	255.9	196.3	72.7	36.1	1365.0
Upper Baro	56.6	33.5	52.0	88.0	190.9	421.4	665.8	841.8	710.8	521.8	184.9	90.7	3858.2
Birbir	189.8	121.2	93.7	92.1	225.6	638.7	1220.3	1721.0	2162.7	1439.9	597.7	322.4	8825.1

6.2.3 Baro at mouth

At the border between South Sudan and Ethiopia shortly upstream of Nasir the Baro is joined by the Pibor. Between Gambela and the Baro mouth discharges above a threshold value of 600 Mm^3/month is partly lost locally and to the Machar swamps; the loss gradually increases for larger flows, see Figure 6.16. According to the water balance analysis presented in Sutcliffe and Parks (1999) the average annual outflow from the Baro at its mouth amounts 9.5 Bm^3 for the Period 1929-1963.

The losses as computed by ENSWM have been calibrated to this value, resulting in an average annual flowfor the Period 1900-2002 of 9.3 Bm^3. The resulting monthly and annual flows are presented in Figure 6.26, Figure 6.17 and Figure 6.18 as well as in Table 6.6. It is observed that the monthly flows at Baro mouth hardly exceed a value of 1,900 Mm^3/month, whereas at Gambela maximum values about double the amount as at the mouth occurred. This damping effect by the outflow to the marshes is also observed from the annual flow sequence, see Figure 6.18. Statistics show that the standard deviation of the annual flows at Gambela is 1,813 Mm^3, whereas in the Baro at mouth it has reduced to 952 Mm^3. From Figure 6.28 it is observed that only the monthly flows above a threshold value are affected by the inflow to the marshes.

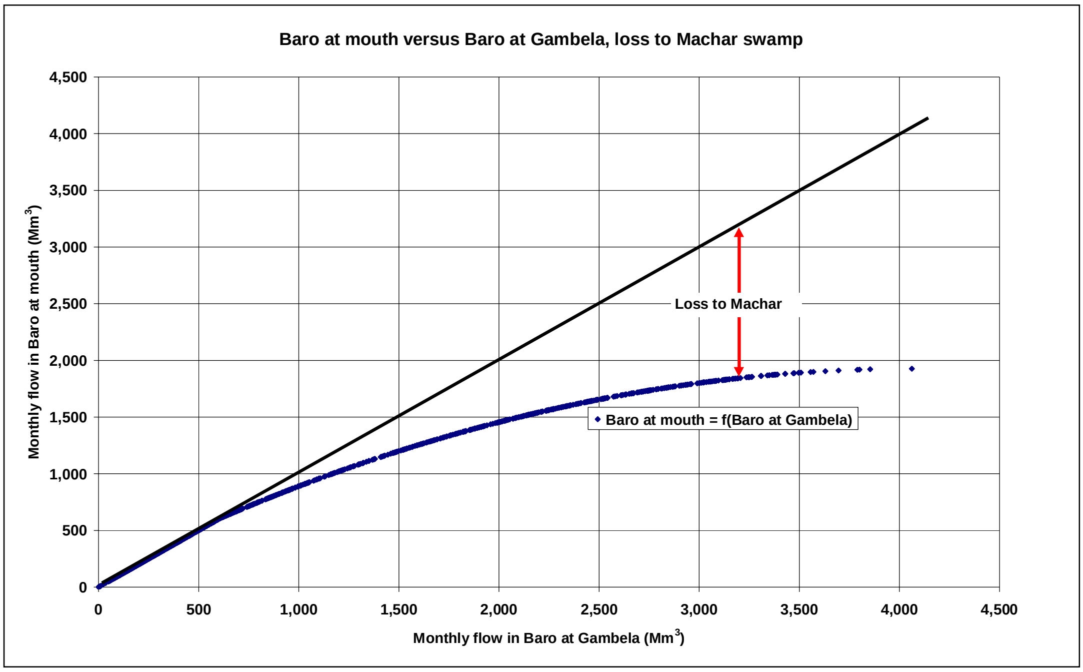

Figure 6.16 Relation between Baro at mouth and at Gambela, loss to Machar swamp

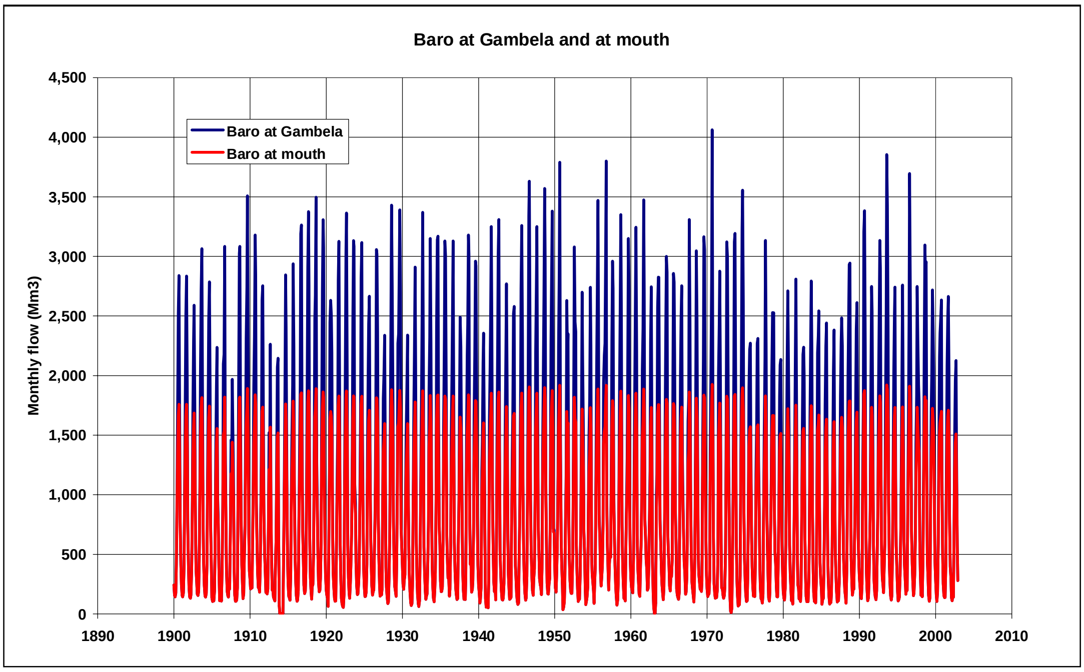

Figure 6.17 Monthly flow in Baro River at Gambela and at mouth, period 1900-2002

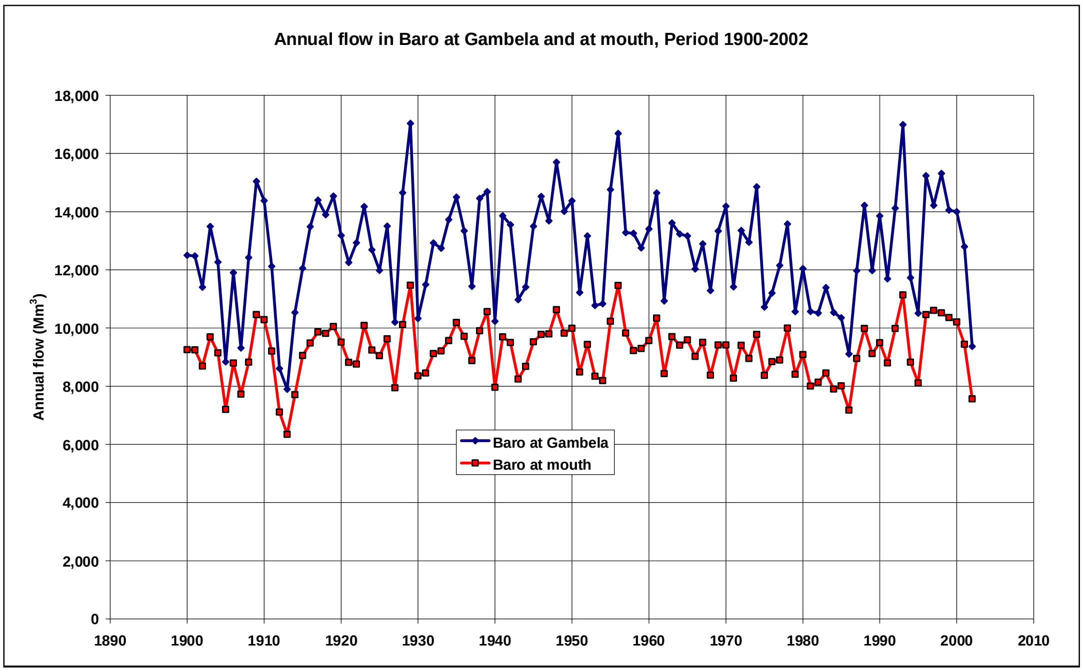

Figure 6.18 Annual flow in Baro at Gambela and at mouth, period 1900-2002

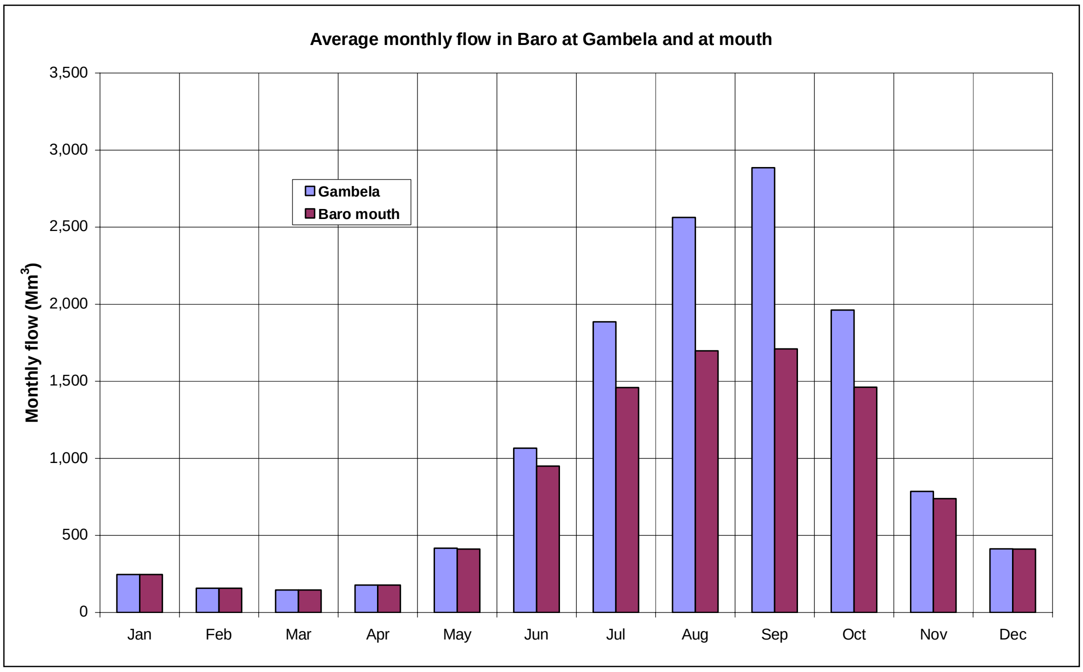

Figure 6.19 Average monthly flow in Baro at Gambela and at mouth, Period 1900-2002

Table 6.6 Monthly and annual flow statistics of the Baro river at mouth (Mm^3), Period 1900-2002

Baro mouth	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Average	246.4	154.7	145.7	180.1	409.8	922.1	1398.0	1646.1	1698.0	1407.6	725.7	411.0	9345.2
Stdev	83.7	60.4	58.8	93.5	179.0	209.8	160.8	143.3	99.2	246.8	185.4	121.0	951.6
Cvar	0.34	0.39	0.40	0.52	0.44	0.23	0.12	0.09	0.06	0.18	0.26	0.29	0.10
Min	4.0	2.0	1.0	0.5	6.2	452.5	1013.4	1043.2	1429.3	720.6	67.8	6.2	6435.6
Max	464.0	369.0	415.0	502.0	975.1	1545.7	1711.6	1900.8	1852.4	1898.7	1348.9	686.7	11650.4

In Sutcliffe and Parks (1999) also average monthly flows of the Baro at Gambela and at mouth are presented for respectively the periods 1905-1959 and 1929-1963, which are presented in Figure 6.20. It is observed that these flow statistics indicate that the Gambela flows seem to be strongly delayed in the flood plains downstream: monthly flows at mouth in November-January exceed those at Gambela. The extent of the delay is questionable. When the river is inbank, i.e. for low and medium flows from the river profile of the Baro between Gambela and the Baro mouth (see Figure 6.21) showing a bed slope of 1.3 x 10^{-4} it can be estimated with a Manning roughness of n = 0.03 and a flow depth of 4 m that the velocity will be about 1 m/s and the celerity 1.5-1.7 m/s or 130-150 km/day. It follows that it takes about 2 days for low and medium flood waves at Gambela to reach the mouth and will not lead to a strong delay and attenuation. The river profile shows also that the bed slope of the last 15 kms is extremely small indicating that gauges near the mouth will be strongly affected by backwater from the Pibor. Since details about the gauging station Baro at mouth and observation practice are missing it is not known whether corrections for backwater have been taken into account in the past. For higher flows at Gambela the flood waters will spread out in the extensive flood plains further downstream leading to the assumed losses to the Machar swamps and also significant delay and attenuation in the Baro flood plains and could at least partly explain the differences in November flows.

To solve the uncertainty in the monthly flow distribution in the Baro at mouth the following actions could be taken:

- Measurements of the water table in the Baro some 30 km upstream of the mouth to avoid effects of backwater of the Pibor on the Baro levels (due to steeper sections) in combination with flow measurements. This option is very easily implemented. Elevations estimated from Google Earth as presented in Figure 6.21 need to be verified.
- Hydraulic modelling of the Baro river and flood plains downstream of Gambela. This will require, however, detailed topographical information and flow measurements at the system boundaries and will involve considerable effort.

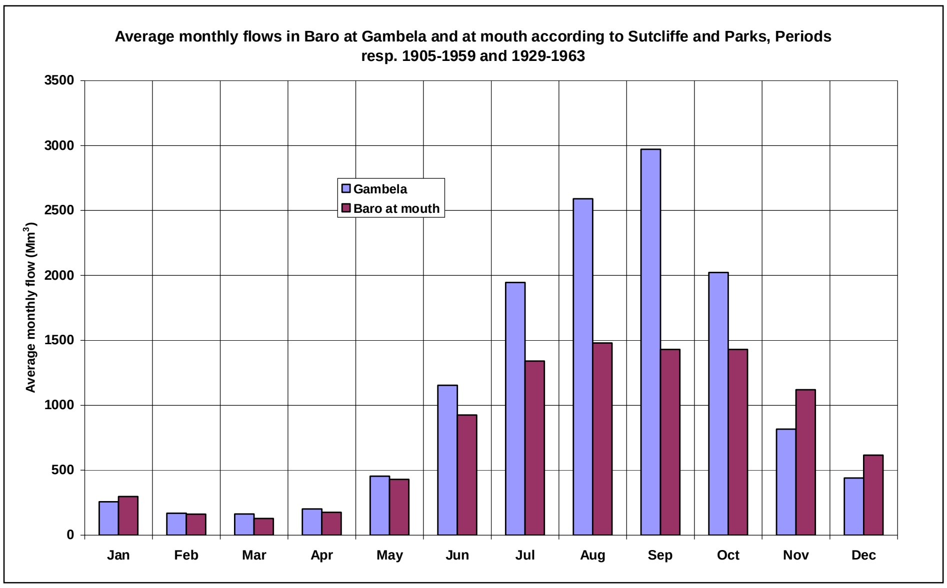

Figure 6.20 Average monthly flows in Baro at Gambela and at mouth in Mm^3, Periods 1905-1959 (Gambela) and 1929-1963 (Baro at mouth) (Source: Sutcliffe and Parks, 1999)

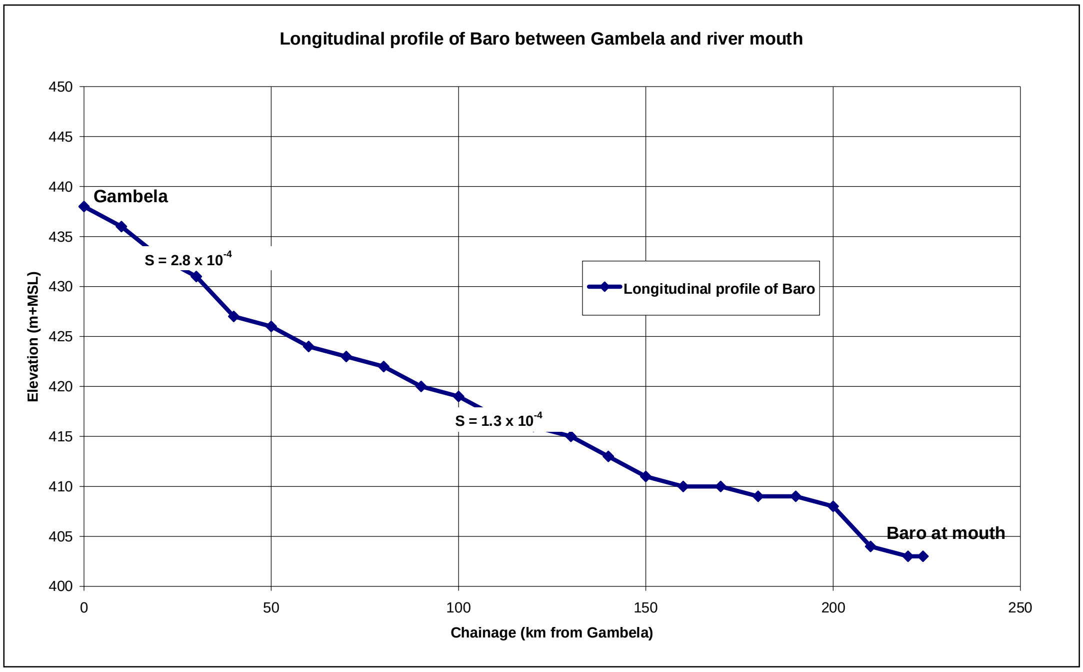

Figure 6.21 Longitudinal profile of the Baro between Gambela and river mouth based on Google Earth (2012)

6.2.4 Alwero, Gilo and Pibor

Historical series for the hydrometric stations Abobo on Alwero and Pugnido on Gilo have been completed for the period 1967-1993 by TAMS-ULG (1996) in their Baro-Akobo Integrated Development Master Plan (Final Report, Volume II, Resource Base and Developmenmt Options). For Pibor at Gilo US monthly flow data are available for the period 1929-1980 with many missing years after 1963.
To create series that are consistent with the Baro and properly reproduce the local monthly flow distribution the ratio of the monthly average of the station and that in the Baro at Gambela have been used to create the series for Abobo, Pugnido and Gilo US. This also avoids doubtful individual monthly flow values at the individual sites. The resulting values in mm/month are applied in ENSWM for all areas upstream of the individual stations to determine the local flows. The monthly average flows are given in Table 6.7 and are shown in Figure 6.21.

The following notes are made to the use of the series for Abobo, Pugnido and Gilo US.

- The reliability of the historical series of the 3 stations is uncertain. Particularly the series of Gilo US is doubtful; the slope of the Pibor river and flood plain between Akobo and the confluence with Baro river is respectively 3.2×10^{-5} and 4.5×10^{-5} which makes backwater effects on the gauge reading at Gilo US very likely, whereas correction for this made in the past is very unlikely. It is essential that the layout, observation practice, discharge measurements, applied discharge ratings, methods of rating curve extrapolation and historical discharge series of these stations are critically reviewed prior to any (pre-) feasibility or design studies in this region.
- When smaller areas are at stake, particularly in the Gilo, the applied procedure presented above may give biased values for the upper reaches of the basins, where runoff ratios are likely to be higher. It is advised then to partition the flow values further, starting off from the flow statistiscs derived by TAMS-ULG. (1996), see Table 6.8 and Table 6.9. (Table data like catchment area, flow values differ from

ENSWM. Annual flow values in Table 6.8 and Table 6.9. are as published and differ due to applied completion procedure and series length. Note that for most of the stations the historical series is very short!).

Table 6.7 Average monthly and annual flow (Mm^3) in Alwero at Abobo, Gilo at Pugnido and Pibor at Gilo US, Period 1900-2002

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Abobo	17.8	9.3	8.6	12.4	42.1	66.1	84.8	104.6	94.6	85.9	43.5	24.9	594.7
Pugnido	109.0	66.4	150.6	113.8	277.6	368.2	397.1	518.1	472.6	412.0	232.9	178.9	3,297.0
Gilo US	241.4	136.6	103.1	32.7	31.6	49.4	96.3	241.6	375.6	387.2	376.1	271.7	2,343.2

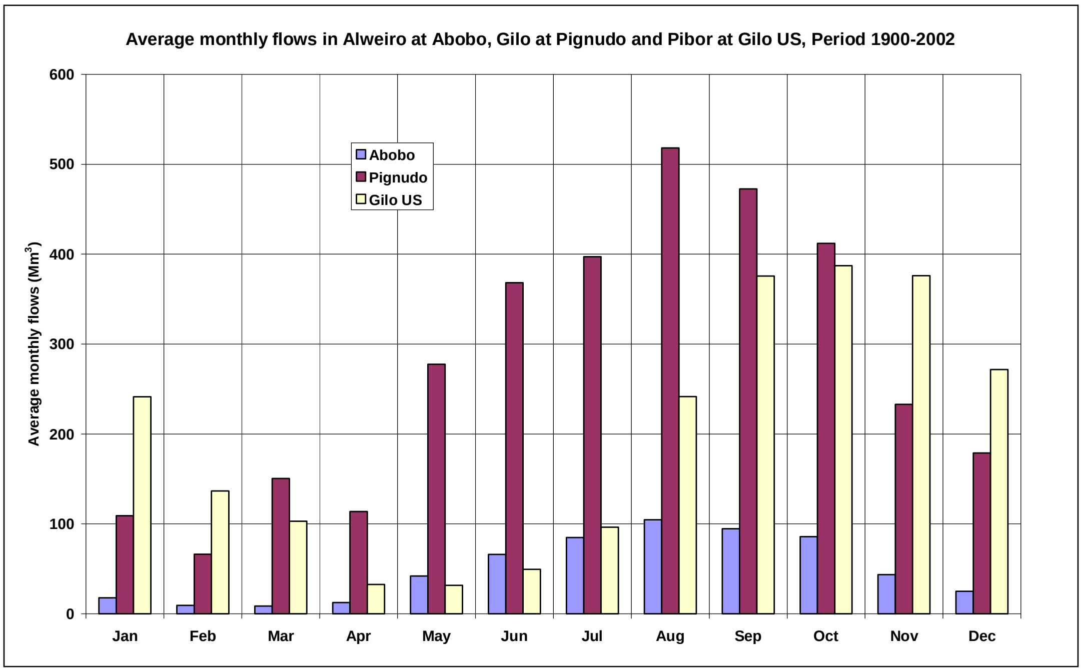

Figure 6.22 Monthly flow in Alwero at Abobo, Gilo at Pugnido and Pibor at Gilo US, period 1900-2002

Table 6.8 Station data, TAMS-ULG (1996) with Mean Annual Flow, Runoff and Precipitation

System	River	Station	Long	Lat	Elevation	Catchment	MAF	Runoff	MAP
					(m+MSL)	(km^2)	(Mm^3)	(mm/year)	(mm/year)
Birbir	Metti	Dembidolo	34-50	8-35	1550	144	78.8	547.2	1750
Birbir	Birbir	Yubdo	35-28	8-57	1500	1563	920.1	588.7	1985
Birbir	Ketto	Chanka	35-02	8-46	1350	1006	580.3	576.8	1810
Birbir	Sor	Metu	35-36	8-18	1700	1648	1,659.6	1007.0	2270
Birbir	Uka	Uka	35-21	8-10	1650	53	37.1	700.0	2020
Birbir	Gumero	Gore	35-29	8-09	1750	106	72.7	685.8	2150
Baro	Baro	Gambela	34-34	8-14	450	23461	11,952.6	509.5	1650
Baro	Baro	Itang	34-16	8-11	425	24636	12,231.0	496.5	1400
Alwero	Alwero	Abobo	34-33	7-51	450	2800	554.2	197.9	1265
Gilo	Gecheb	M. Teferi	35-33	7-00	1300	79	60.0	759.5	1950
Gilo	Bitun Wuha	Tepi	35-28	7-12	1150	220	33.0	150.0	2120
Gilo	Beg Wuha	Tepi	35-26	7-12	1150	125	104.7	837.6	2040
Gilo	Gilo	Pugnido	34-15	7-37	450	10137	3,014.3	297.4	1320

Table 6.9 Monthly and annual flows (Mm^3) at hydrometric stations, after filling in. Source: TAMS-ULG (1996)

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Dembidolo	2.00	1.07	1.29	1.64	3.79	6.21	11.93	15.79	15.71	12.29	5.57	2.86	80.2
Yubdo	35.00	24.25	22.25	21.13	30.13	56.19	119.62	180.00	209.13	126.56	63.19	45.13	932.6
Chanka	4.79	3.93	1.93	1.93	8.79	39.64	95.86	141.36	134.21	72.93	31.57	18.43	555.4
Metu	21.96	12.30	9.52	12.70	35.96	118.30	265.81	383.30	434.04	246.22	74.00	37.33	1,651.4
Uka	0.86	0.29	0.29	0.43	1.57	2.93	5.21	6.07	8.07	8.00	3.00	1.50	38.2
Gore	0.42	0.33	0.08	0.25	1.33	4.58	12.25	13.92	16.08	11.00	3.08	1.33	64.7
Gambela	215.6	127.8	113.0	156.3	356.3	969.3	1817.0	2426.3	2745.2	1948.5	767.0	373.7	12,016.0
Itang	300.5	179.5	166.5	218.5	410.0	976.5	1779.0	2418.0	2695.0	2076.5	812.5	427.0	12,459.5
Abobo	15.61	7.72	6.67	10.94	35.94	60.33	81.67	99.00	90.39	85.28	42.67	22.56	558.8
M. Teferi	1.00	0.58	1.00	1.67	4.58	10.17	12.42	10.25	8.42	6.00	2.33	1.42	59.8
Tepi, Bitun	1.29	1.14	1.14	1.86	3.00	3.43	4.14	3.71	4.14	4.14	3.00	2.00	33.0
Tepi, Beg	5.86	4.00	3.71	8.14	10.14	9.86	11.00	14.29	12.14	11.71	8.29	6.00	105.1
Pugnido	95.35	54.82	116.76	100.12	237.24	336.06	382.53	490.47	451.53	409.18	228.24	161.82	3,064.1

6.2.5 Sobat at Hillet Doleib

The flow record of station Hillet Doleib at the mouth of the Sobat River as published by the Nile Control Staff covers the years 1905-1983. The series has been extended to the period 1900-2002 by regression on Mongalla and Malakal as follows:

$$Q_{Sobat} = Q_{Malakal} - Q_{Swamp}$$
$$Q_{Swamp} = 6,574 + 0.29 Q_{Mongalla} \quad (Mm^3) \qquad (6\text{-}6)$$

Above expression for Q_{Swamp} refers to annual flows from April to March being the difference between the flow at Malakal and at Hillet Doleib. Since the variation in sequential monthly flows from the Sudd swamp is virtually nil, the same variation in monthly flows as observed at Malakal has been applied for the Sobat series extension.

The statistics of the monthly flows and the annual flow series are presented in Table 6.10 Table 6.1 and Figure 6.22 and Figure 6.23. The low absolute value of the standard deviation in the wet months July to November is an effect of the spill to the swamps above a threshold level, which reduces the natural variation observed at Gambela to a large extent further downstream.

Table 6.10 Monthly and annual flow statistics of the Sobat at Hillet Doleib (Mm^3), Period 1900-2002

Hillet Doleib	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Average	950.3	406.2	246.3	211.0	387.8	829.4	1285.1	1569.7	1732.2	1935.5	1919.5	1673.8	13,146.8
Stdev	682.5	418.2	312.3	164.6	192.3	214.6	188.2	169.3	204.1	252.1	310.9	563.5	2,543.5
Cvar	0.72	1.03	1.27	0.78	0.50	0.26	0.15	0.11	0.12	0.13	0.16	0.34	0.19
Min	15.3	0.0	0.0	0.0	0.0	267.1	724.0	1178.0	1290.6	1290.0	898.0	340.0	7,342.1
Max	3230.0	3000.0	2890.0	1180.0	942.0	1390.0	1840.0	2230.0	2490.0	2770.0	2840.0	3140.0	23,052.0

The annual series do not show a break in the flows in the early sixties as is apparent for the White Nile. The annual flow varied between 7 and 23 Bm^3/year, with a long term average value of 13.1 Bm^3/year. The average annual flow in the period 1900-1960 was 13.3 Bm^3 against 12.9 Bm^3 in the period 1961-2002.

The monthly averages are compared with those at Gambela in Figure 6.24. It is observed that the peak values in the Baro at gambela in September have shifted to October-November in the Sobat at Hillet Doleib.

In Figure 6.25 and Figure 6.36 the double mass curves of the annual flows in the Sobat at Hillet Doleib with the flows in the Baro at Gambela and in the Blue Nile at Khartoum for the years 1900-2002 are presented. The graphs do not show inconsistencies between the series.

To get a closed balance for the Sobat between Baro mouth, Abobo, Pugnido and Gilo US and Sobat mouth at Hillet Doleib an inflow and loss series have been added to ENSWM. Effectively, 2.3 Bm^3/year on average is the net loss in this reach, equivalent to 46 mm/year.

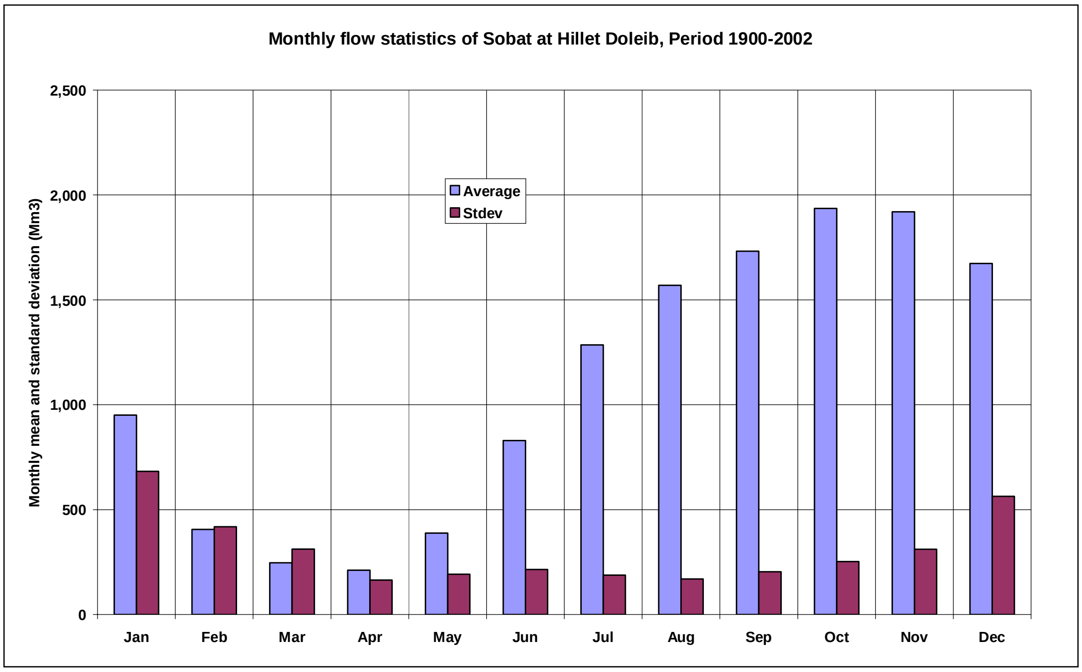

Figure 6.23 Mean and standard deviation of monthly flows in Sobat at Hillet Doleib

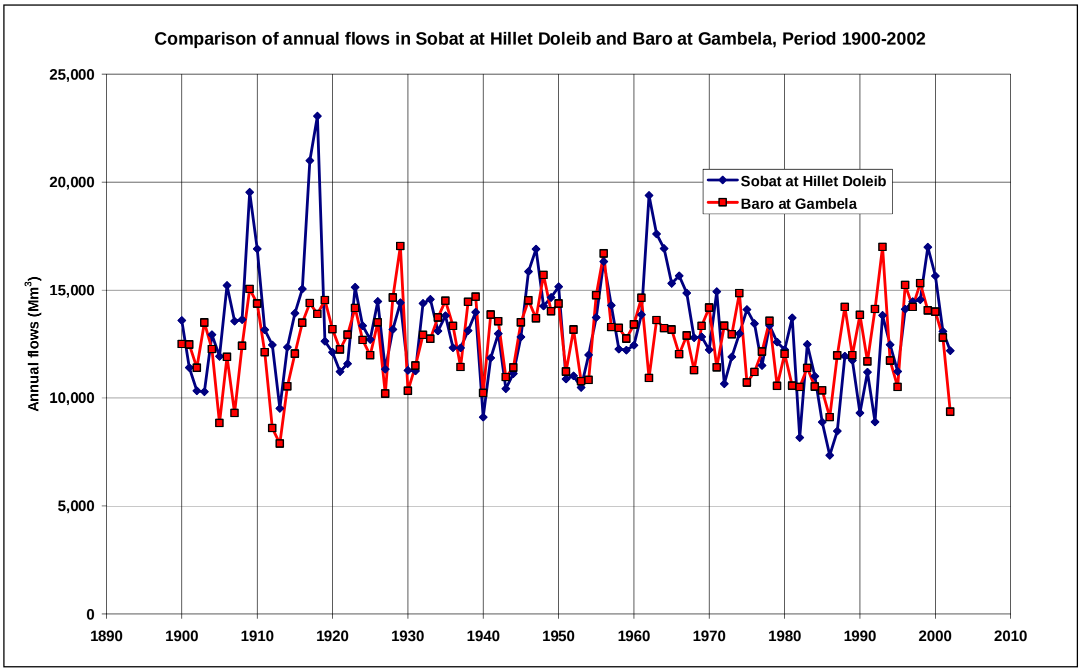

Figure 6.24 Annual flow in Sobat at Hillet Doleib and Baro at Gambela, Period 1900-2002

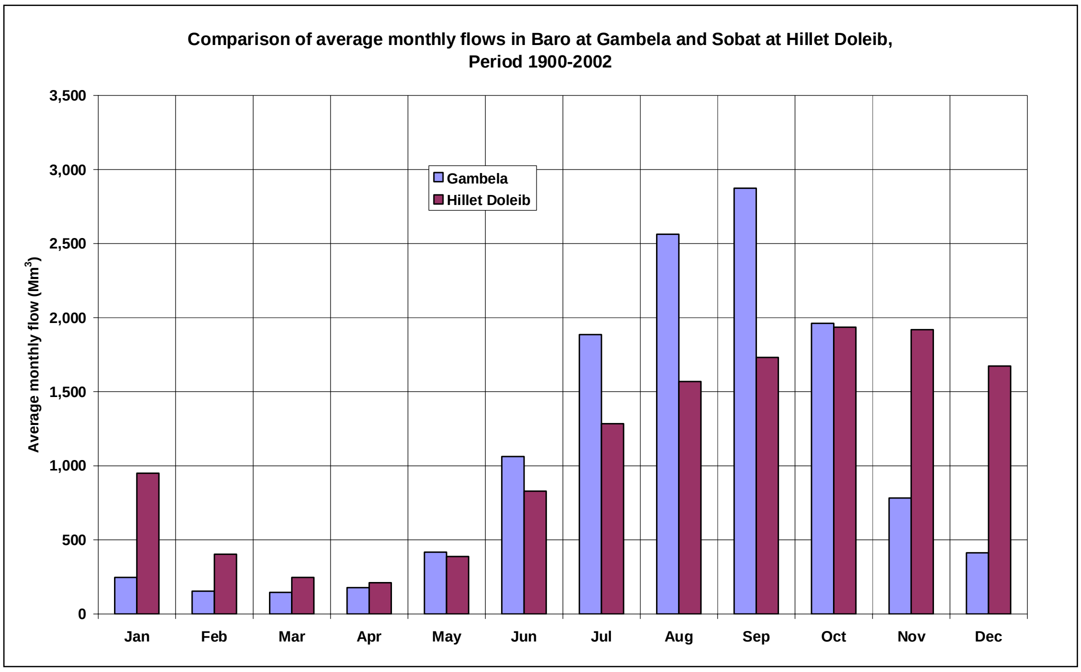

Figure 6.25 Average monthly flows in Baro at gambela and Sobat at Hillet Doleib, period 1900-2002

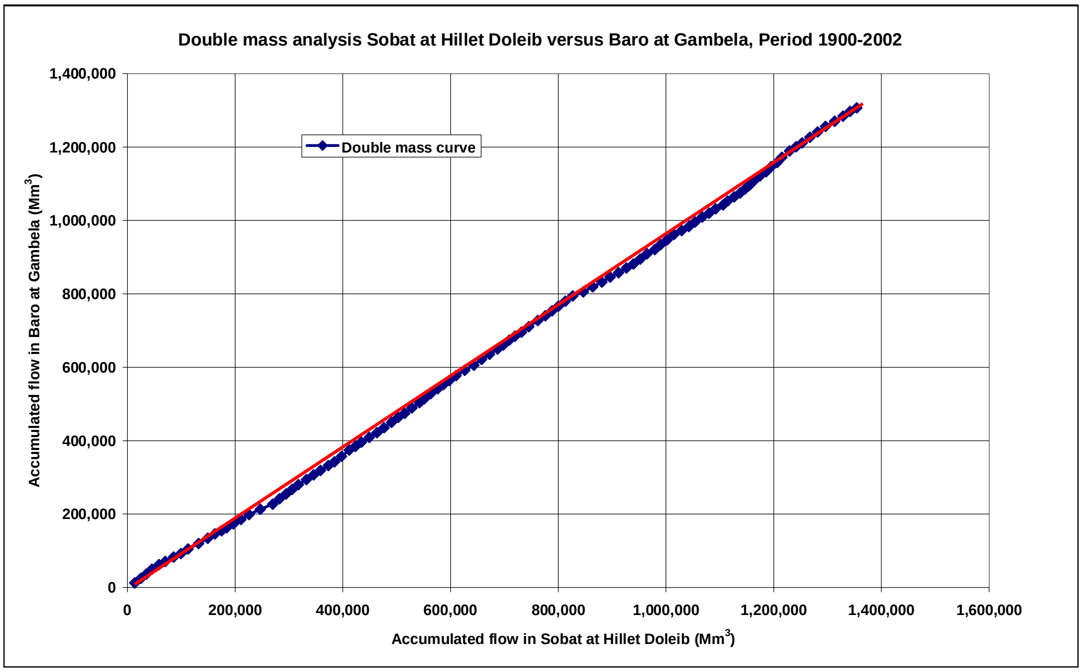

Figure 6.26 Double mass analysis of Sobat at Hillet Doleib versus Baro at Gambela, Period 1900-2002

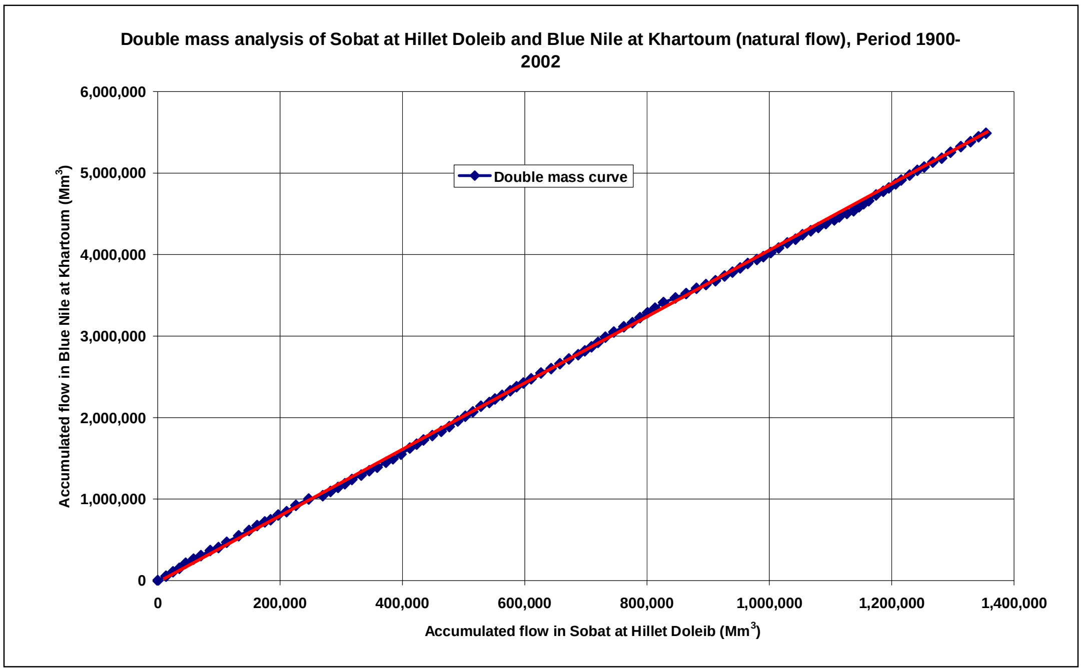

Figure 6.27 Double mass analysis of Sobat at Hillet Doleib versus Blue Nile at Khartoum, Period 1900-2002

6.2.6 White Nile at Mongalla

The flow series of the White Nile at Mongalla covers the period 1904-1983. The flow at Mongalla is equal to the flow at Pakwach plus the inflow by the Torrents between Pakwach and Mongalla. The completion of the series of Mongalla and of the Torrents has been carried out as follows:

- For the periods 1900-1904, 1984-1992 and 1996 a 4 step approach has been used:

- annual flows at Mongalla have been derived from regression on Pakwach (excluding the years 1916, 1917 and 1964):

$$Q_{Mongalla} = 4,655 + 0.941 Q_{Pakwach} + \varepsilon(0,1771) \quad (Mm^3) \qquad (6\text{-}7)$$

  where: $\varepsilon(a,b)$= is a normal deviate with mean *a* and standard deviation *b*

- annual Torrent flows have been computed for above years as the difference between Mongalla and Pakwach;
- monthly Torrent flows have been estimated from the annual Torrent flows by scaling according to the average monthly percentage of the annual flow;
- monthly flow values for Mongalla have been derived from the monthly flows at Pakwach and of the Torrents.

• For the periods 1993-1995 and 1997-2002 Ten Day Mean Gauge Heights of Juba have been used to estimate the gauge height at Mongalla (data obtained from Eng. Ahmed Fahmi, 2007, pers. comm.), which were subsequently transformed to discharges:

$$h_{Mongalla} = 1.02\, h_{Juba} - 1.07 \quad (m)$$
$$Q_{Mongalla} = 24.8 h_{Mongalla} - 191.2 \quad (Mm^3/day) \qquad (6\text{-}8)$$

Sutcliffe and Parks (1999) indicate that the rating curve for Mongalla has shifted in the past several times. From double mass analysis with the flow at Kamdini it was revealed that the above procedure leads to too low flows at Mongalla. By multiplying the flows at Mongalla for the above periods with 1.17 a series is created that is consistent with Jinja and Kamdini. Subsequently, the Torrent flows between Pakwach and Mongalla were completed as the difference between the two.

The monthly and annual flow statistics of the White Nile at Mongalla have been presented in Table 6.11 and the annual flow series and monthly flow statistrics are shown in Figure 6.30 and Figure 6.31. From the annual flow series it is observed that since the early sixties flows have been substantially larger the between 1900 and 1961. This is also shown in the monthly averages of the periods 1900-1961 and 1962-2002 in Figure 6.30. The difference is due to small increase in the difference between rainfall over and evaporation of Lake Victoria. Since the outflow from the lake is only a small component in the water balance of the lake, the increase of the difference had a major impact on the outflow from the lake.and hence on the White Nile flow at Mongalla: the average annual flow in the period 1900-1961 amounted 27.9 Bm^3/year against 47.8 Bm^3/year in the period 1962-2002, i.e. 1.7 times as much. The break in the series is also clearly visisble from the double mass analysis of the series of Mongalla with the Sobat at Hillet Doleib, presented in Figure 6.31.

Table 6.11 Monthly and annual flow statistics of the White Nile at Mongalla (Mm^3), Period 1900-2002

Mongalla	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Average	2,698.8	2,427.6	2,506.2	2,569.2	2,955.9	2,882.8	3,145.3	3,533.6	3,525.0	3,459.6	3,176.6	2,924.6	35,805.1
Stdev	1,028.7	964.7	989.7	976.3	1,027.6	1,005.8	1,031.1	1,078.6	1,179.4	1,216.8	1,116.1	1,079.0	12,029.1
Cvar	0.38	0.40	0.39	0.38	0.35	0.35	0.33	0.31	0.33	0.35	0.35	0.37	0.34
Min	1,079.0	913.0	924.0	927.0	1,290.0	1,212.0	1,292.0	1,615.0	1,520.0	1,583.0	1,434.0	1,159.0	15,898.0
Max	5,490.0	4,750.0	5,030.0	5,010.0	6,280.0	5,870.0	5,920.0	6,520.0	7,090.0	7,613.0	5,970.0	5,472.0	66,402.0

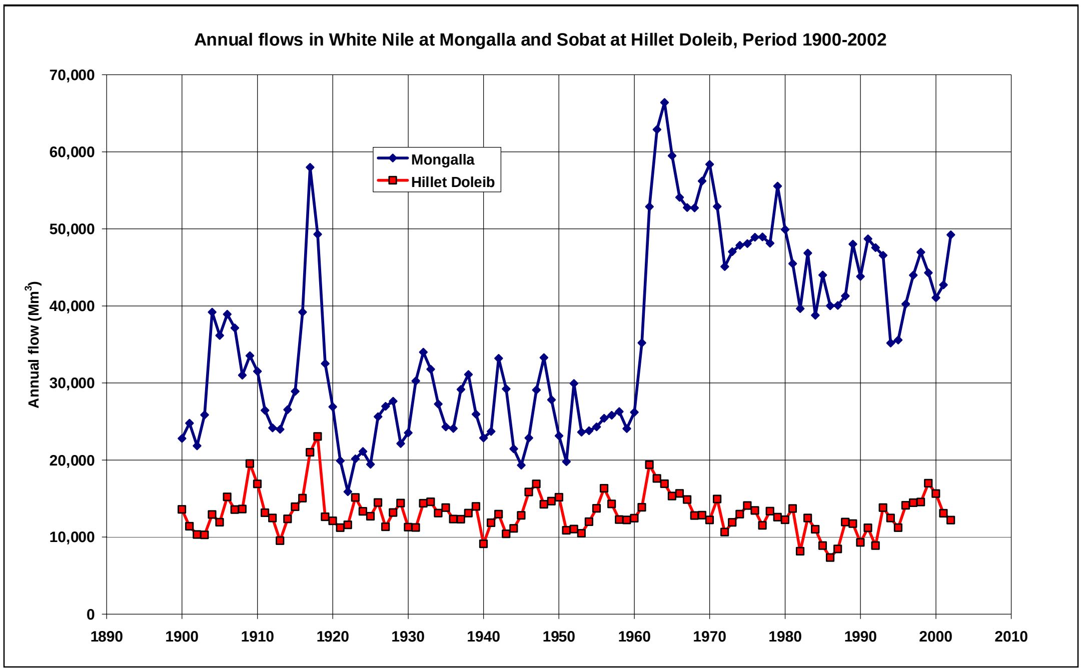

Figure 6.28 Annual flows in White Nile at Mongalla and Sobat at Hillet Doleib, Period 1900-2002

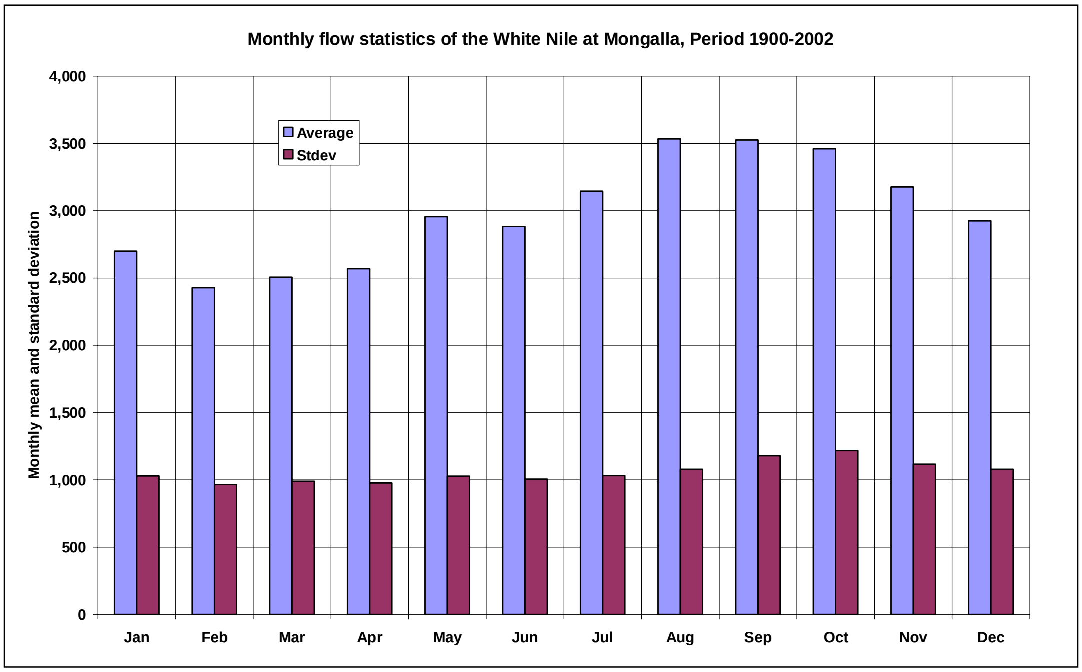

Figure 6.29 Monthly flow statistics in White Nile at Mongalla, Period 1900-2002

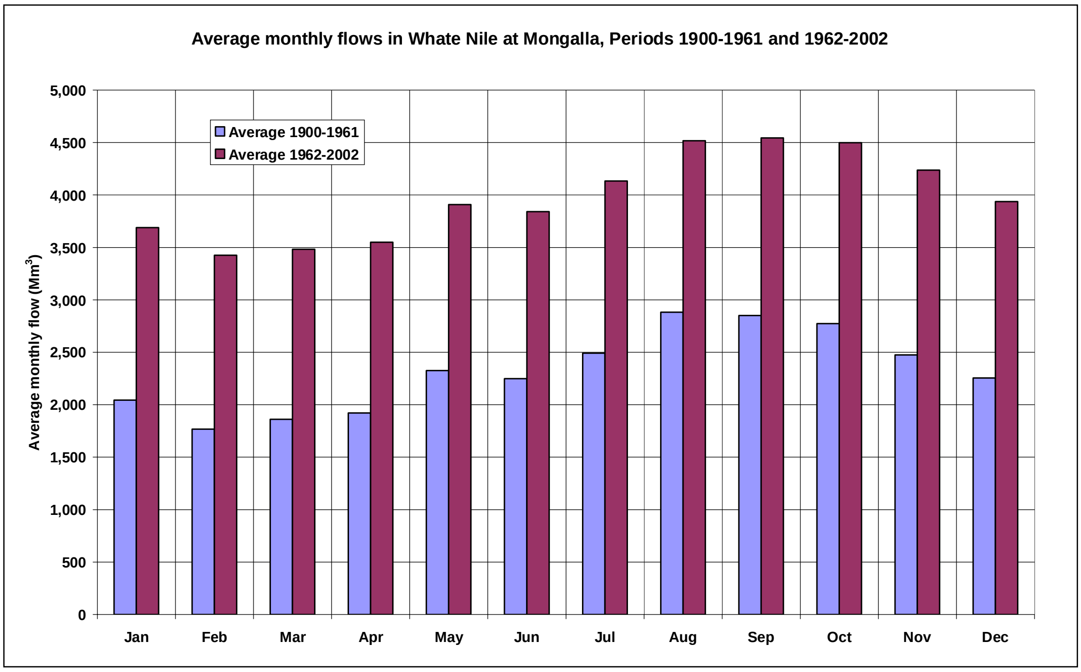

Figure 6.30 Average monthly flows in White Nile at Mongalla, Periods 1900-1961 and 1962-2002

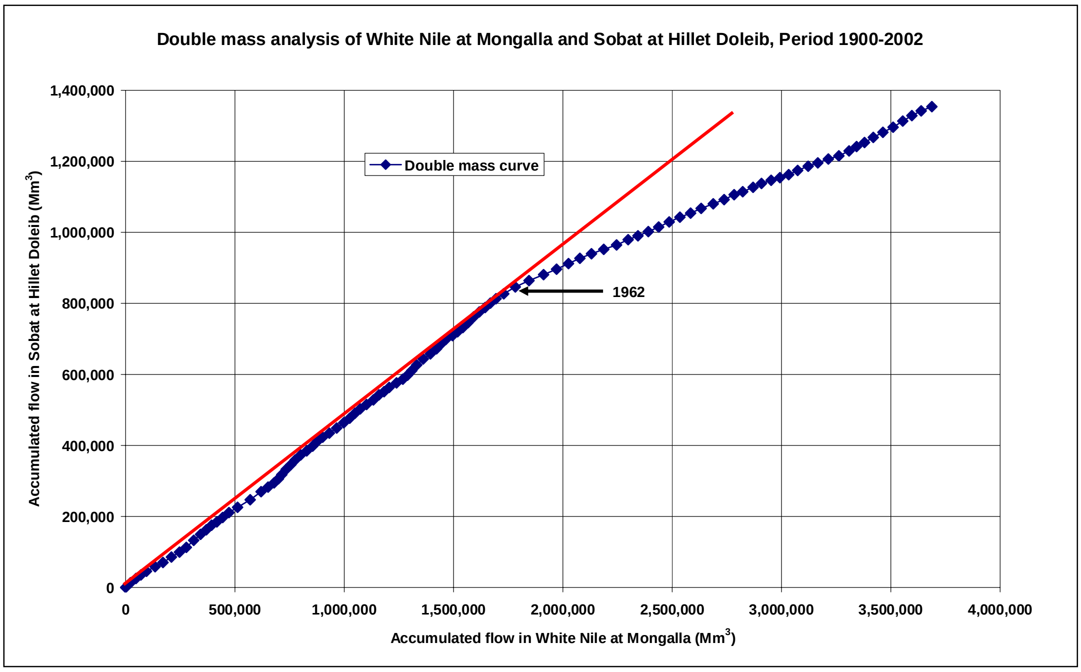

Figure 6.31 Double mass analysis of White Nile at Mongalla versus Sobat at Hillet Doleib, Period 1900-2002

6.2.7 Bahr el Ghazal

To create monthly inflow series to the Bahr el Ghazal swamp for the period 1900-2002 the following procedure has been used:

- Annual inflows to the swamp are available from Sutcliffe and Parks (1999) for the periods 1942-1962 and 1970-1986.

- The annual inflow series has first been extended with the period 1904-1941 based on series of the Jur at Wau, the main contributor to the inflow to the swamp:

$$Q_{Bahr\ el\ Ghazal} = 1{,}792 + 2.0823 Q_{Jur} \quad (Mm^3) \tag{6-9}$$

The relation is depicted in Figure 6.31.

- For the periods 1900-1903, 1963-1969 and 1987-2002 annual inflows were created by regression on annual flow from the Torrents between Lake Albert and Mongalla:

$$Q_{Bahr\ el\ Ghazal} = 5866 + 1.342 Q_{Torrents} + e(0,3300) \tag{6-10}$$

A random component was added to preserve the variance in the annual flows of the Bahr el Ghazal.

- Monthly flows for the Bahr el Ghazal were created as a fixed percentage of the annual flow taken from statistics presented in Sutcliffe and Parks (1999). It is noted that an exact reproduction of the variation of the monthly inflow of the Bahr el Ghazal is of less importance as only some 3% of the inflow to the swamp is observed as outflow in Khor Doleib. The monthly variation is presented in Figure 6.33.

The annual inflow to the Bahr el Ghazal is presented in Figure 6.42. It shows a variation in the annual inflow from 4 to over 20 Bm^3 annually, with an average of nearly 12 Bm^3/year.

Double mass analysis of the Bahr el Ghzal series with the flow in the Sobat at Hillet Doleib in Figure 6.43 shows a very similar runoff pattern at both sites, indicating climatic similarity.

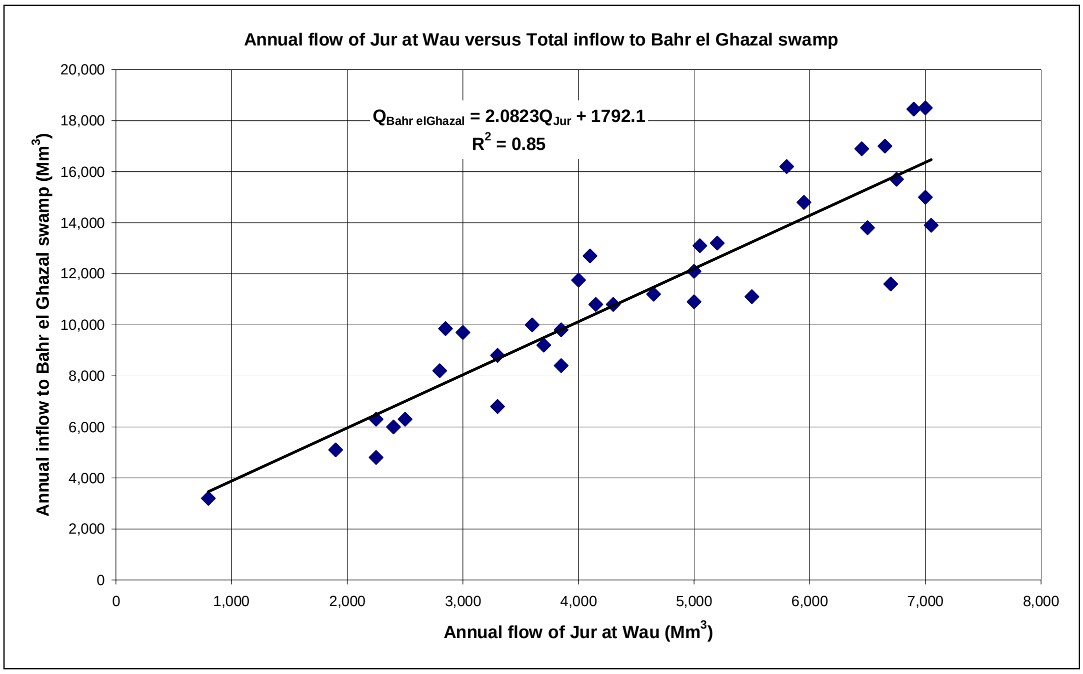

Figure 6.32 Annual inflow to Bahr el Ghazal as function of flow of Wau at Jur (1942-1986)

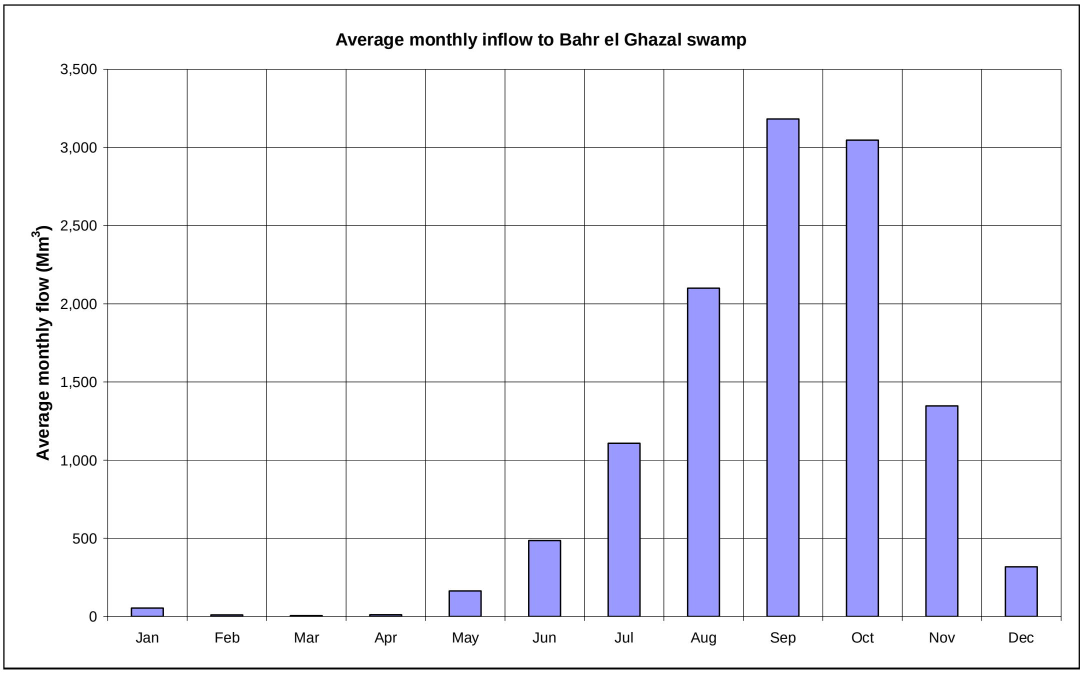

Figure 6.33 Average monthly inflow to Bahr el Ghazal swamp

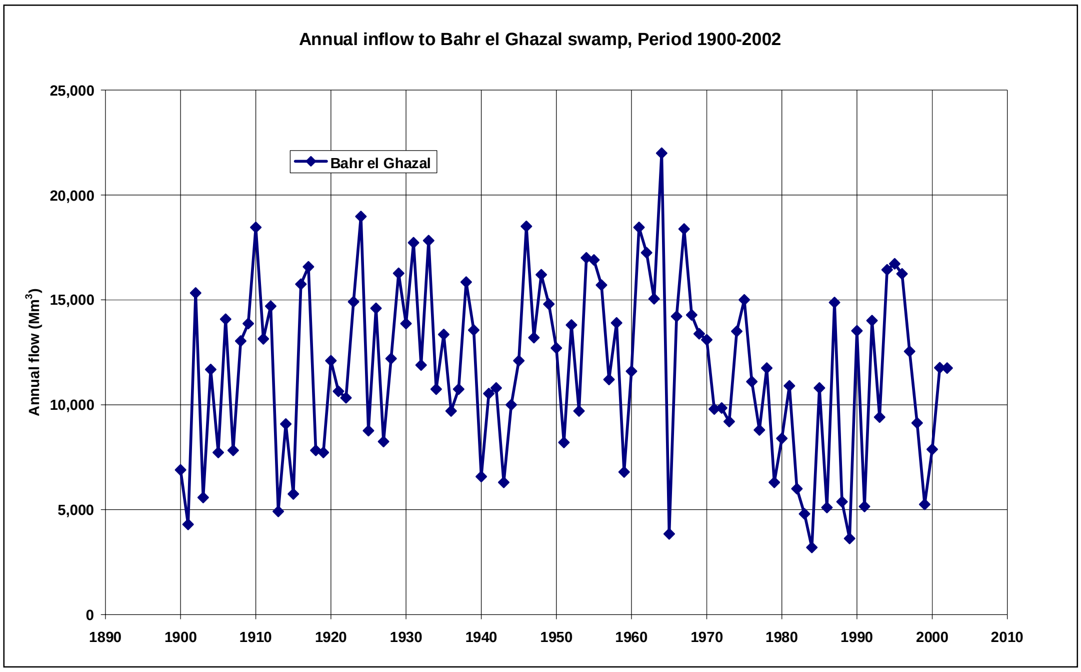

Figure 6.34 Annual inflow to Bahr el Ghazal swamp, Period 1900-2002

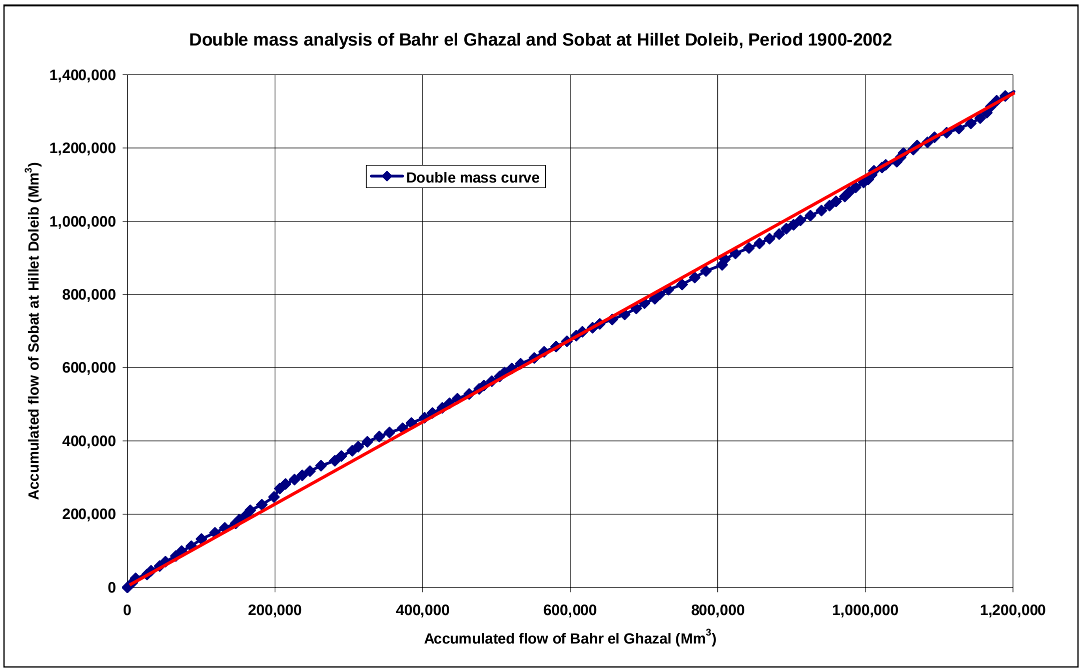

Figure 6.35 Double mass analysis of Bahr el Ghazal versus Sobat at Hillet Doleib, Period 1900-2002

6.2.8 White Nile at Malakal

The monthly flow record for the White Nile at Malakal as published by the Nile Control Staff covers the period 1906-2002. The period 1900-1905 has been estimated from the water balance from the natural flow at Aswan corrected for losses and the Blue Nile and Atbara flows. For the period 1906-1932, prior to the operation of Jebel Aulia dam a reasonable balance is obtained if the loss is taken as 6,500 Mm^3/year, with exception of a number of years, see Figure 6.44. For the period 1933-1965 closing balances are obtained when the annual loss is increased to 7,500 Mm^3. Larger losses are to be considered to close the balance for the more recent periods. The annual values for the period 1900-1905 have therefore been obtained from the flows at Aswan increased with losses of 6,500 Mm^3/year and corrected for the contributions of the Atbara and the Blue Nile. The monthly record has subsequently been obtained as the average monthly percentage of the annual flow.

The monthly statistics of the flow at Malakal are presented in Table 6.12 and Figure 6.45. In comparison with Mongalla (Figure 6.45) the monthly variation at Malakal is seen to be more pronounced. Since the Sudd flattens out the White Nile flow almost entirely, the seasonal variation at Malakal is to be attributed to the contribution of the Sobat. The annual flows at Malakal are presented in Figure 6.47 together with the annual flows of the Bahr el Ghazal and the Sobat. The figure shows that, whereas prior to 1962 the annual flows were of the same order of magnitude, as from 1962 onward the annual flow at Mongalla exceeds the flow at Malakal with nearly 15 Bm^3, see also Table 6.13. In this table also estimates of the Sudd area are presented. Total losses on average amounted about 31 Bm^3, or 1136 mm. It is observed that since 1961 the area inundated by the Sudd has increased with approximately 11,000 km^2. Though the effect of the increased rainfall over the equatorial lakes is less pronounced in Malakal then in Mongalla the flows have increased with about 5.45 Bm^3 per year, equally distributed over the months as shown in Figure 6.48.

The double mass curve presented in Figure 6.49 shows that the flow series of Malakal is statistically non-homogeneous in comparison to the Sobat at Hillet Doleib.

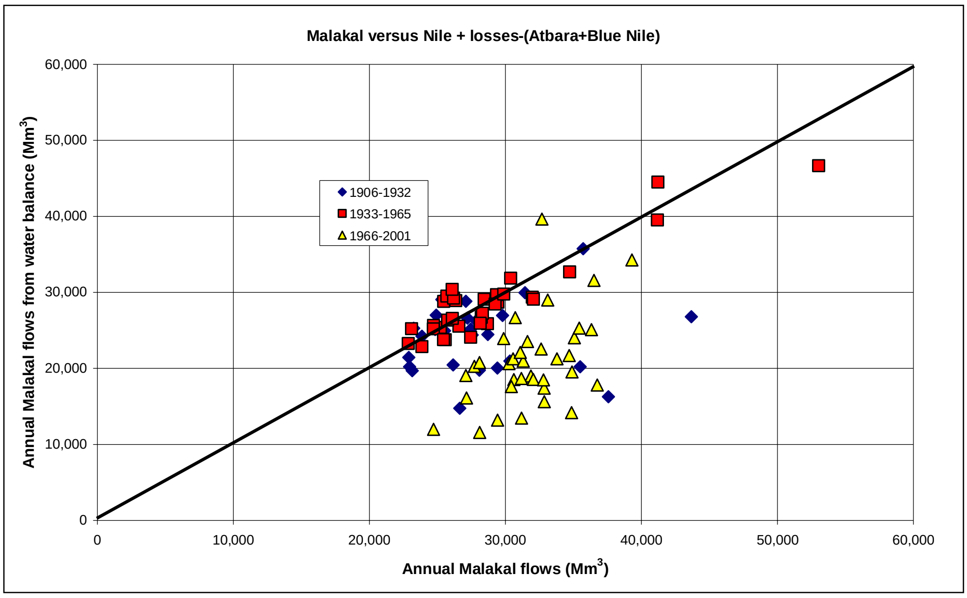

Figure 6.36 Annual flow at Malakal versus Aswan Natural +losses – (Atbara + Blue Nile), for different periods

Table 6.12 Monthly and annual flow statistics of the White Nile at Malakal (Mm^3), Period 1900-2002

Malakal	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Average	2490.6	1772.4	1675.3	1525.1	1694.2	2055.4	2558.3	2911.1	3098.6	3384.2	3310.8	3150.2	29,626.1
Stdev	822.6	598.0	507.7	342.6	316.6	307.4	321.3	353.3	423.9	529.0	542.1	701.7	4,928.8
Cvar	0.33	0.34	0.30	0.22	0.19	0.15	0.13	0.12	0.14	0.16	0.16	0.22	0.17
Min	1400.0	1040.0	963.0	860.0	1040.0	1560.0	1978.7	2251.9	2396.5	2180.0	2220.0	1630.0	22,593.0
Max	6060.0	4620.0	4840.0	3070.0	2800.0	2910.0	3500.0	4150.0	5200.0	6090.0	6210.0	6420.0	48,750.7

Table 6.13 Annual flows to and out of the Sudd and estimated Sudd area for different periods

Period	Out	In				
	Malakal Mm^3	Mongalla Mm^3	Ghazal Mm^3	Sobat Mm^3	In-Out Mm^3	Sudd-area km^2
1900-2002	29,626	35,805	11,663	13,147	30,989	27,278
1900-1961	27,388	27,897	12,122	13,338	25,969	22,859
1962-2002	33,010	47,764	10,969	12,857	38,580	33,961

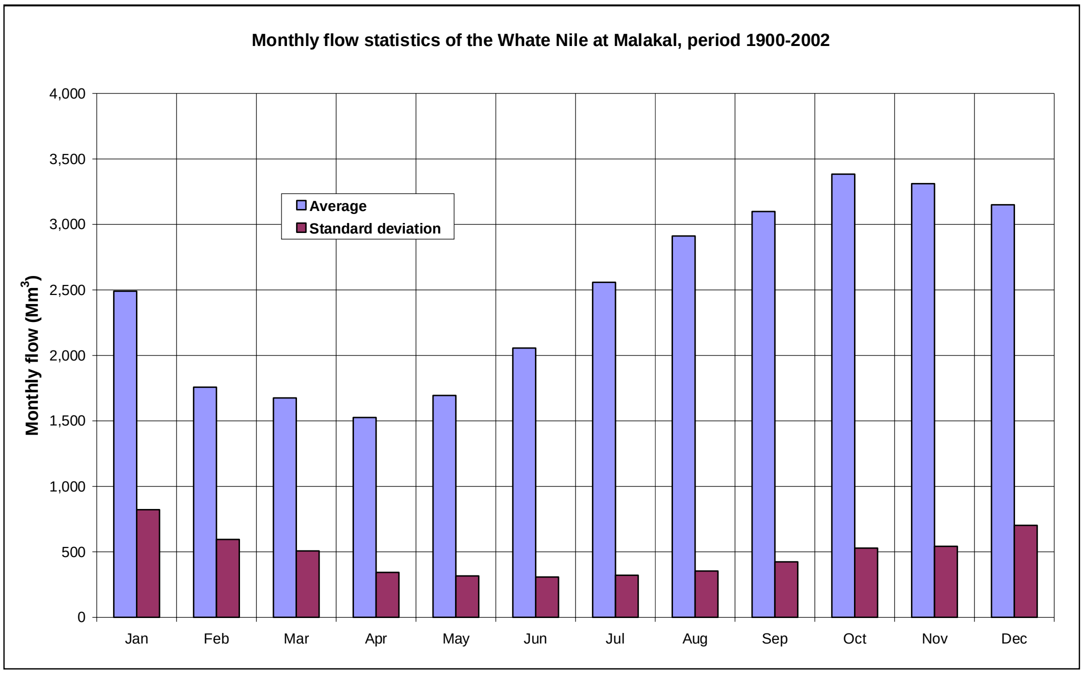

Figure 6.37 Mean and standard deviation of monthly flow of White Nile at Malakal, period 1900-2002

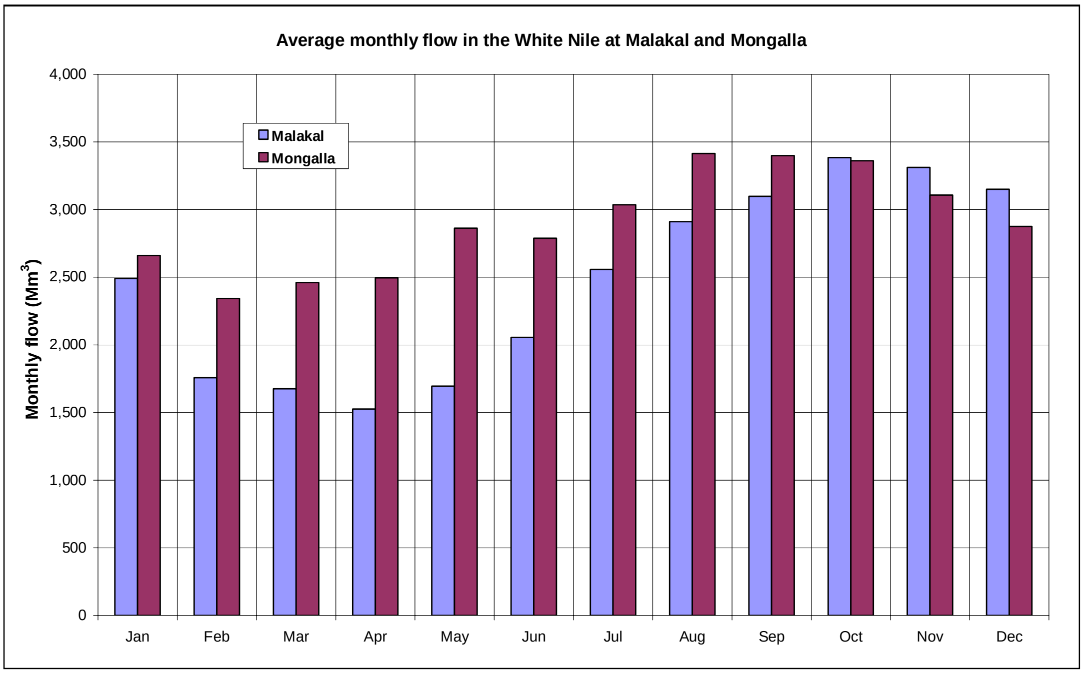

Figure 6.38 Average monthly flow in the White Nile at Malakal and Mongalla

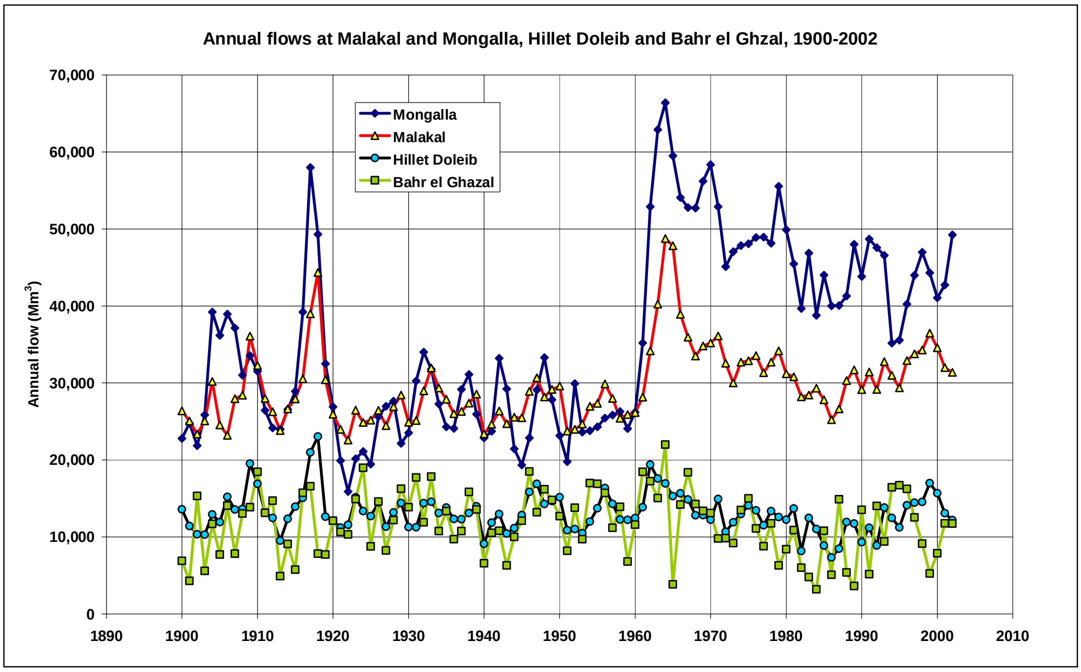

Figure 6.39 Annual flow in the White Nile at Malakal and Malakal, Bahr el Ghazal and the Sobat at Hillet Doleib, period 1900-2002

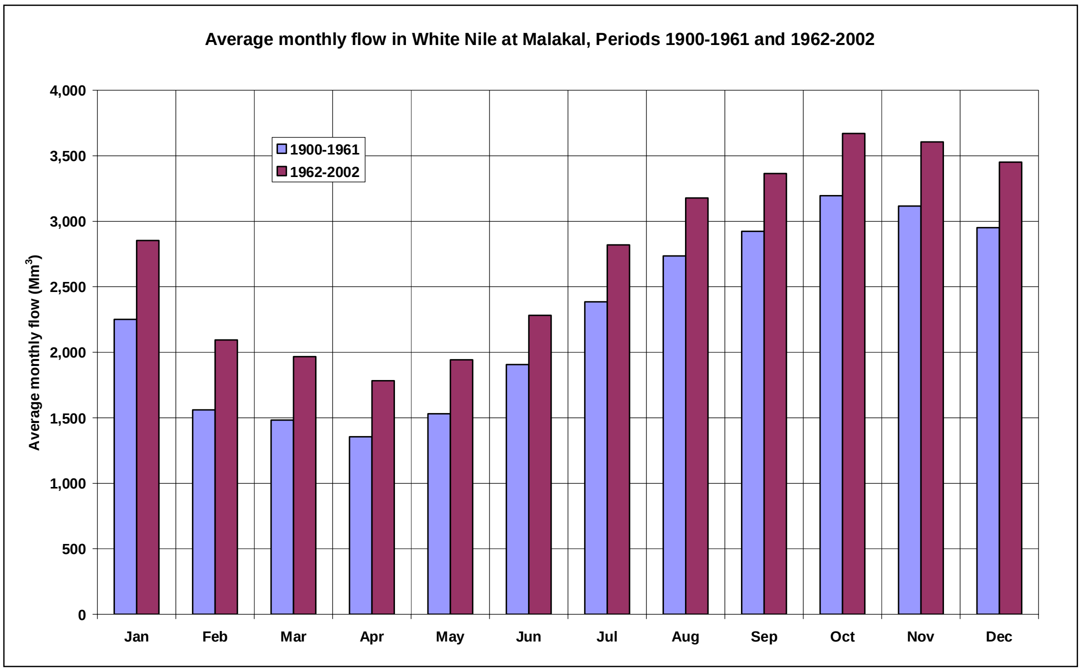

Figure 6.40 Average monthly flow in White Nile at Malakal for the periods 1900-1961 and 1962-2002

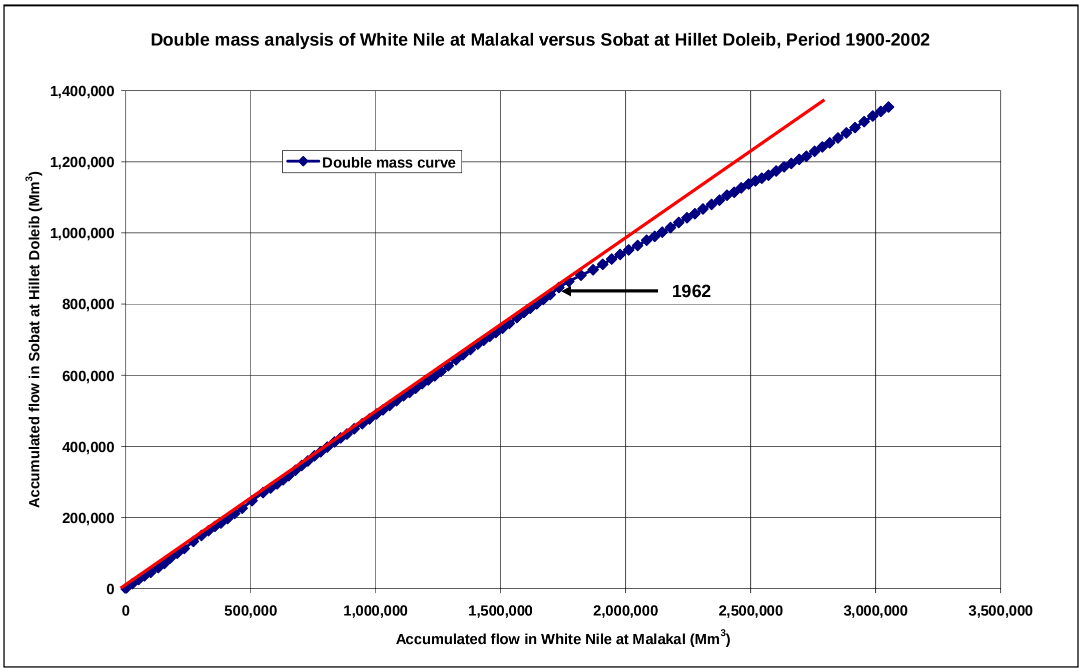

Figure 6.41 Double mass analysis of White Nile at Malakal versus Sobat at Hillet Doleib, Period 1900-2002

6.3 Abay-Blue Nile sub-basin

6.3.1 Blue Nile overview of flow extension/completion procedure

The flow series of the Abay/Blue Nile and its tributaries are largely based on the flows observed at:

- Khartoum on Blue Nile
- Hawata on Rahad
- Gwasi on Dinder
- Roseires/Deim on Blue Nile
- Guder DS on Abay
- Kessie on Abay, and
- Bahir Dar on Abay.

With respect to the Blue Nile in Sudan the flow series of Khartoum published by the Nile Control Staff covers the full period 1900-2002. As of 1925 the Khartoum observations have to be adjusted for irrigation water abstraction to arrive at natural flows. At Roseires observations started in 1912. These series have been extended backward to 1900 based on Khartoum, corrected for inflows from Dinder and Rahad and river evaporation losses. With the operation of Roseires reservoir in 1966 the measurement of the Blue Nile inflow to Sudan was shifted to the border gauging station Deim, where the monitoring continued ever since. The Roseires flows prior to 1966 have been transferred to Deim to create a complete natural flow record at Deim for the period 1900-2002. Between Roseires and Khartoum on Dinder and Rahad observations started in respectively 1907 and 1908. Records at the two sites Gwasi and Hawata are available until 1961 from the Nile Control Staff. The series have been completed by data from the Nile DST database until 1977 and by regression on natural flows at nearby stations.

In Ethiopia an almost complete record is available for the Abay at Kessie as from 1954 onward. NORPLAN (2006) completed these records and transferred the data to Guder DS, at the location where the Karadobi dam site was proposed, based on recorded flows in the years 1961-1969. In the completion of the records also use has been made of the series at Deim/Roseires. For Bahir Dar at the outlet of Lake Tana oldest records are available for the period 1920-1933. Thereafter only records are present as from 1973 onward, which were used by NORPLAN (2006). For ENSWM use has been made of the NORPLAN data presented for Bahir Dar, Kessie and Guder DS for the period 1954-2003. Series have been extended backward to 1900 by using monthly regression equations between Guder DS and Deim and subsequently for Kessie and Bahir by monthly regression on Guder DS. The partitioning of the flow between Guder DS and Deim has been based on basin area and average annual rainfall. Inflows to Lake Tana have largely been based on the outflow record at Bahir Dar and the Lake Tana water level-outflow relation. With these quantities the storage change of the lake has been reconstructed and together with an assumed fixed monthly evaporation pattern the lake inflow and lake rainfall sum has been derived. The latter two have been partitioned based on relations developed from estimated inflow and observed lake rainfall, estimated evaporation, observed storage change and outflow for the period 1964-2004.

A detailed description of the applied procedures is presented in the following sub-sections. The Abay/Blue Nile flows are discussed from upstream to downstream for hydrological consistency, though the actual computational procedure basically ran from downstream to upstream. The applied methods ensure consistent values at the various key locations, but may be less accurate for smaller upstream parts of the sub-basins. To improve on the partitioning the modeller may update the flows by making use the monthly flow statistics available for a number of locations from the Master Plan study for the Abay (BCEOM. 1998) relative to the partionined flows applied in ENSWM. The required procedure is presented as well.

6.3.2 Blue Nile at Lake Tana

ENSWM requires inflow series to Lake Tana. The ENTRO database for Abay-Blue Nile contains flow series of basins draining to Lake Tana, covering the period 1960-2005. The series are assumed to have been derived from rainfall, but details are missing. The average annual runoff is presented in Figure 6.42, whereas in Figure 6.51 the average monthly distribution is shown. The latter figure shows that all follow the same monthly pattern with the peak in August, only the intensities differ. The annual flows are to be compared with the annual rainfall distribution around Lake Tana, which is given in Figure 6.44 (Water Works Design & Supervision Enterprise, 2007). The isohyets indicate that highest rainfall occurs in the upper regions of the basins to the south and the east of the lake; the rainfall in the basins to the west and the north is considerably less. Note that the reference evapo-transpiration around Lake Tana is approximately 1400-1500 mm/year. The rainfall distribution is approximately reflected in the annual runoff pattern presented in Figure 6.50, though the large differences between Ribb and Gumero runoff is not in line with the presented isohyets. Similarly, the large runoff in parts of the Gilgel Abay basin as well as the low runoff for the Gelda is in conflict with the average annual rainfall pattern. It has therefore been decided not to include this database in ENSWM but to make use only of the overall features, including the monthly pattern and approximate spatial runoff distribution.

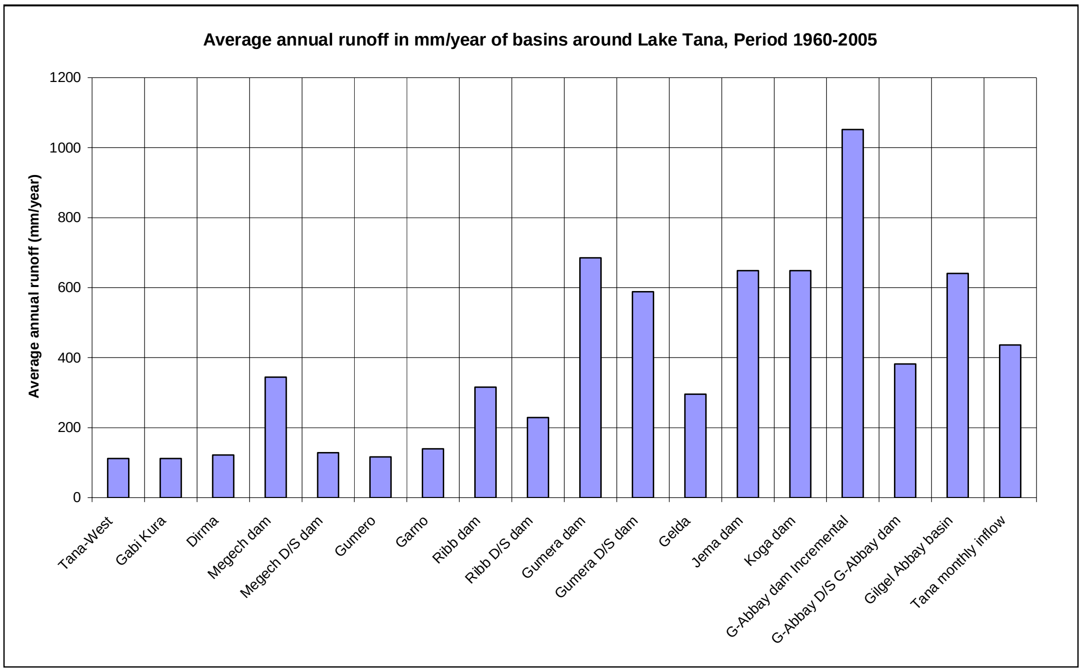

Figure 6.42 Average annual runoff (mm/year) of basins around Lake Tana, Period 1960-2005 (ENTRO database)

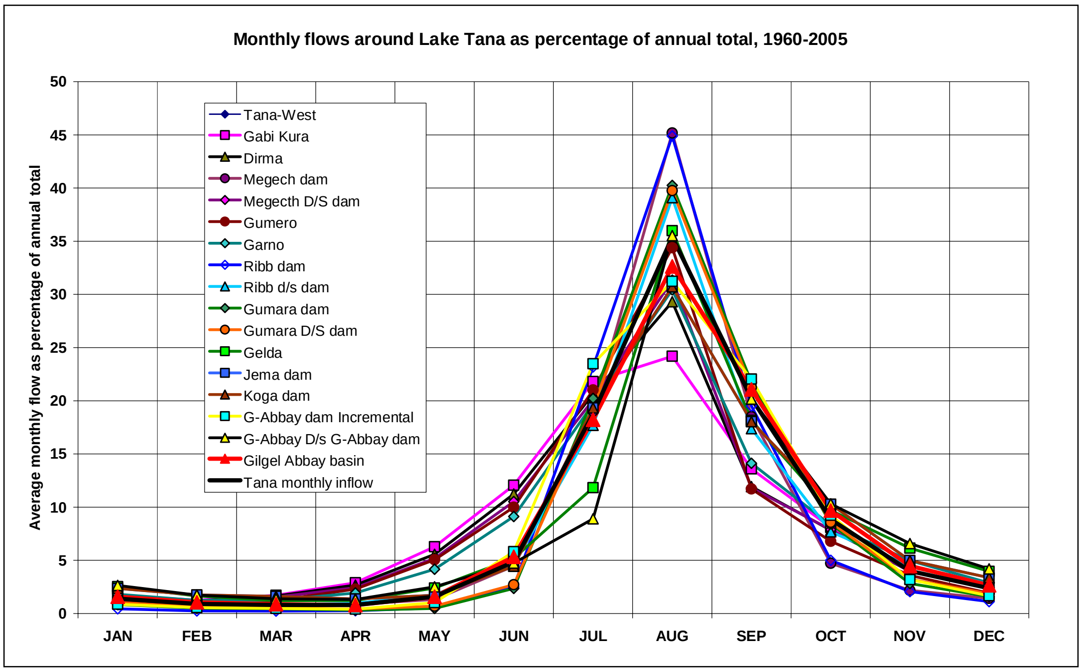

Figure 6.43 Monthly flows of basins around Lake Tana expressed as percentage of annual flow (ENTRO database)

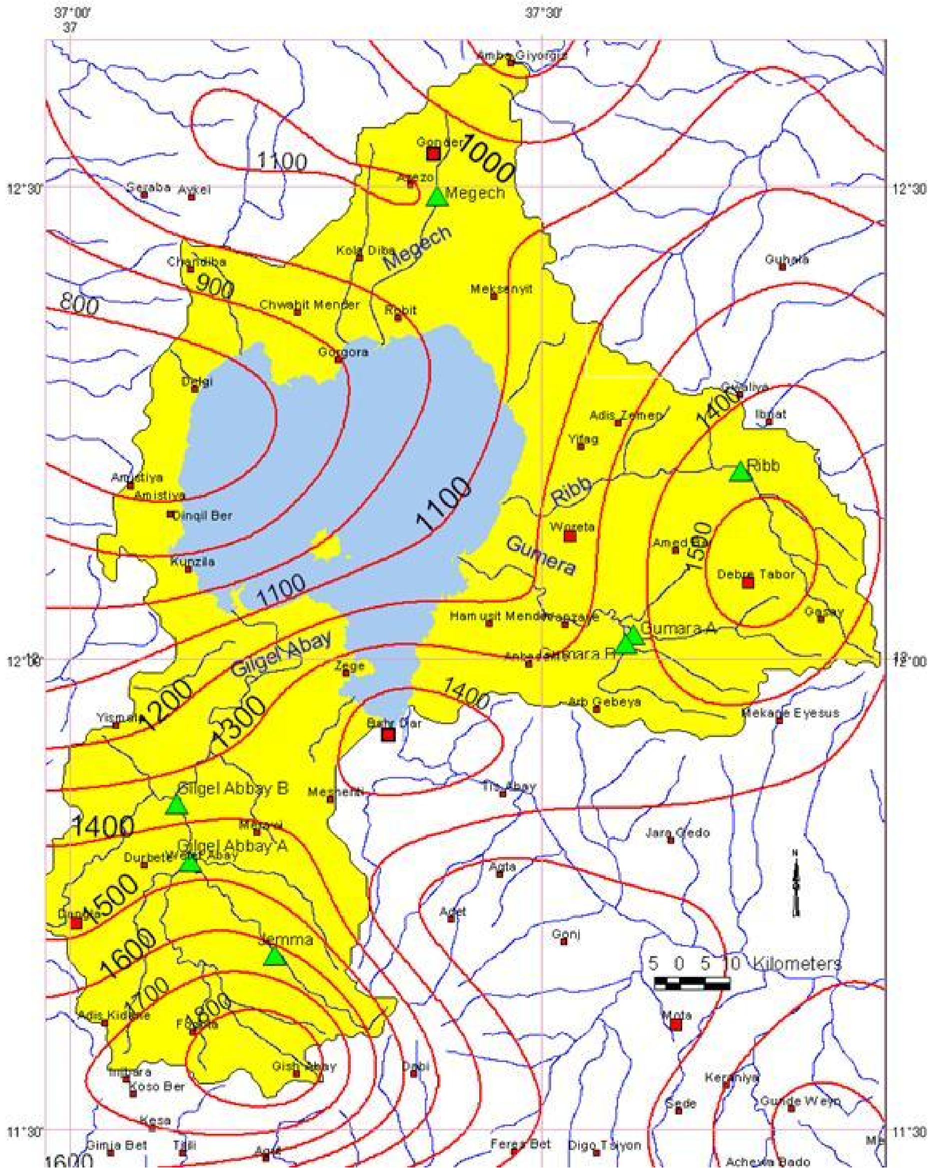

Figure 6.44 Annual rainfall around Lake Tana (Water Works Design & Supervision Enterprise, 2007)

The average monthly inflow (period 1964-2003), as can be derived from water balance analysis of Lake Tana, is presented in Figure 6.53 based on:

- Net lake rainfall derived from observed rainfall over the lake at the average of Gonder and Bahir Dar and computed open water evaporation from FAO reference evapo-transpiration times 1.15;
- Observed end of month water levels of Lake Tana to compute monthly storage changes, and
- Observed/estimated outflow from Lake Tana in the Abay at Bahir Dar.

It is observed that the lake strongly attenuates the inflow by shifting the peak from August to September-October and reducing the peak value by more than 50%.

In the figure also the average monthly inflow from the inflow series available in the ENTRO database is shown. It can be observed that the water balance derived inflow closely resembles the inflow distribution from the database series.

In Figure 6.55 the estimated annual Lake Tana inflows resulting from the databaseseries and from the lake water balance calculations are compared. It is observed that the variability in the water balance derived inflow series is slightly higher than in the database series, but the double mass analysis of the series as presented in Figure 6.56 shows acceptable overall consistency between the series. The difference between the series, however, indicates that application of the database series will not accurately reproduce the observed/estimated lake outflow series at Bahir Dar.

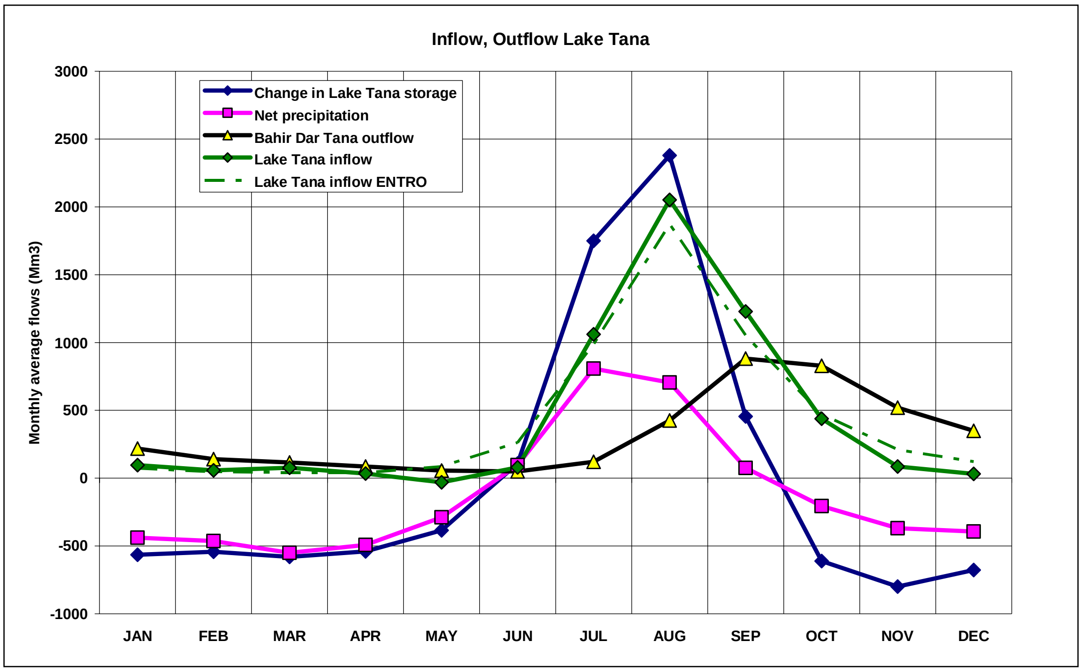

Figure 6.45 Lake Tana inflow, net rainfall, storage change and outflow for the period 1964-2003

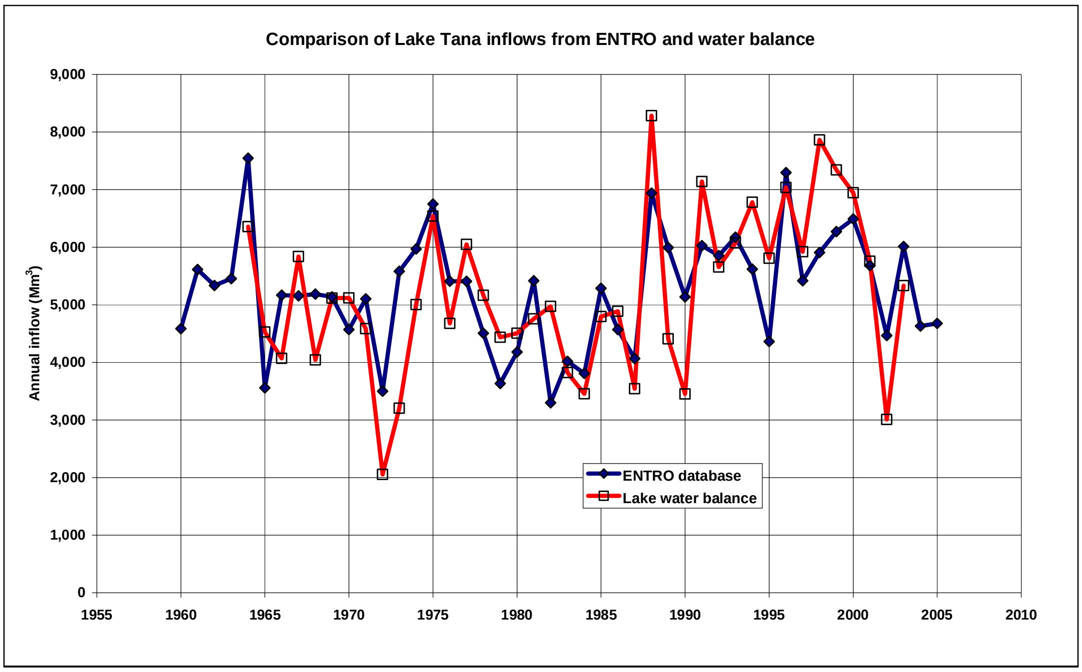

Figure 6.46 Comparison of Lake Tana inflows from ENTRO database and water balance

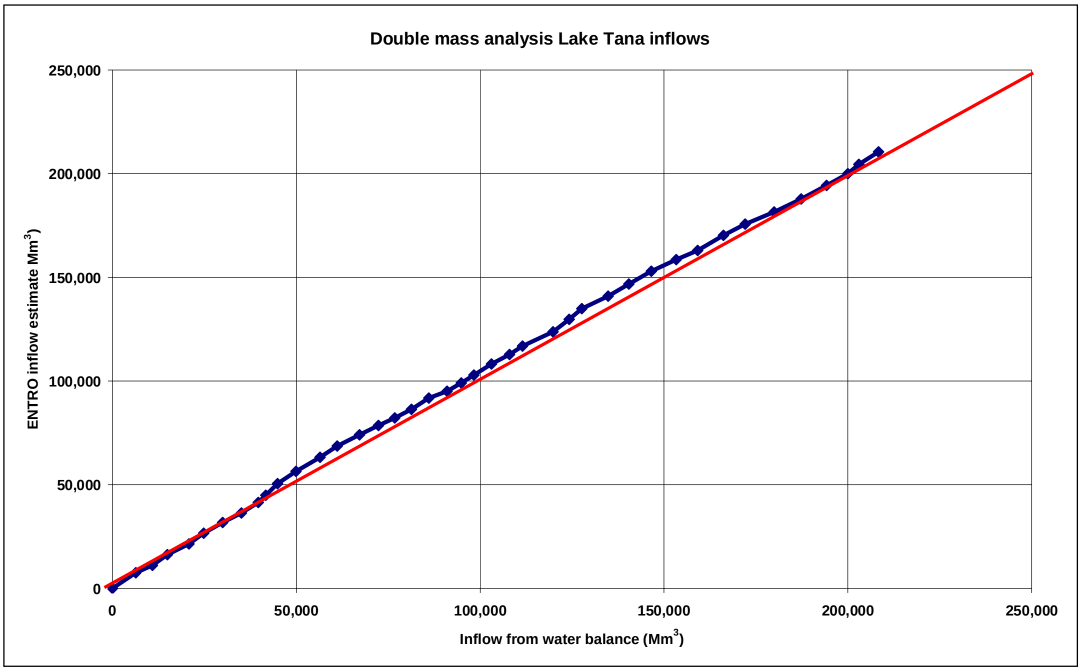

Figure 6.47 Double mass analysis of Lake Tana inflow from water balance and database, Period 1964-2003

The monthly distribution and annual flows as applied in recent feasibility studies for Megech and Gumero irrigation projects have been compared in Figure 6.57 with the monthly averages and annual flows that can be derived from the ENTRO database series. It is seen that the average monthly pattern (apart from the peak value for Megech) is similar. The annual flows though differ substantially for a number of years. Some uniformity, which also is consistent with Lake Tana outflows, is therefore required, to make results comparable.

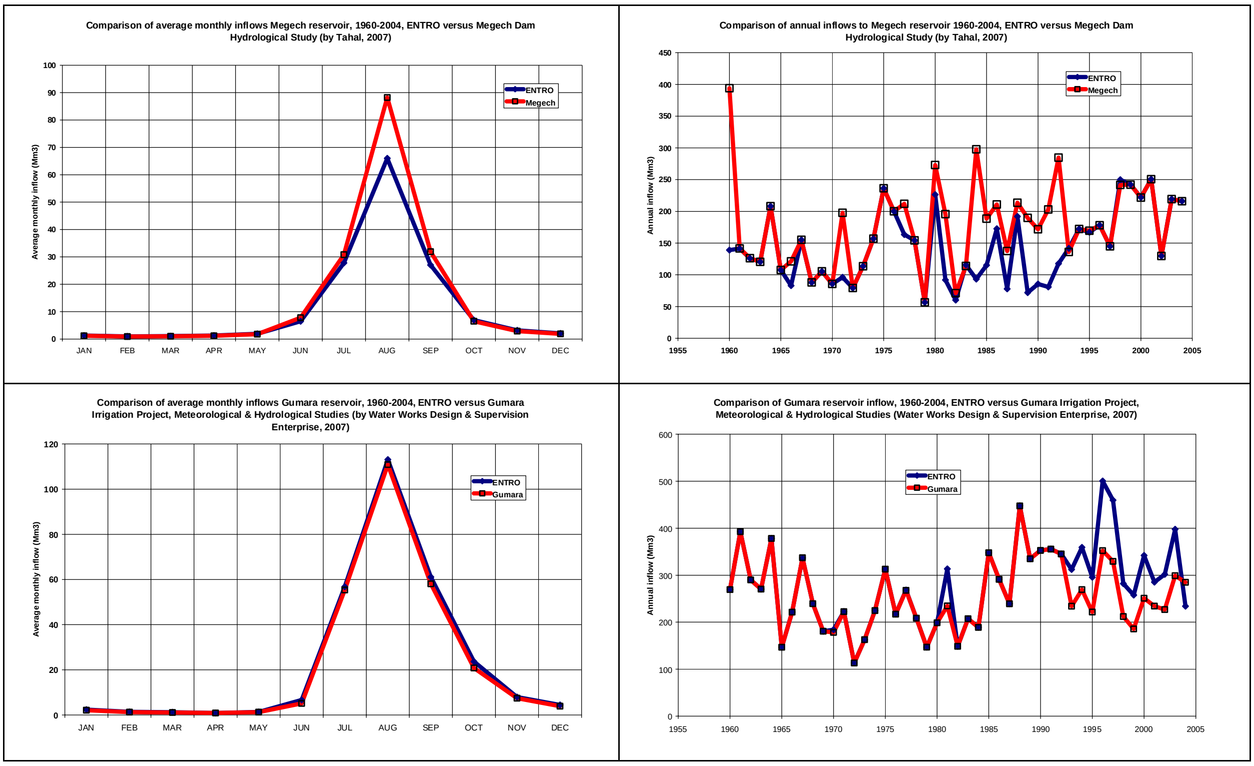

Figure 6.48 Comparison of monthly flow patterns and annual flows as applied in recent feasibility studies for Megech and Gumero irrigation projects with ENTRO database series

To ensure overall consistency, the inflow series used for ENSWM is based on the Lake Tana water balance, which reads:

$$dV = (I + (P - E)A - O)\,dt \qquad (6\text{-}11)$$

where:

- dV = increase in lake storage in dt (Mm3)
- I = inflow to the lake (Mm^3/dt)
- P = rainfall on the lake (mm/dt)
- E = open water evaporation E_0 from the lake (mm/dt)
- A = lake area (10^{-3} km^2)
- O = lake outflow at Bahir Dar (Mm^3/dt)
- dt = computational interval, here taken as 1 month

The outflow series (Abay at Bahir Dar) is available for the period 1900-2002, see Subsection 6.3.3. The lake water level and hence lake storage and surface area can be estimated from the lake outflow, using an inversed discharge rating for Lake Tana derived from observed lake levels and Bahir Dar flows:

$$H_t = a\,(O_t - b)^c + H_0 \qquad (6\text{-}12)$$

where:

- H_t = lake water level in month t (m+MSL)

O_t = lake outflow in month t (Mm^3)

a,b,c = coefficients

H_0 = reference level (m+MSL)

The coefficients of equation (6-12) have been derived from mean monthly lake levels and lake outflow for the period 1959-1979, which proved to be a stable relation and which can also be considered representative for earlier years.

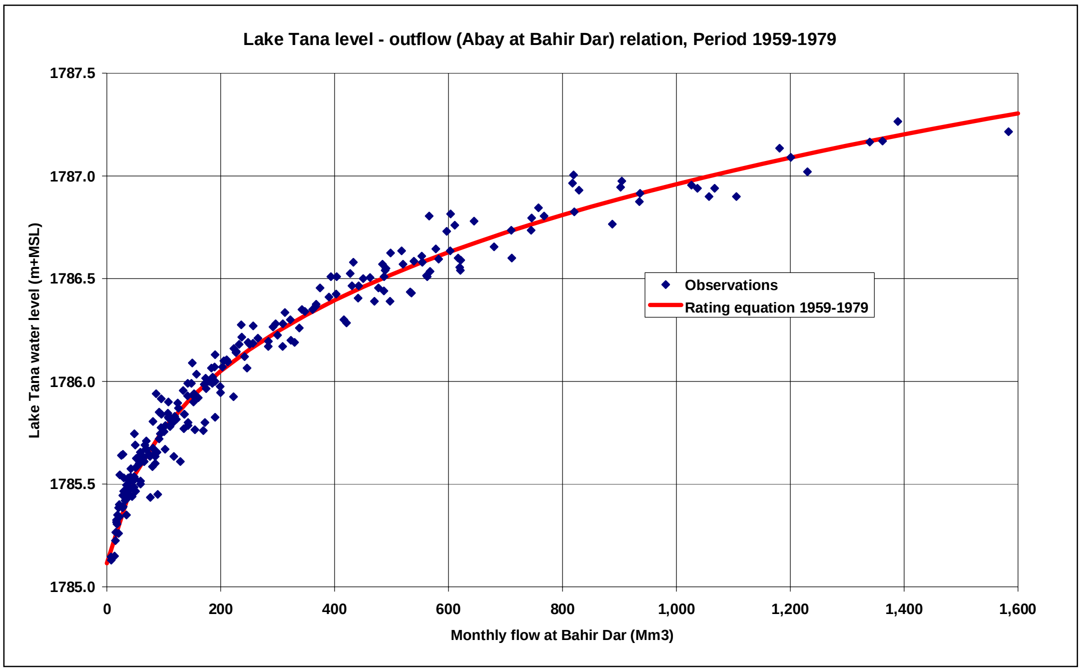

Figure 6.49 Lake Tana water level – Abay at Bahir Dar flow relation, Period 1959-1979

The applied coefficients read:

- *a* = 0.571
- *b* = -16.7
- *c* = 0.238
- H_0 = 1784 (m+MSL)

Lake Tana surface area and Lake Tana volume have been estimated from:

$$A_{Lake\ Tana}\ (ha) = 781.21\ (H - 1780)^2 - 2{,}715.1\ (H - 1780) + 297{,}198 \qquad (6\text{-}13)$$

$$V_{Lake\ Tana}\ (Mm^3) = 3{,}059.2\ (H - 1780) \qquad (6\text{-}14)$$

The inflow to and rainfall on Lake Tana are calculated from (6-11) as follows:

- Monthly flow series of Bahir Dar as available from 1900-2002.
- Compute Lake Tana mid-monthly water levels from (6-12).
- Calculate end of month lake levels as average of successive mid-month levels.
- Calculate end of month volume and storage change.
- Determine lake area from mid-month water level.
- Calculate monthly evaporation from E_0 times lake surface area.

- Calculate lake inflow *I* and rainfall *P.A* from sum of lake evaporation *E.A*, lake outflow *O* and storage change *dV.*
- Remove possible negative monthly values and adjust total for correct annual total.
- Calculate annual and monthly inflows using the relations and coefficients of Table 6.14. The annual flow (see Figure 6.59) as well as the monthly flows from April to October are computed from the water balance components evaporation, outflow and storage change (= inflow and lake rainfall sum) and thereafter the monthly flows are determined as a function of the flow in the preceding month to properly include flow recession.
- Adjust monthly inflow values for calculated annual total and observed average monthly flow distribution.
- Determine lake rainfall from the observed and estimated the water balance components.
- Remove negative rainfall values and adjust monthly values to the correct annual total; this series replaces the estimated lake rainfall series of the period 1964-2003 based on the average of Gonder and Bahir Dar.

Table 6.14 Regression equations used to compute annual and monthly inflows from lake inflow and rainfall sum

Month/year	**$I_t = a\, I_{t-1}$**		**$I_t = a\,(E.A + O + dV)_t + b$**	
	a	**b**	**a**	**b**
Year			0.6571	-770.6
January	0.574	0.0		
February	0.637	0.0		
March	0.851	0.0		
April			0.172	19.0
May			0.180	23.4
June			0.344	-11.0
July			0.412	-30.6
August			0.702	-165.8
September			0.712	-46.6
October			0.570	53.0
November	0.424	0.0		
December	0.583	0.0		

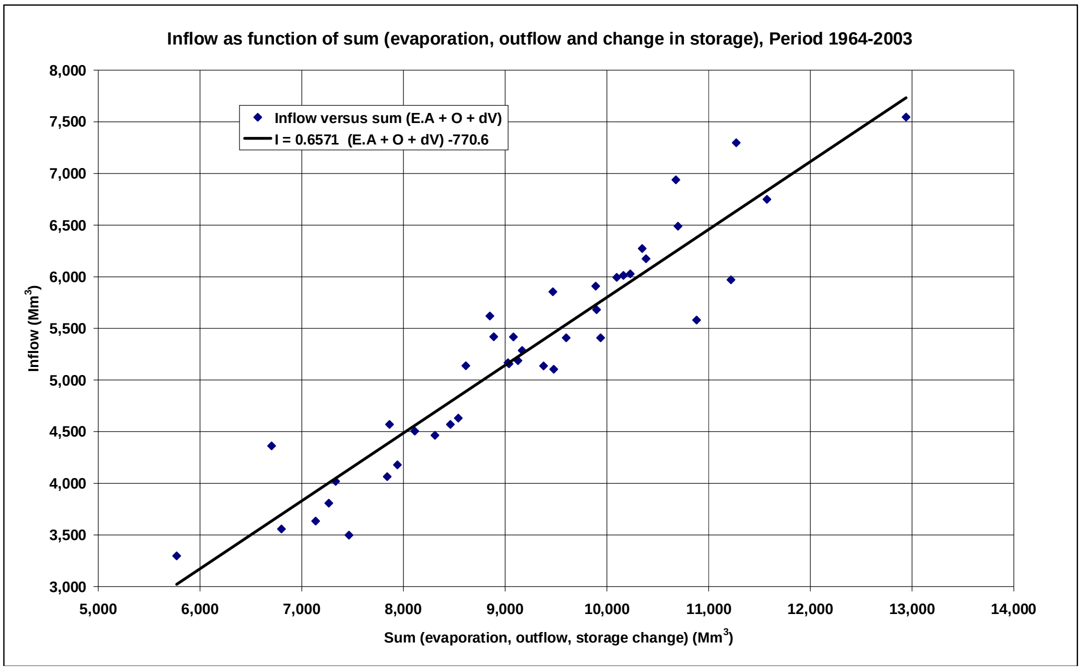

Figure 6.50 Annual inflow as function of water balance components evaporation, outflow and storage change, Period 1964-2003

The resulting annual inflow series compared with the lake outflow is shown in Figure 6.51 and the consistency proof of the two series with double mass analysis is presented Figure 6.70. The monthly and annual lake inflow statistics are presented in Table 6.15 and Figure 6.71. The flow values have subsequently been partitioned for ENSWM according to the scheme given in Table 6.16.This partitioning is in line with the monthly flow distribution as available from the ENTRO database series, with the notification that for Gilgel Abay the differentiation upstream of the dams as available in the series has been ignored to create consistency with the isohyets.

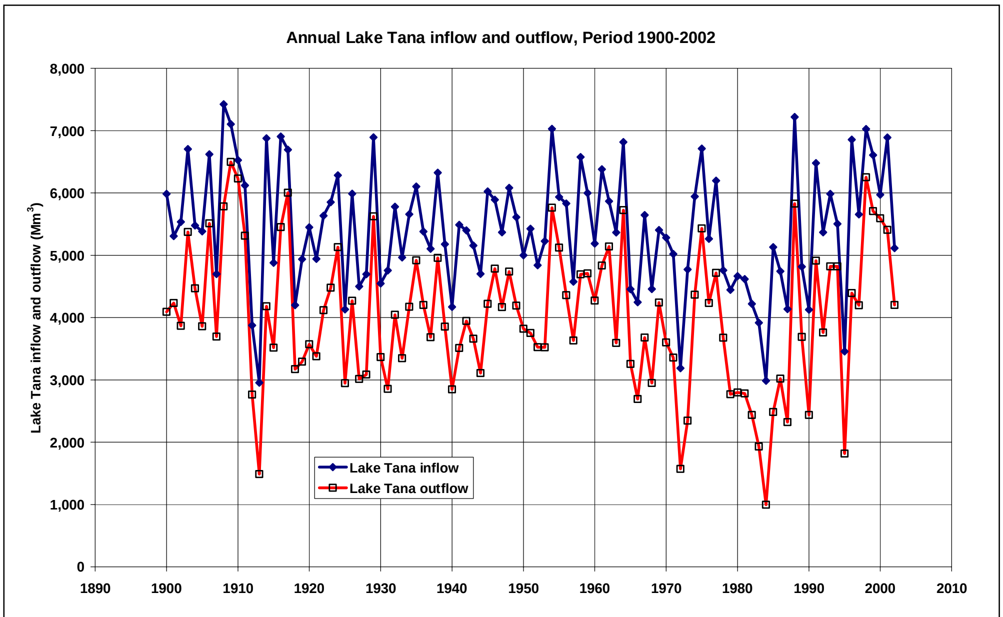

Figure 6.51 Annual Lake Tana inflow and outflow, Period 1900-2002

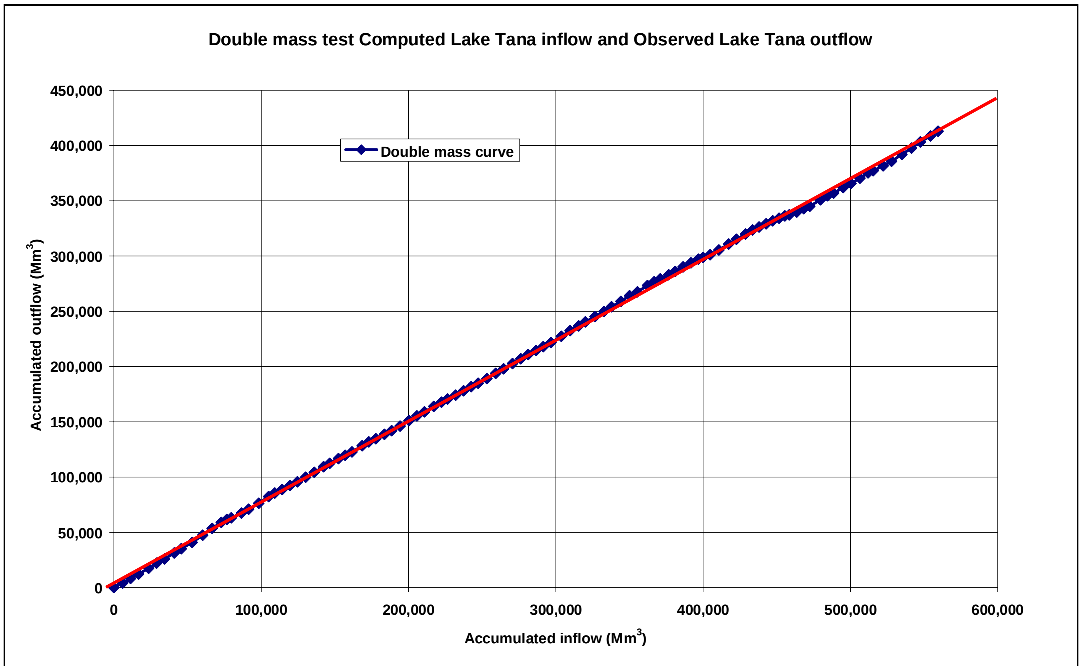

Figure 6.52 Double mass analysis of Lake Tana inflow and outflow, Period 1900-2002

Table 6.15 Monthly and annual flow statistics of the inflow (Mm^3) to Lake Tana, Period 1900-2002

Tana inflow	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Average	97.4	71.2	88.6	59.6	38.2	137.4	1059.0	2049.9	1230.3	443.7	108.6	48.6	5432.3
Stdev	42.3	30.9	38.4	43.4	23.0	58.8	217.8	395.4	313.4	194.3	47.6	21.3	970.6
Cvar	0.43	0.43	0.43	0.73	0.60	0.43	0.21	0.19	0.25	0.44	0.44	0.44	0.18
Min	11.8	8.6	10.7	14.4	9.2	6.8	551.0	947.5	556.9	39.5	9.7	4.3	2953.7
Max	256.3	187.2	233.0	243.7	119.5	352.8	1582.4	2924.4	2152.2	978.3	239.4	107.2	7423.2

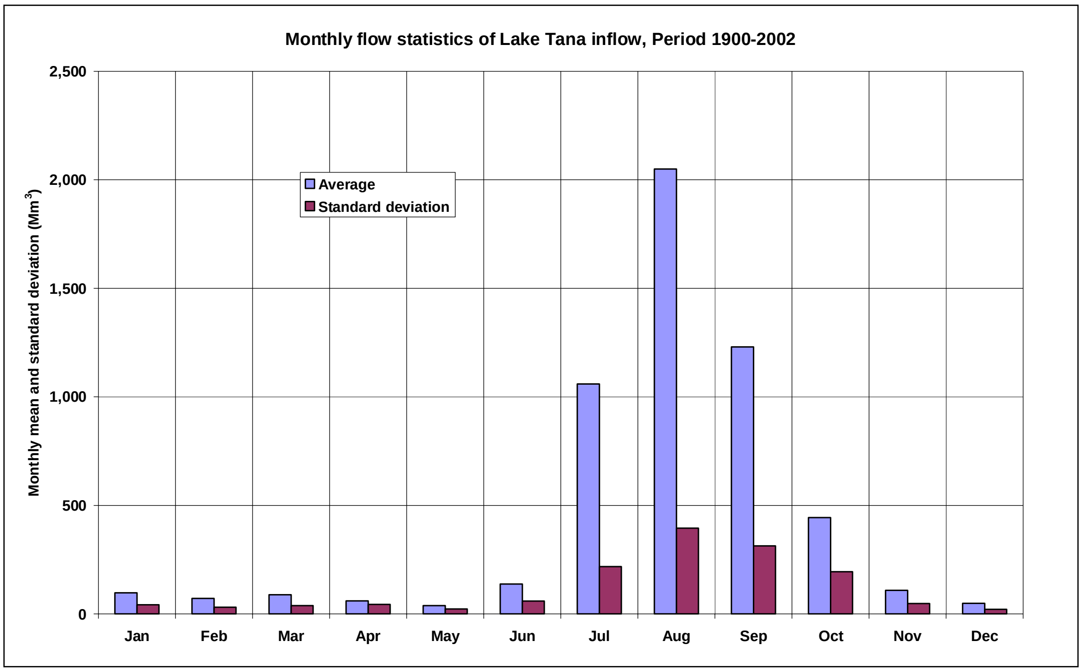

Figure 6.53 Monthly flow statistics of the inflow to Lake Tana, Period 1900-2002

Table 6.16 Partitioning of total Lake Tana inflow to sub-basins upstream and downstream of proposed dams

Sub-basin	Area	Partitioning of inflow (fraction)												
US/DS dams	(km^2)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Gilgel Abay	2,223.8	0.3087	0.3129	0.2973	0.2680	0.2717	0.2990	0.2642	0.2508	0.2833	0.2974	0.3050	0.3059	US dams
Megech	273.73	0.0112	0.0131	0.0167	0.0195	0.0151	0.0165	0.0183	0.0230	0.0165	0.0096	0.0098	0.0108	US dam
Ribb	715.04	0.0137	0.0113	0.0122	0.0139	0.0145	0.0222	0.0533	0.0547	0.0416	0.0244	0.0223	0.0204	US dam
Gumera	376.89	0.0298	0.0266	0.0268	0.0192	0.0149	0.0241	0.0531	0.0561	0.0530	0.0469	0.0349	0.0330	US dam
Rest	8,404.98	0.6365	0.6362	0.6469	0.6793	0.6838	0.6383	0.6111	0.6153	0.6056	0.6217	0.6279	0.6298	DS dams
Total	11,994.44	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	

Note that any other partitioning may be applied when detailed investigations of local conditions so require and can easily be introduced in ENSWM by adjusting the inflows at the concerning model Vif nodes.

6.3.3 Abay at Bahir Dar

Outflow series for Lake Tana at Bahir Dar are available for the periods 1920-1933 and 1973-2003. The latter period was extended in the pre-feasibility study of Karadobi Multipurpose Project (NORPLAN, 2006) to the period 1954-2003 by multiple regression. The series was further extended backwards to 1900 by regression on Guder DS, which series in turn was first completed by regression on the flow record of Deim/Roseires. The regression equations used to complete the Guder DS and Bahir Dar series backward are summarised in Table 6.17.

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The monthly flows statistics of the Blue Nile at Bahir Dar are presented in Table 6.18 and Figure 6.63. The average annual flow at the outlet of Lake Tana is 4,008 Mm^3/yr, whereas it has varied in the period 1900-2002 from 997 to 6,497 Mm^3/yr, see Figure 6.51.

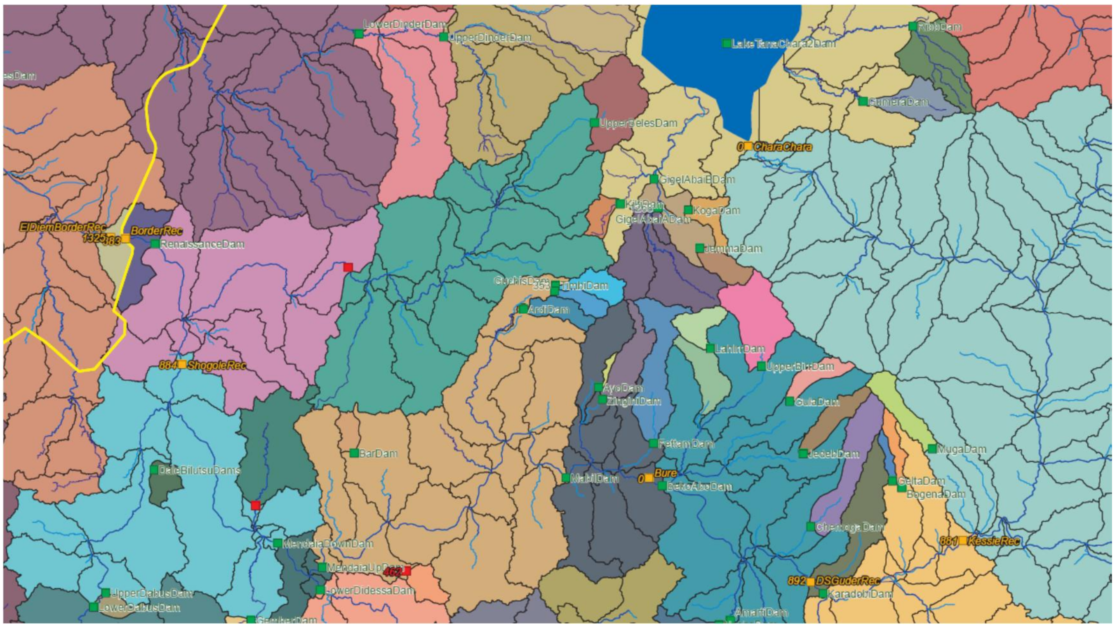

Figure 6.54 Hydrometric stations in Abay sub-basin along the main river

Table 6.17 Regression equations used to extend the series of the Blue Nile at Bahir Dar and Guder DS

Month	$Q_{Guder\ DS} = a + bQ_{Deim}$		$Q_{Bahir\ Dar} = c + dQ_{Guder\ DS}$	
	a	b	c	d
January	0	0.5389	0	0.5261
February	0	0.5514	0	0.5394
March	-76.3	0.8945	0	0.3708
April	0	0.6629	0	0.3701
May	0	0.3756	0	0.2485
June	-262.1	0.3193	0	0.1629
July	-1551.1	0.7137	0	0.0350
August	-504.2	0.5559	-68.3	0.0650
September	-401.8	0.3907	0	0.2278
October	0	0.2719	0	0.4682
November	0	0.3661	0	0.5591
December	0	0.4515	0	0.5823

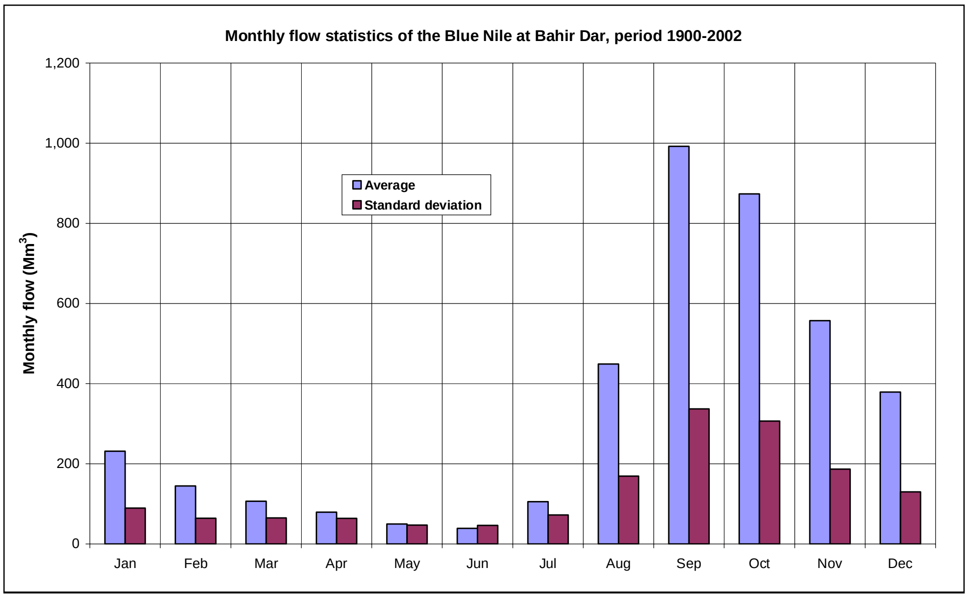

Figure 6.55 Monthly flow statistics of the Blue Nile at Bahir Dar, period 1900-2002

Table 6.18 Monthly and annual flow statistics (Mm^3) of the Abay at Bahir Dar, Period 1900-2002

Bahir Dar	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Average	231.5	146.0	106.8	79.5	49.9	39.1	105.4	448.9	992.0	873.5	557.1	378.9	4008.7
Stdev	89.6	64.6	65.0	63.6	47.0	46.5	72.4	169.3	337.1	306.5	186.8	129.8	1130.8
Cvar	0.39	0.44	0.61	0.80	0.94	1.19	0.69	0.38	0.34	0.35	0.34	0.34	0.28
Min	53.1	38.5	19.4	15.6	7.5	1.6	2.8	87.9	172.4	205.2	141.3	82.6	997.2
Max	555.3	407.2	442.7	453.9	317.1	312.6	539.2	1040.0	1758.9	1522.8	1024.5	823.7	6497.1

6.3.4 Abay at Kessie

At Kessie stream gauging commenced in 1954. NORPLAN (2006) analysed the flow series for the Karadobi pre-feasibility study. The location of the hydrometric station is shown in Figure 6.72. After updating of the discharge ratings the flow record was completed by the Consultants for the period 1954-2003. The record of this station played a key role in the development of inflow series for the various proposed damsites. The series of Kessie has been extended backward to 1900 by means of monthly regression on the extended flow series of Guder DS (near to Karadobi proposed dam site); first and second order polynomials have been applied (see Table 6.20). The resulting flow statistics are presented in Table 6.19 and Figure 6.73 Annual flows in comparion with Lake Tana inflow are shown in Figure 6.74, whereas in Figure 6.75 the results of the double mass analysis are presented, indicating proper consistency between the two series.

Table 6.19 Monthly and annual flow statistics (Mm^3) of the Abay at Kessie, Period 1900-2002

Kessie	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Average	346.7	219.5	211.0	185.6	180.6	203.3	2449.2	6305.3	3350.2	1499.7	844.9	534.4	16330.5
Stdev	108.2	86.7	120.6	102.6	111.1	181.0	1321.1	2051.4	1140.6	511.3	258.7	151.9	4498.6
Cvar	0.31	0.39	0.57	0.55	0.62	0.89	0.54	0.33	0.34	0.34	0.31	0.28	0.28
Min	80.7	56.6	40.7	31.4	36.7	7.7	64.3	973.4	1076.7	409.5	214.4	113.5	4407.7
Max	645.4	606.8	638.5	555.2	515.1	1071.3	6433.5	11351.1	7097.1	2493.9	1343.3	1131.7	25757.9

Figure 6.56 Abay at Kessie (Source: Google Earth)

Table 6.20 Regression equations used to transfer Guder DS to Kessie for period 1900-1953

Month	$Q_{Kessie} = a(Q_{Guder\ DS})^2 + b\,Q_{Guder\ DS} + c$			
	a	b	c	condition
January	-0.00048	1.18446	-70.0	
February		0.8037		
March		0.7771		
April		0.8083		
May	-0.00039	1.02508	-16.9	
June		0.7942		
July		0.8000/0.8742	0.0/-216.9	$Q_{GDS} \leq 800/>800$
August	-0.000059	2.123072	-65449.0	
September	0.0/0.00007	0.7400/0.3059	0.0/562.2	$Q_{GDS} \leq 1455/>1455$
October	-0.00011	1.24658	-397.0	
November	-0.00040	1.67941	-391.0	
December	-0.00069	1.6396	-213.9	

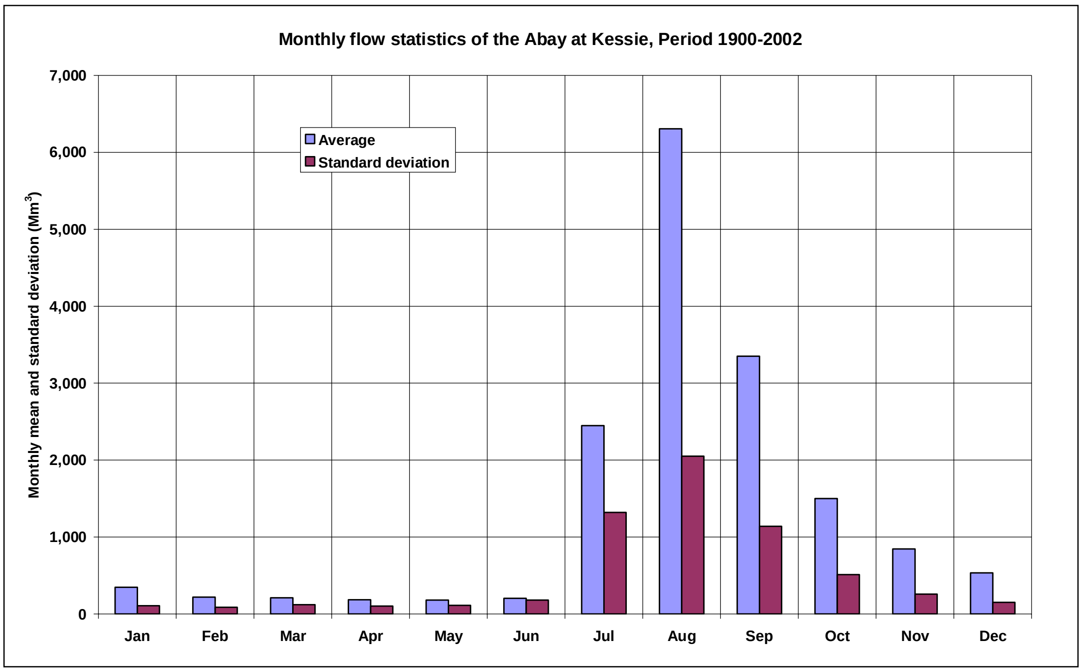

Figure 6.57 Monthly flow statistics of the Abay at Kessie, Period 1900-2002

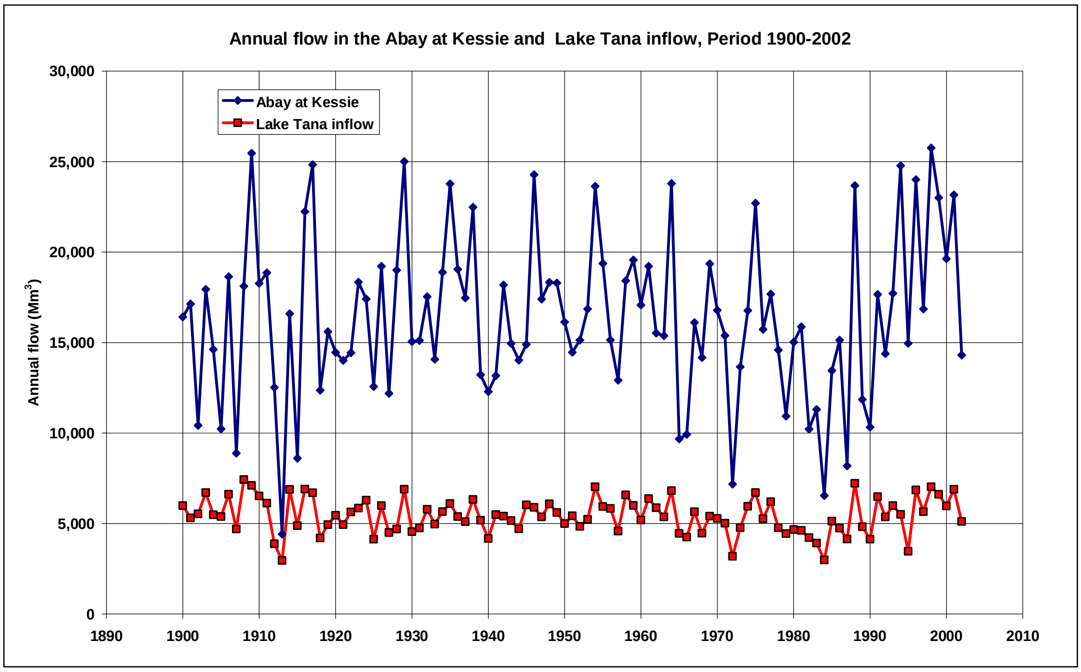

Figure 6.58 Annual flow in the Abay at Kessie and Lake Tana inflow, Period 1900-2002

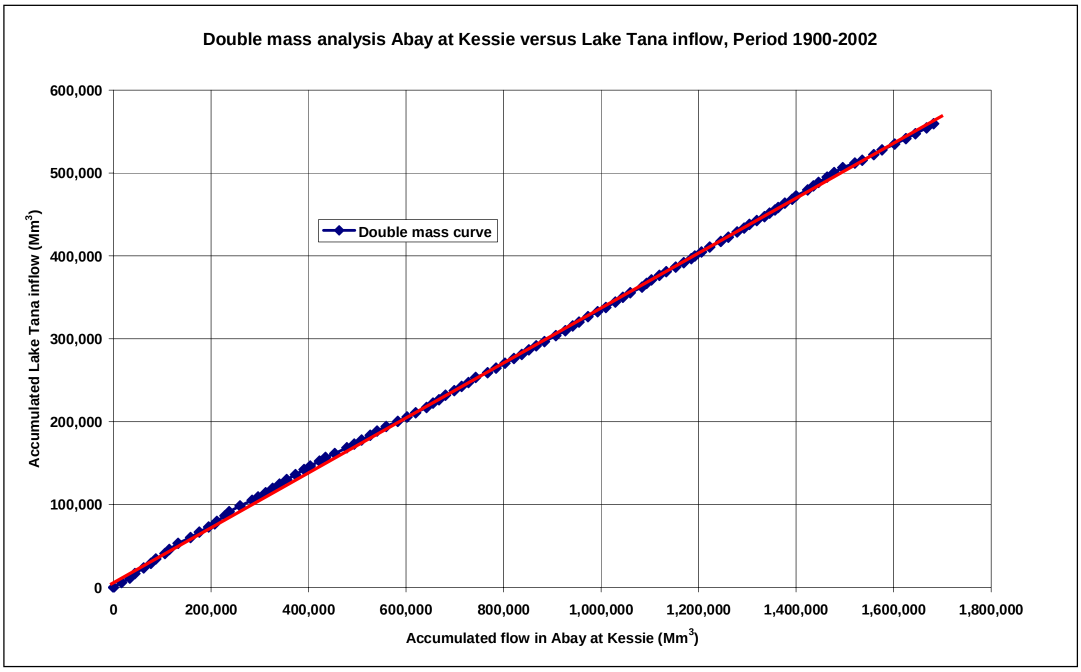

Figure 6.59 Double mass analysis of flows in the Abay at Kessie versus Lake Tana inflow, Period 1900-2002

In ENSWM the incremental flow between Kessie and Bahir Dar has been applied to all Vif nodes of the basins draining to the Abay upstream of Kessie and downstream of Lake Tana. The same procedure has been applied for the reach between Kessie and Guder DS; the incremental flow between the two sites has been attributed to all Vif nodes in this area. Reference is made Sub-section 6.3.6 for alternative procedures.

6.3.5 Abay at Guder DS

The record of station Guder DS, which is located 1 km upstream of the proposed Karadobi dam site, originally covered the period 1961-1969. Through regression on the much longer discharge record of station Kessie and by multiple regression the series of Guder DS was completed for the 50-year period 1954-2003 by NORPLAN (2006), The series was extended backward to 1900 by regression on the series of Deim/Roseires. The regression equations varied per month and are summarised in Table 6.17. Statistics of the Blue Nile at station Guder DS are presented in Table 6.21 and Figure 6.60. The annual flow series at Guder DS are compared with the Abay at Kessie in Figure 6.61. In Figure 6.78 the double mass curve of the flow at Guder DS versus the flow at Kessie is presented. The figure shows that the series are consistent, as expected based on the history of the creation/extension of both series.

Table 6.21 Monthly and annual flow statistics (Mm^3) of the Abay at Guder DS

Guder DS	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Average	439.2	277.1	269.6	230.2	219.3	257.6	3039.2	7852.2	4382.1	1860.9	997.4	650.6	20475.5
Stdev	156.3	105.5	157.8	125.4	147.2	225.9	1527.8	1811.8	1226.6	621.3	316.9	215.4	4745.6
Cvar	0.36	0.38	0.59	0.54	0.67	0.88	0.50	0.23	0.28	0.33	0.32	0.33	0.23
Min	100.9	62.9	52.4	51.1	57.3	9.7	80.4	3121.9	1455.1	573.3	268.0	141.9	7044.6
Max	1055.5	755.0	839.9	695.2	708.7	1332.0	7917.4	13721.4	7721.0	3252.5	1832.4	1414.6	31995.1

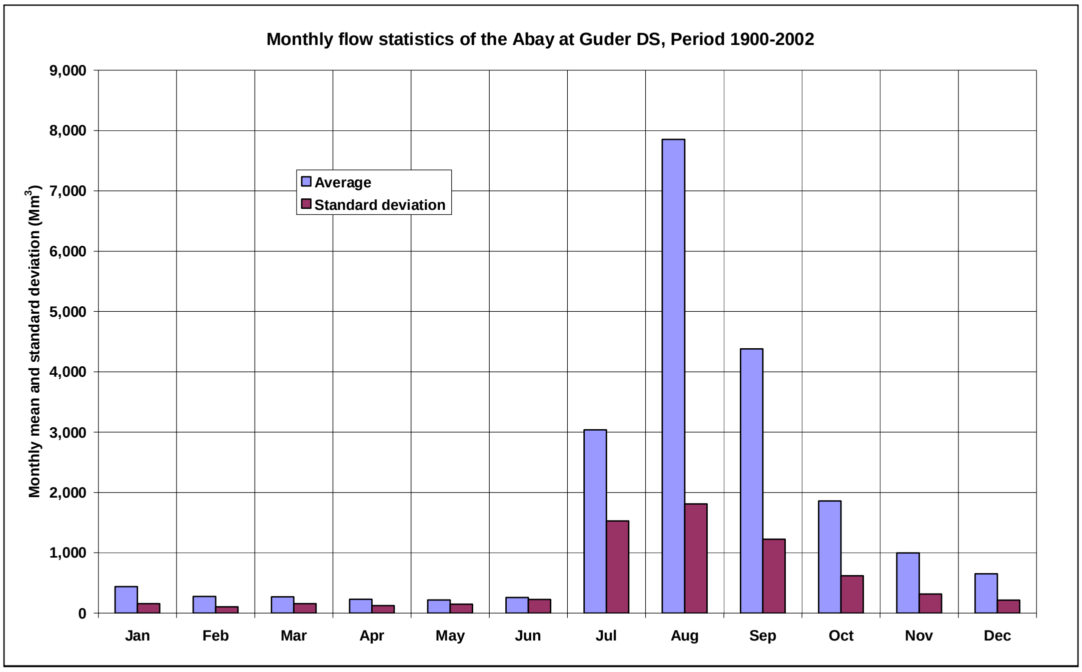

Figure 6.60 Monthly flow statistics of the Blue Nile at Guder DS, period 1900-2002

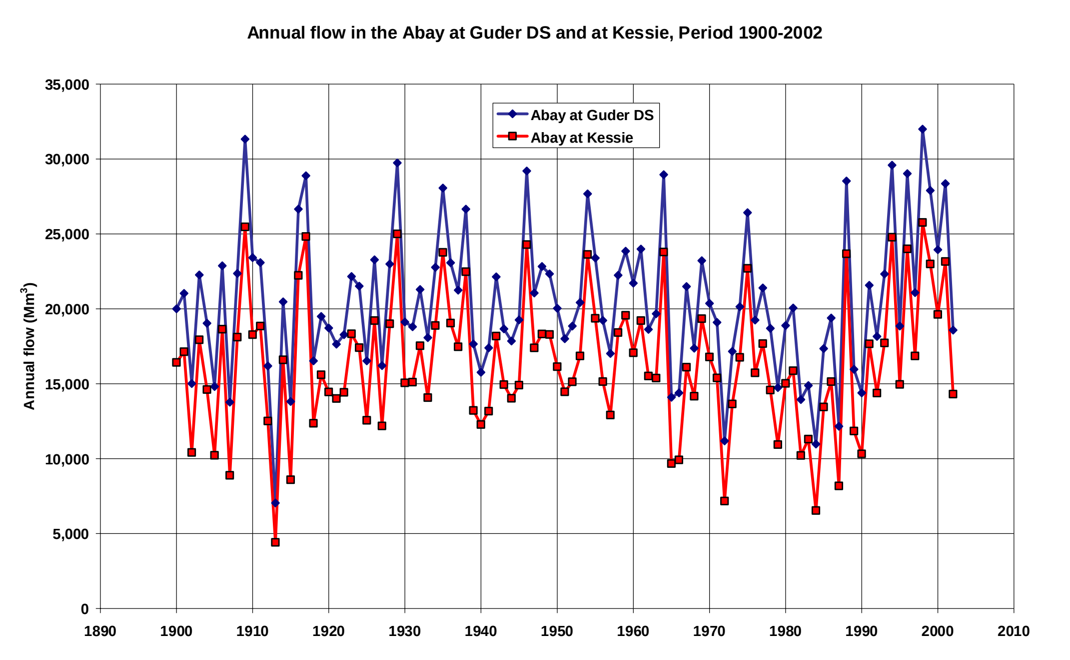

Figure 6.61 Annual flow in Abay at Guder DS and at Kessie, Period 1900-2002

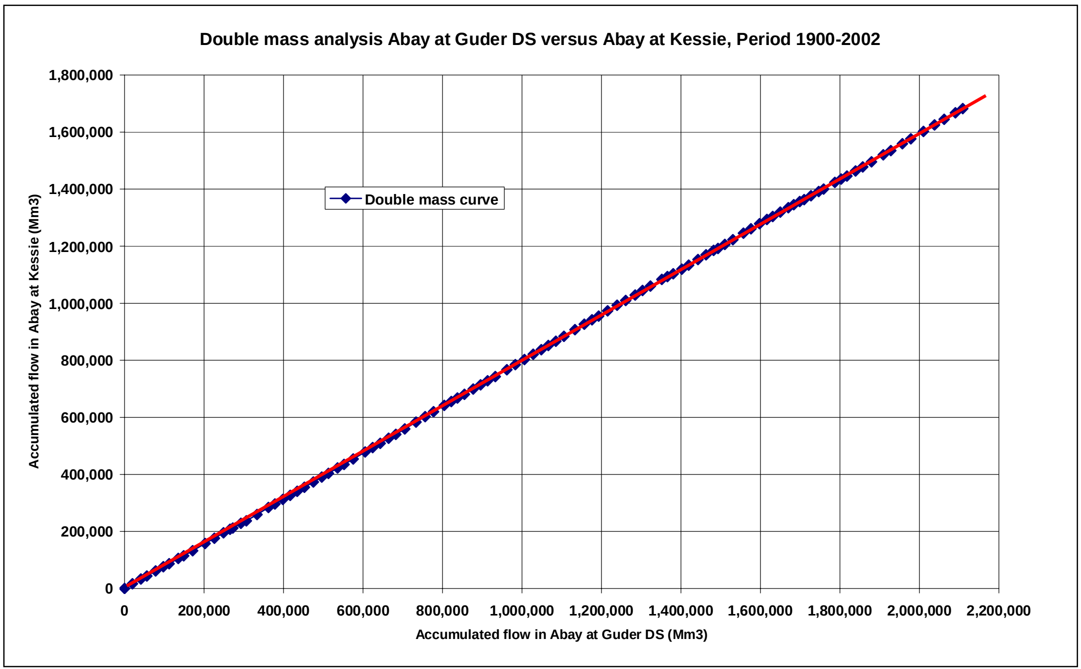

Figure 6.62 Double mass analysis of Abay at Guder DS versus Abay at Kessie, Period 1900-2002

6.3.6 Distribution of flows between Guder DS and Deim

To obtain the series for lateral inflow downstream of Guder DS up to Deim in ENSWM the incremental flow between Guder DS and Deim have been partitioned in accordance with the contributing area and local average annual rainfall, the latter taken from NORPLAN (2011).

The partitioning has been carried out for all developing/potential dam sites that have been investigated in past (pre-) feasibility studies and hydrometric stations Guder DS (= Karadobi dam site), Bure bridge (= Beko Abo dam site), Shogole, Border and Deim on the main stream. The fraction of the incremental flow attributed to each section in presented in Table 6.21.

Table 6.22 Partitioning of incremememental flow between Guder DS and Deim as applied in ENSWM

Section	Rainfall	Area	Fraction of	Annual flow	Ann. runoff
	(mm)	(km^2)	Q Deim – Q Guder DS	(Mm^3/yr)	(mm/yr)
Guder DS – Bure bridge	1395.00	12,554.4	0.114760	3,255.2	259.3
Bure bridge - Mabil	1576.00	4,510.1	0.046576	1,321.1	292.9
Mabil – Upper Mandaia	1550.00	10,816.0	0.109854	3,116.0	288.1
Upper Mandaia - Didessa	1626.00	28,053.2	0.298898	8,478.2	302.2
Didessa mouth - Mandaia	1300.00	655.9	0.005587	158.5	241.6
Mandaia - Shogole	1472.00	19,704.0	0.190057	5,390.9	273.6
Shogole - Renaissance	1472.00	23,442.1	0.226112	6,413.7	273.6
Renaissance - Border	1126.00	795.5	0.005869	166.5	209.3
Border - Deim	1126.00	310.0	0.002287	64.9	209.3
Guder DS - Deim	1513.36	100,841.1	1.000000	28,365.0	281.3

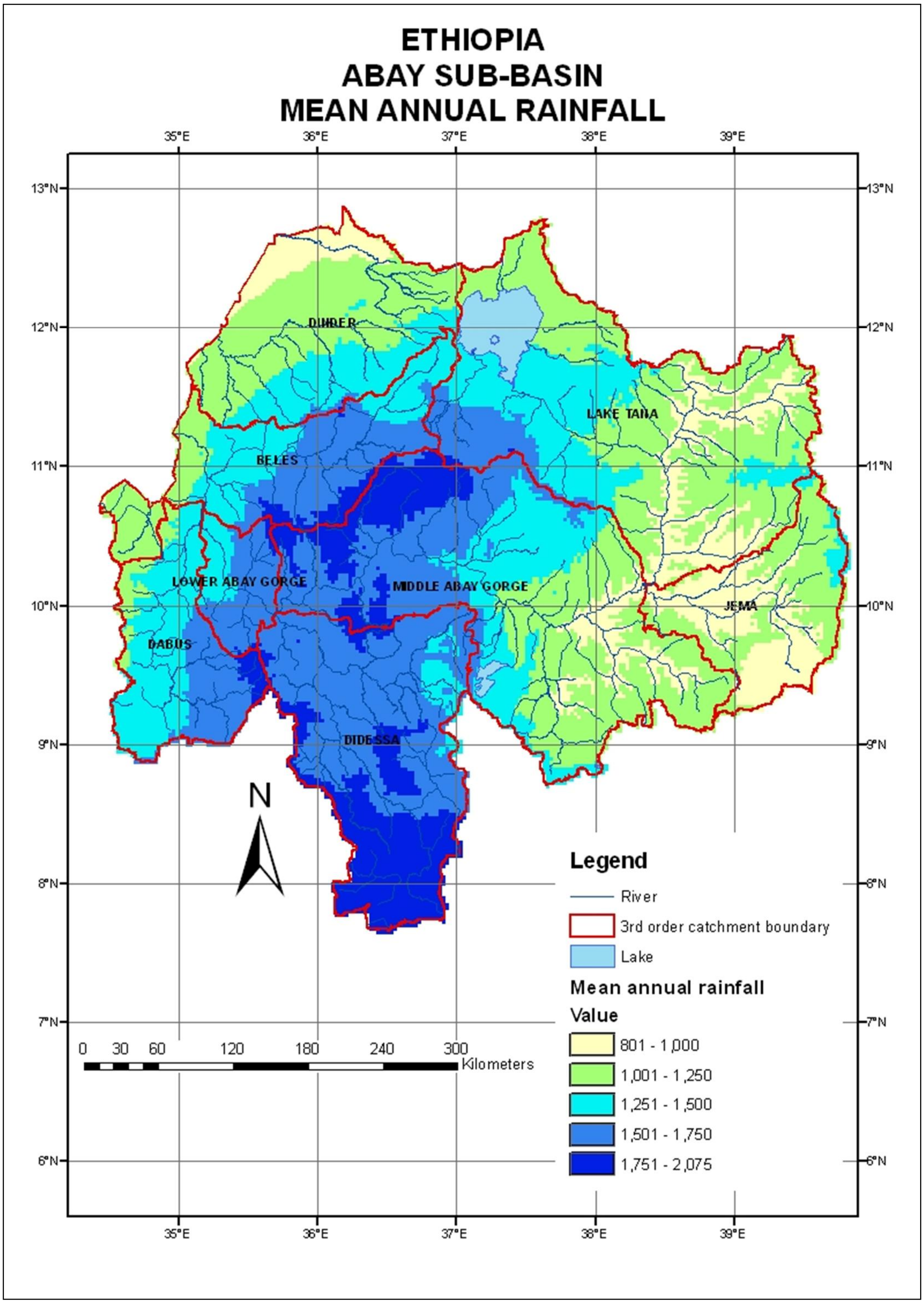

Figure 6.63 Annual rainfall pattern in the Abay basin in Ethiopia (EDF et al., 2007)

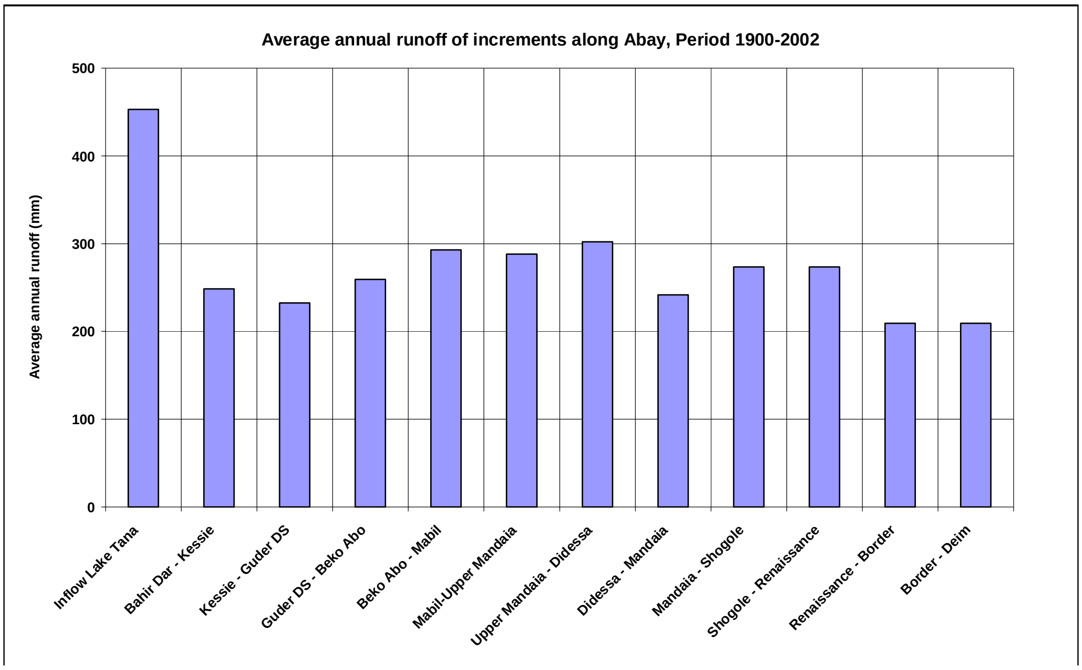

Figure 6.64 Average annual runoff of increments along Abay, Period 1900-2002

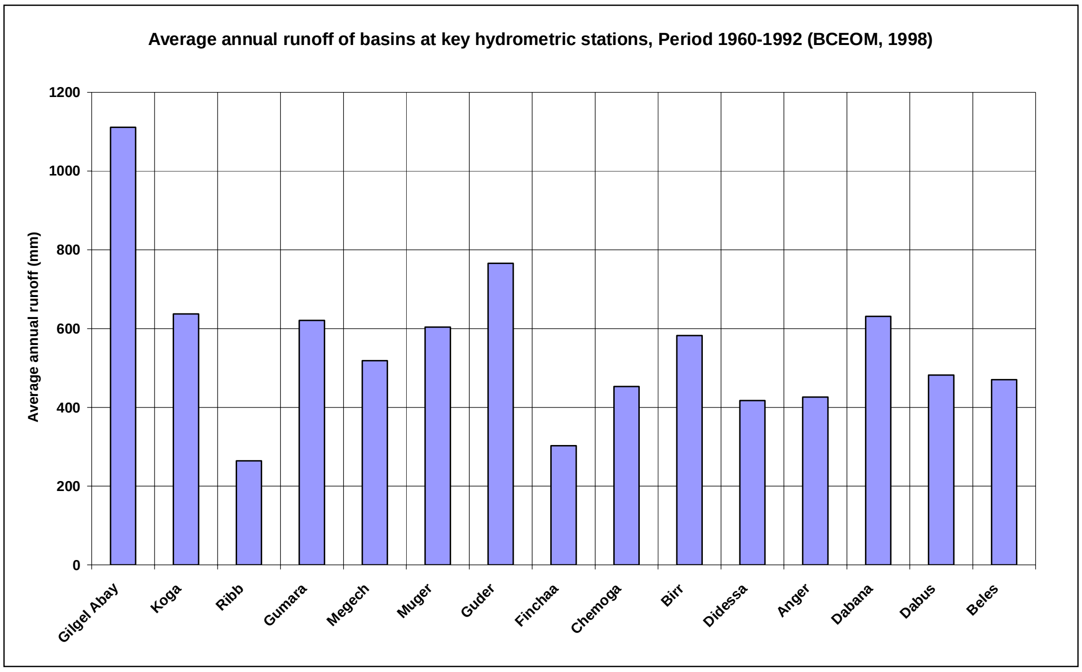

Figure 6.65 Average annual runoff of basins at key hydrometric stations in Abay, Period 1960-1992 (derived from BCEOM, 1998)

The assumption of a uniform runoff per unit area per increment is acceptable for properly estimating the inflow to the reservoirs along the main stream, but is too simple when projects on the tributaries have to be evaluated. From Figure 6.79 it is observed that annual rainfall pattern varies considerably within an increment. This may also be observed from a comparison between Figure 6.80 and Figure 6.81.

Whereas Figure 6.64 represents the assumed distribution following from the partitioning, Figure 6.81 is based on the flow values at the hydrometric stations, which are usually located in the upper reaches of the tributaries, where rainfall is often much higher than in the downstream areas, evaporation less and consequently runoff higher. The quality of the discharge series at the hydrometric stations on the tributaries could not be assessed. The series of the stations presented in the Abay River Basin Master Plan Project, Phase 3 (BCEOM, 1998) generally have a large percentage of filled-in values, whereas the validation of the observations is not given. As applies for all stations in the Nile basin it is necessary to validate the existing series first before these can be used. Tributary flow statistics as derived by BCEOM (1998) are presented in Table 6.22 and Table 6.23.

Table 6.23 Overview of hydrometric stations with flow data in Master Plan Study (BCEOM, 1998)

Code	River	Station	Lat	Long	Area (km^2)	Mm3/year	mm/year
1002	Gilgel Abay	Merawi	11-22	37-02	1,664	1,849.1	1111.2
1003	Koga	Merawi	11-22	37-03	244	155.5	637.2
1005	Ribb	Addis Zemen	12-00	37-43	1,592	420.6	264.2
1006	Gumara	Bahir Dar	11-50	37-38	1,394	865.6	620.9
1007	Megech	Azezo	12-29	37-27	462	239.5	518.4
2002	Muger	Chancho	9-18	'38-44	489	295.2	603.8
3005	Guder	Guder	8-57	37-45	524	401.3	765.9
3007	Finchaa	Shambo	9-33	37-23	1,391	420.9	302.6
3008	Chemoga	Debre Markos	10-18	37-44	364	164.9	452.9
3013	Birr	Jiga	10-39	37-23	978	569.7	582.5
4001	Didessa	Arjo	8-41	36-25	9,981	4,163.9	417.2
4002	Anger	Nekemte	9-26	36-31	4,674	1,992.5	426.3
4005	Dabana	Abasina	9-02	36-03	2,881	1,818.1	631.1
5002	Dabus	Asosa	9-52	34-54	10,139	4,886.7	482.0
6003	Beles	Pawe/Metekel	11-12	36-20	3,474	1,634.8	470.6

Table 6.24 Flow statistics (Mm^3) of Abay tribuarties hydrometric stations used in Master Plan Study, Period 1960-1992 (BCEOM, 1998)

Code	Statistic	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
1002	Average	18.99	12.23	10.42	8.48	17.57	95.80	430.10	576.71	414.23	170.19	61.59	32.81	1,849.1
	Stdv	5.36	2.95	2.76	2.51	9.70	39.89	82.41	70.25	53.50	47.19	23.22	14.84	
	Cvar	0.28	0.24	0.26	0.30	0.55	0.42	0.19	0.12	0.13	0.28	0.38	0.45	
1003	Average	3.56	2.71	2.52	2.07	2.46	5.81	30.51	50.41	28.85	14.09	7.41	5.09	155.5
	Stdv	0.94	0.95	0.86	0.73	1.12	4.12	15.32	20.22	13.35	5.65	2.46	1.69	
	Cvar	0.26	0.35	0.34	0.35	0.46	0.71	0.50	0.40	0.46	0.40	0.33	0.33	
1005	Average	1.39	0.90	0.80	0.83	1.31	7.75	91.47	199.41	85.87	18.75	8.55	3.56	420.6
	Stdv	0.94	0.63	0.75	1.17	1.23	11.64	47.65	81.32	46.34	12.56	9.46	2.41	
	Cvar	0.67	0.70	0.93	1.41	0.94	1.50	0.52	0.41	0.54	0.67	1.11	0.68	
1006	Average	5.97	3.54	3.03	2.10	3.32	12.36	158.48	370.56	197.54	75.61	21.59	11.46	865.6
	Stdv	2.44	1.42	1.93	0.86	2.57	13.87	99.42	100.98	82.68	69.99	10.50	5.20	
	Cvar	0.41	0.40	0.64	0.41	0.77	1.12	0.63	0.27	0.42	0.93	0.49	0.45	
1007	Average	0.62	0.37	0.37	0.62	1.12	8.48	46.63	135.61	37.51	4.87	2.15	1.15	239.5
	Stdv	0.37	0.29	0.32	1.22	1.10	18.46	52.39	95.16	32.58	3.00	1.40	0.72	
	Cvar	0.61	0.80	0.86	1.96	0.98	2.18	1.12	0.70	0.87	0.62	0.65	0.63	
2002	Average	0.72	0.61	0.72	0.86	0.86	1.74	56.84	159.95	62.52	7.45	2.02	0.96	295.2
	Stdv	0.75	0.61	0.72	0.83	0.67	1.79	33.59	91.84	24.08	7.82	5.00	1.47	
	Cvar	1.04	1.00	1.00	0.97	0.78	1.03	0.59	0.57	0.39	1.05	2.47	1.53	
3005	Average	1.93	1.73	2.49	2.05	3.35	20.17	91.12	133.57	104.82	32.54	5.11	2.46	401.3
	Stdv	0.48	0.81	3.62	1.22	2.49	14.26	27.08	23.65	25.09	20.49	4.59	0.64	
	Cvar	0.25	0.46	1.45	0.59	0.74	0.71	0.30	0.18	0.24	0.63	0.90	0.26	
3007	Average	10.74	6.71	5.17	4.07	3.51	4.87	26.28	82.36	110.21	94.28	50.26	22.47	420.9
	Stdv	2.33	1.29	1.26	1.17	0.86	1.43	7.12	22.20	19.57	20.41	13.92	8.84	
	Cvar	0.22	0.19	0.24	0.29	0.24	0.29	0.27	0.27	0.18	0.22	0.28	0.39	
3008	Average	1.23	1.24	1.45	1.14	1.63	4.12	37.07	66.50	35.04	10.39	2.80	2.22	164.9
	Stdv	0.86	1.90	2.28	0.78	1.39	4.15	16.85	15.40	12.57	8.25	2.13	2.49	
	Cvar	0.70	1.53	1.57	0.68	0.85	1.01	0.45	0.23	0.36	0.79	0.76	1.12	
3013	Average	2.76	1.42	1.15	0.96	1.98	9.18	129.42	265.88	106.66	33.51	10.89	5.89	569.7
	Stdv	1.77	0.76	0.67	0.65	1.37	8.06	60.32	98.75	34.11	17.28	6.87	4.45	
	Cvar	0.64	0.53	0.58	0.68	0.69	0.88	0.47	0.37	0.32	0.52	0.63	0.75	
4001	Average	46.74	29.85	26.09	33.59	64.95	220.11	705.62	1142.95	1002.79	627.52	175.32	88.36	4,163.9
	Stdv	19.45	13.89	15.53	23.33	33.00	90.36	200.02	284.45	280.04	397.77	82.27	40.31	
	Cvar	0.42	0.47	0.60	0.69	0.51	0.41	0.28	0.25	0.28	0.63	0.47	0.46	
4002	Average	32.73	17.87	12.62	10.19	18.08	61.56	265.67	544.87	546.32	322.02	103.37	57.21	1,992.5
	Stdv	10.50	6.69	5.30	5.03	5.95	18.35	96.15	154.22	133.80	122.78	28.80	18.59	
	Cvar	0.32	0.37	0.42	0.49	0.33	0.30	0.36	0.28	0.24	0.38	0.28	0.32	
4005	Average	32.94	18.94	15.37	14.83	31.42	95.88	239.42	405.32	495.80	320.82	94.69	52.66	1,818.1
	Stdv	8.70	7.01	5.38	7.70	18.27	44.84	49.82	78.29	141.81	161.32	27.27	16.39	
	Cvar	0.26	0.37	0.35	0.52	0.58	0.47	0.21	0.19	0.29	0.50	0.29	0.31	
5002	Average	147.87	79.33	53.14	35.35	60.67	208.58	466.85	818.25	1137.45	1026.10	566.79	286.32	4,886.7
	Stdv	17.03	14.28	11.54	8.42	27.35	55.83	94.01	178.33	101.09	113.72	76.75	45.77	
	Cvar	0.12	0.18	0.22	0.24	0.45	0.27	0.20	0.22	0.09	0.11	0.14	0.16	
6003	Average	4.39	2.71	2.46	1.61	3.48	24.81	322.45	674.18	445.67	126.45	19.54	7.02	1,634.8
	Stdv	3.43	1.98	1.96	1.35	3.16	17.34	403.61	405.48	265.91	90.42	12.78	3.88	
	Cvar	0.78	0.73	0.79	0.84	0.91	0.70	1.25	0.60	0.60	0.72	0.65	0.55	

The monthly flows as percentage of the annual total for the stations presented in Table 6.23 are shown in Figure 6.82. It is observed that the regimes of the Abay tributaries in the direction of Deim gradually change in occurrence of their peak value from August to September. A proper reproduction of the monthly runoff pattern is of importance for simulation of irrigation water supply. Note that the current ENSWM monthly flow distribution is easily adapted to include these local variations.

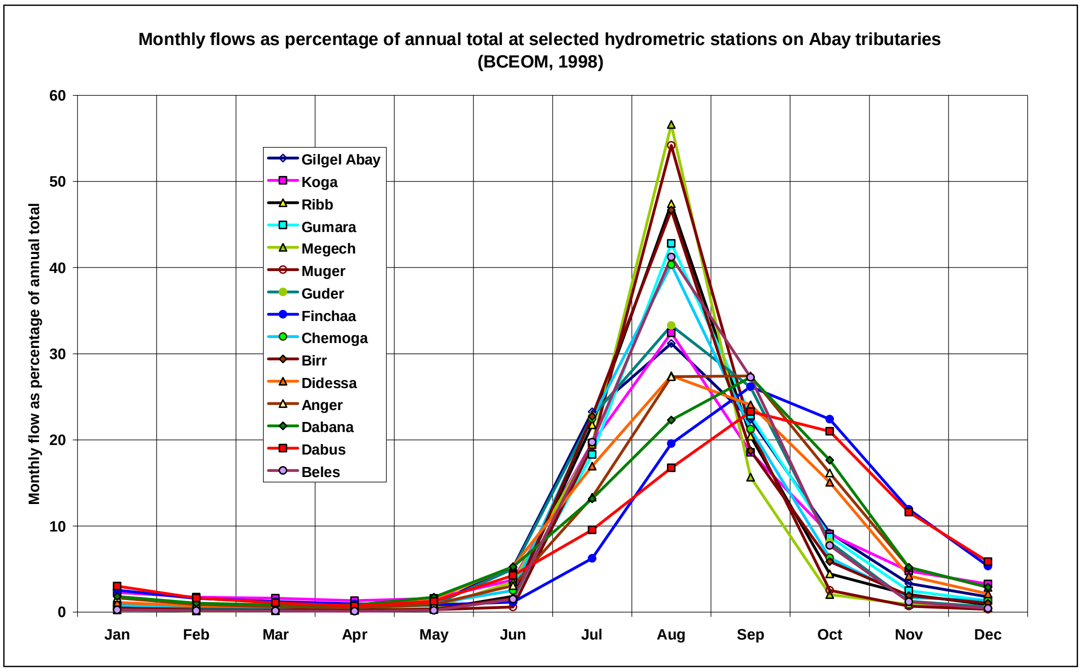

Figure 6.66 Average monthly flows as percentage of annual total at selected hydrometric stations on Abay tributaries as available from Abat Master Plan Study (BCEOM, 1998)

The monthly flow distribution that results from Guder DS – Deim increment is presented in Table 6.24 and compared with the distributions of the Abay tributaries draining downstream of Guder DS in Figure 6.83. The figure shows that the incremental regime reproduces the monthly flow distribution of the tributaries draining to the Abay from the south (left bank tributaries) acceptably, whereas the regimes of Chemoga, Birr and Beles deviate from this pattern. Local adjustments here may therefore be required when irrigation water abstractions have to be determined. This requires first a proper screening if the available tributary flow data.

Table 6.25 Monthly and annual flow statistics (Mm^3) of incremental flow between Guder DS and Deim, Period 1900-2002

Guder DS - Deim	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Average	381.1	215.5	123.0	118.5	371.9	1351.5	3394.7	7179.9	7862.6	4869.7	1710.7	785.7	28365.0
Stdev	137.9	86.7	39.1	73.9	205.1	452.7	848.1	1508.4	1800.6	1857.4	577.4	271.0	5349.3
Cvar	0.36	0.40	0.32	0.62	0.55	0.33	0.25	0.21	0.23	0.38	0.34	0.34	0.19

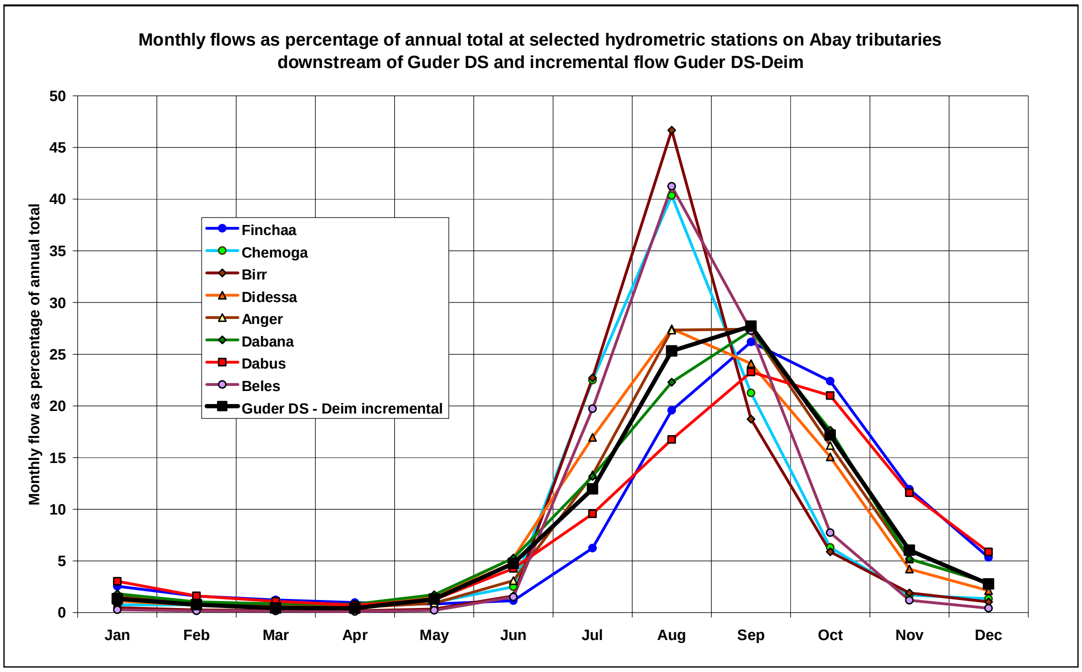

Figure 6.67 Average monthly flows as percentage of annual total for incremental flow between Guder DS and Deim Abay tributaries draining downstream of Guder DS.

6.3.7 Blue Nile at Deim

Station Deim, just downstream of the Ethiopian-Sudanese border (marked on Google Earth), was established in May 1965 to replace Roseires to record the Blue Nile inflow to Sudan. It has a continuous discharge record up to 2002. The station has a stable stage-discharge relation. The control section of the station is out of the backwater reach of Roseires reservoir. The monthly flow series of Deim was extended backwards based on the flow recorded at Roseires prior to the operation of the reservoir using the conversion:

$$Q_{Deim} = \frac{1}{1.01488} Q_{Roseires} \qquad (6\text{-}15)$$

This relation is established based on the annual flows determined at both sites, where Roseires has been corrected for reservoir losses. The statistics of the monthly flows at Deim are presented in Table 6.26 and Figure 6.68. In Figure 6.69 the monthly flow regimes at the key locations along the Abay-Blue Nile are presented. Apart from Bahir Dar at all locations the peak flow is generally experienced in August, though the difference between August and September diminish towards Deim. Compared to Kessie/Guder DS it is observed that at Deim in May the monthly averages already start rising, one to two month earlier than in Kessie/Guder DS, also due to the delayed outflow from Lake Tana, which effect gradually reduces further downstream with increasing flow.

The annual flow at Deim with the 11-year moving average is shown in Figure 6.86. The average annual total for the period 1900-2002 amounts nearly 49 Bm^3, or 56 % of the natural annual flow at Aswan. Though in comparison with the flow at Mongalla and Malakal no distinct great breaks are observed in the Blue Nile record, however, from the early sixties onwards for over 2 decades the flows were on average declining to restore only with the 1988 flood. It seems that in the early sixties increasing rainfall around Lake Victoria, causing the White Nile to increase sharply, coincided with a decrease of rainfall in the Abay basin.

The moving average series clearly shows that a careful selection of the simulation period is to be made in case series length much shorter than the 103 years used in ENSWM is taken. In Figure 6.87 the double mass curve of the flow at Deim with the flow at Guder DS is presented. The graph shows a proper consistency for the full period.

Table 6.26 Monthly and annual flow statistics (Mm^3) of the Blue Nile at Deim, Period 1900-2002

Deim	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Average	820.3	494.9	386.7	348.3	588.0	1618.6	6433.9	15032.1	12244.7	6730.6	2708.1	1436.4	48842.5
Stdev	272.6	179.3	157.6	172.5	310.9	621.0	1937.5	3001.5	2819.5	2406.8	865.5	465.0	9355.5
Cvar	0.33	0.36	0.41	0.50	0.53	0.38	0.30	0.20	0.23	0.36	0.32	0.32	0.19
Min	187.2	140.9	138.0	107.0	184.3	390.2	2286.0	6522.9	6000.7	2108.6	732.1	314.3	20388.5
Max	1958.7	1369.2	1083.9	1271.1	1852.4	4069.4	12600.0	24830.4	20790.5	13893.2	5005.1	3133.1	72803.8

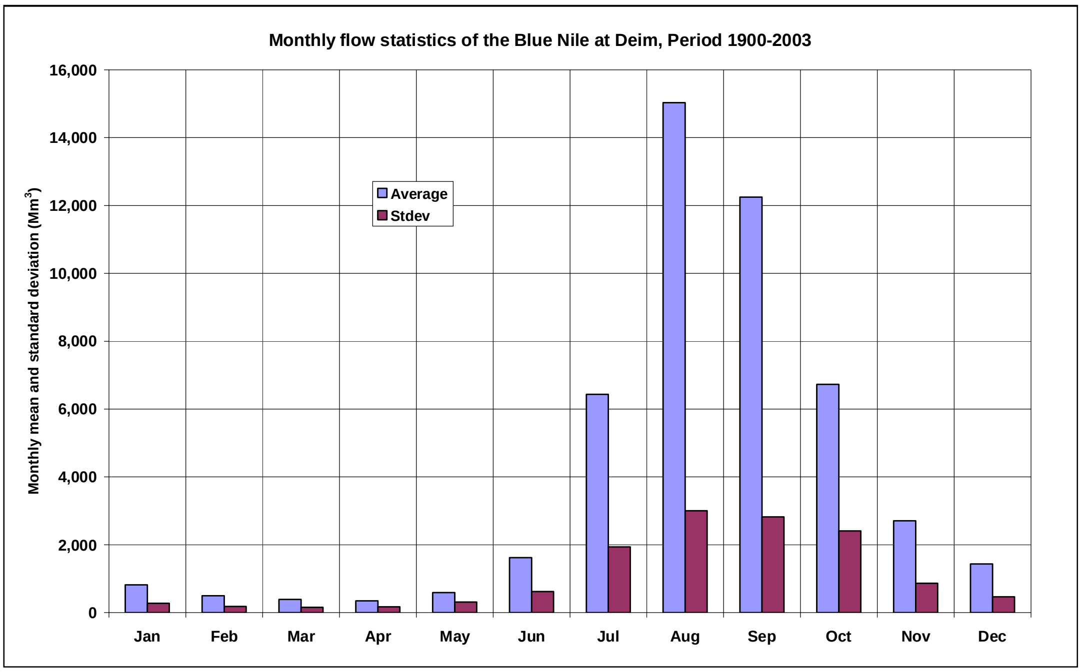

Figure 6.68 Monthly flow statistics of the Blue Nile at Deim, period 1900-2002

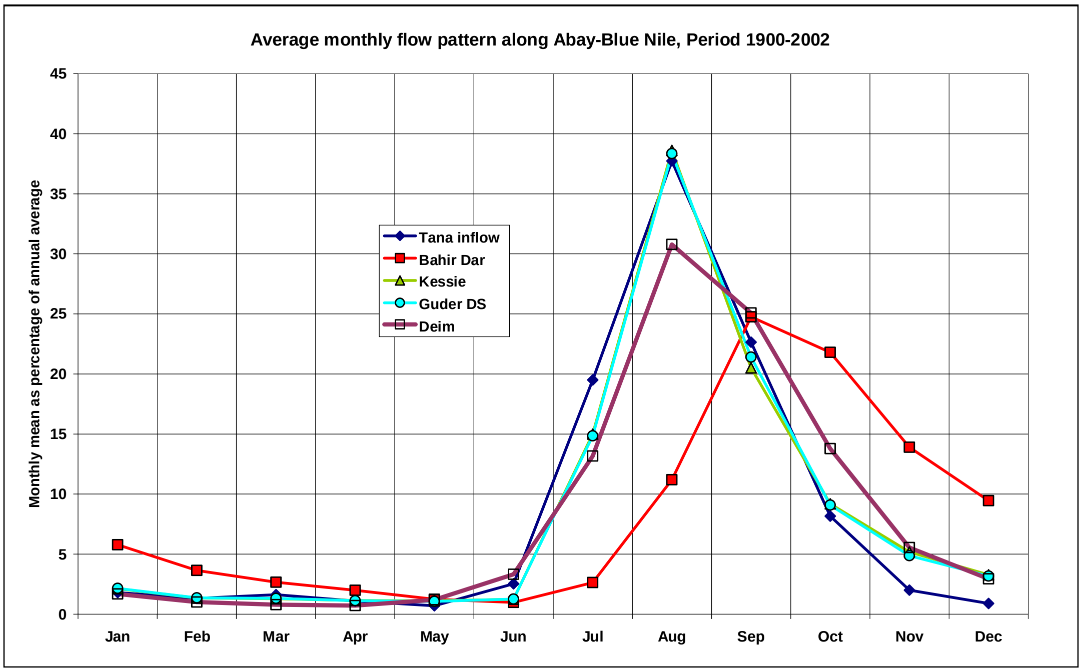

Figure 6.69 Average monthly flow pattern along Abay-Blue Nile from Lake Tana inflow to Deim, Period 1900-2002

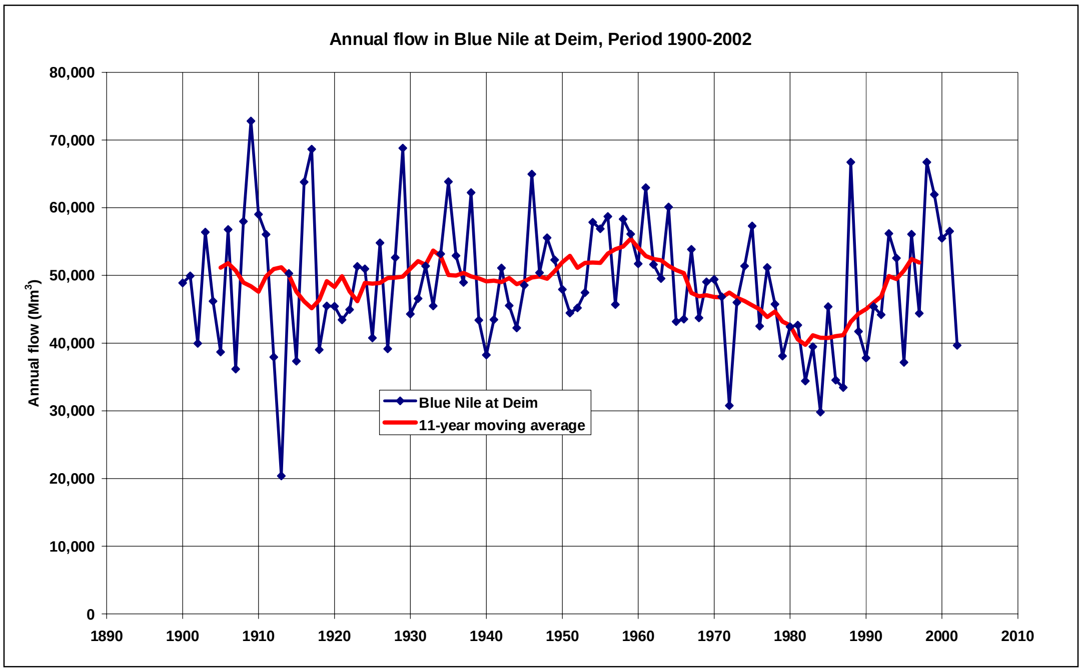

Figure 6.70 Annual flow in the Blue Nile at Deim with 11- year moving average, Period 1900-2002

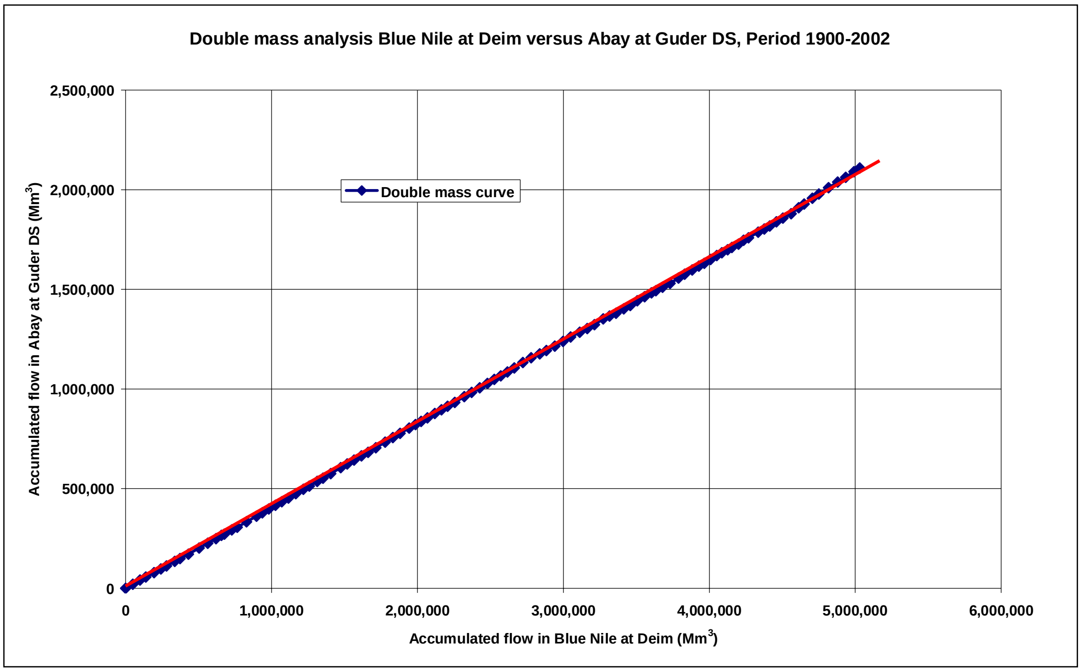

Figure 6.71 Double mass analysis of flows in the Blue Nile at Deim versus the Abay at Guder DS, period 1900-2002

6.3.8 Blue Nile at Roseires

The published flow record of Roseires starts in 1912 and can be considered as natural til 1966. Thereafter the series is affected by the operation of Roseires reservoir. The natural series of the Blue Nile at Roseires is composed of:

- Period 1900-1911: series is derived from the flow record of Khartoum corrected for Dinder and Rahad and Blue Nile evaporation losses.
- Period 1912-1965: as published by the Nile Control Staff
- Period 1966-2002: derived from the flow observations at Deim:

$$Q_{Roseires} = 1.01488\, Q_{Deim} \qquad (6\text{-}16)$$

Reference is made to the previous subsection dealing with Deim for a description of the flow statistics; one should add 1.5% to it to get Roseires.

6.3.9 Dinder at mouth

According to Sutcliffe and Parks (1999) data is available of the Dinder at its mouth (station Gwasi/El-Quwaysi) for the period 1907-1997. However, the data published by the Nile Control Staff runs only up to 1961. The completion of the flow record of the Dinder at mouth has been carried out as follows:

- Period 1900-1906:

$$\begin{aligned} &Annual: && Q_{Dinder} = 0.111 Q_{AtbaraK3} + 0.033 Q_{Khartoum} - 77 \quad (Mm^3) \\ &Months\ Jul - Sep: && Q_{Dinder} = 0.0724 Q_{Kartoum} - 45 \quad (Mm^3) \end{aligned} \qquad (6\text{-}17)$$

- The remaining months have been filled in proportional to the average monthly distribution up to the estimated annual flow.

- Period 1907-1961: data published by the Nile Control Staff in The Nile Basin, Volume IV
- Period 1962-1977: data available as unimpaired flows in the Nile DST
- Period 1978-2002:

$$Annual: \quad Q_{Dinder} = 0.1288Q_{AtbaraK3} + 0.0314Q_{Deim} - 141 \quad (Mm^3)$$
$$Months\ Jul - Sep: \quad Q_{Dinder} = 0.0115Q_{AtbaraK3} + 0.0766Q_{Deim} - 107 \quad (Mm^3) \qquad (6\text{-}18)$$

The remaining months have been filled-in proportional to the average monthly distribution up to the estimated annual flow. The values at Atbara K3 refer to the natural flow at K3.

The long term average annual flow of Dinder at mouth as applied in ENWSM amounts 2,795 Mm^3/yr with a standard deviation of 789 Mm^3/yr. The monthly flow statistics of the Dinder at mouth are presented in Table 6.26 and Figure 6.88. It is observed that in the first five months of the year the river does not carry any flow. Substantial flow only occurs in the period July – October. In Figure 6.73 a comparison is made of the accumulated flow in the Dinder with the Blue Nile at Khartoum, corrected for abstractions. The double mass curve shows that the flows at the two sites are mutually consistent.

Table 6.27 Monthly and annual flow statistics (Mm3) in Dinder at mouth, Period 1900-2002

Dinder	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Average	0.0	0.0	0.0	0.0	0.0	7.8	352.9	1017.5	982.0	370.8	52.8	10.9	2794.5
Stdev	0.0	0.0	0.0	0.0	0.0	22.2	159.2	270.6	327.3	266.8	44.9	14.4	788.7
Cvar	0.00	0.00	0.00	0.00	0.00	2.85	0.45	0.27	0.33	0.72	0.85	1.32	0.28
Min	0.0	0.0	0.0	0.0	0.0	0.0	115.0	337.0	422.0	0.0	0.0	0.0	1238.0
Max	0.0	0.0	0.0	0.0	0.0	153.0	877.0	1696.0	1977.0	1367.0	230.0	106.0	5028.0

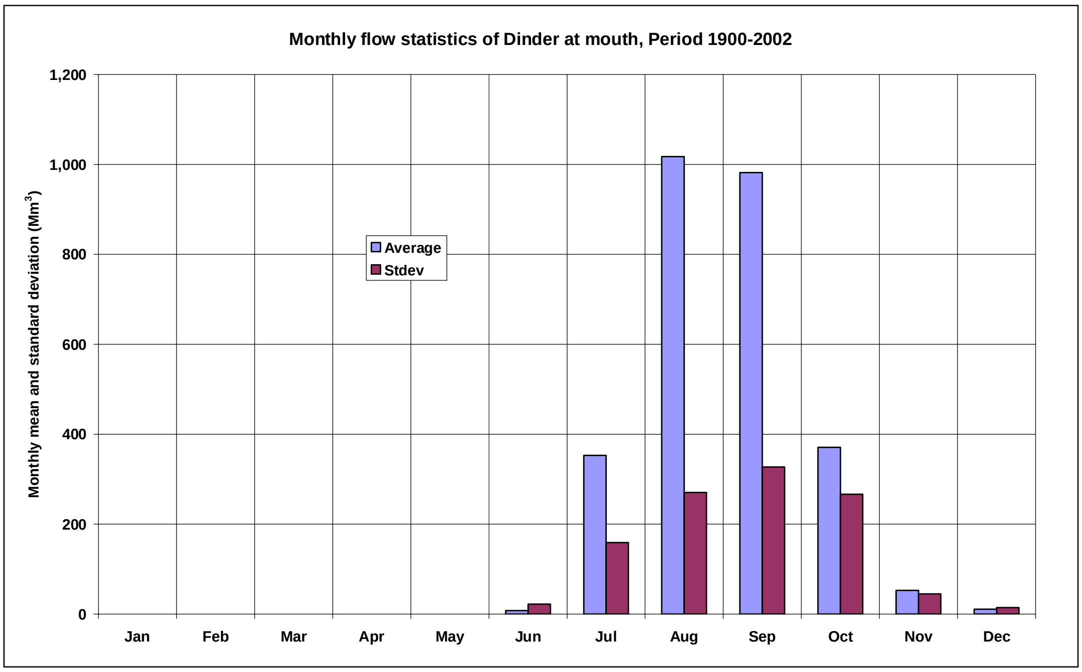

Figure 6.72 Monthly flow statistics of the natural flow of Dinder at mouth, period 1900-2002

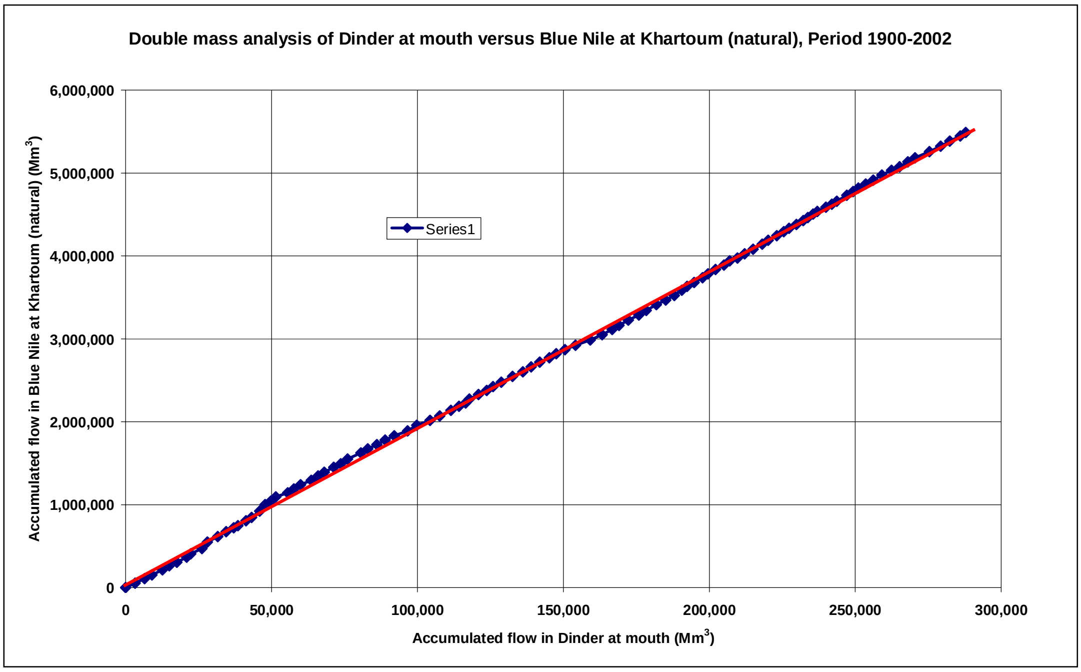

Figure 6.73 Double mass analysis of flow in Dinder at mouth versus Blue Nile at Khartoum (natural), Period 1900-2002

Note that the flow series of the Dinder, Rahad and Atbara of the years 1909, 1916 and 1917 have been reduced to improve the reproduction of the natural flow series at Aswan for those years.

6.3.10 Rahad at mouth

According to Sutcliffe and Parks (1999) data is available of the Rahad at its mouth (station El-Hawata) for the period 1908-1997. However, the data published by the Nile Control Staff runs only up to 1961. The completion of the flow record of the Dinder at mouth has been carried out as follows:

- Period 1900-1907:

$$\begin{aligned} &Annual: && Q_{Rahad} = 0.0345 Q_{AtbaraK3} + 0.0108 Q_{Khartoum} + 161 \quad (Mm^3) \\ &Months\ Jul - Sep: && Q_{Rahad} = 0.0228 Q_{Kartoum} + 7.3 \quad (Mm^3) \end{aligned} \quad (6\text{-}19)$$

- The remaining months have been filled-in proportional to the average monthly distribution up to the estimated annual flow.
- Period 1908-1961: data published by the Nile Control Staff in The Nile Basin, Volume IV, and missing data in the period 1908-1913 filled in by regression on Dinder
- Period 1962-1977: data available as unimpaired flows in the Nile DST
- Period 1978-2002:

$$\begin{aligned} &Annual: && Q_{Rahad} = 0.0445 Q_{AtbaraK3} + 0.0028 Q_{Deim} + 436 \quad (Mm^3) \\ &Months\ Jul - Sep: && Q_{Rahad} = 0.0103 Q_{AtbaraK3} + 0.0018 Q_{Deim} + 21 \quad (Mm^3) \end{aligned} \quad (6\text{-}20)$$

The remaining months have been filled in proportional to the average monthly distribution up to the estimated annual flow. The values at Atbara K3 refer to the natural flow at K3.

The long term natural average annual flow of the Rahad at mouth as applied in ENWSM amounts 1,067 Mm^3/yr with a standard deviation of 236 Mm^3/yr. The monthly flow statistics of the Rahad at mouth are presented in Table 6.27 and Figure 6.90. It is observed that in the first five months of the year the river does not carry any flow. Substantial flow only occurs in the period July – October, like in the Dinder. In Figure 6.75 the double mass curve between the flows in Rahad and in the Blue Nile at Khartoum (natural) is presented and shows that the series are mutually consistent.

The annual flows in Rahad and Dinder at mouth (stations Hawata, Gwasi) are presented in Figure 6.91 and their double mass comparison in Figure 6.92 The latter shows a mutual consistency between the series.

Table 6.28 Monthly and annual flow statistics (Mm^3) of the Rahad at mouth, Period 1900-2002

Rahad	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Average	0.0	0.0	0.0	0.0	0.0	1.5	116.6	335.0	348.0	232.7	29.9	2.9	1066.7
Stdev	0.0	0.0	0.0	0.0	0.0	4.8	51.6	74.1	92.0	116.1	23.5	4.3	236.3
Cvar	0.00	0.00	0.00	0.00	0.00	3.25	0.44	0.22	0.26	0.50	0.78	1.48	0.22
Min	0.0	0.0	0.0	0.0	0.0	0.0	20.0	129.0	161.0	4.0	0.0	0.0	531.0
Max	0.0	0.0	0.0	0.0	0.0	29.0	270.0	551.0	652.0	597.0	151.0	30.0	1826.0

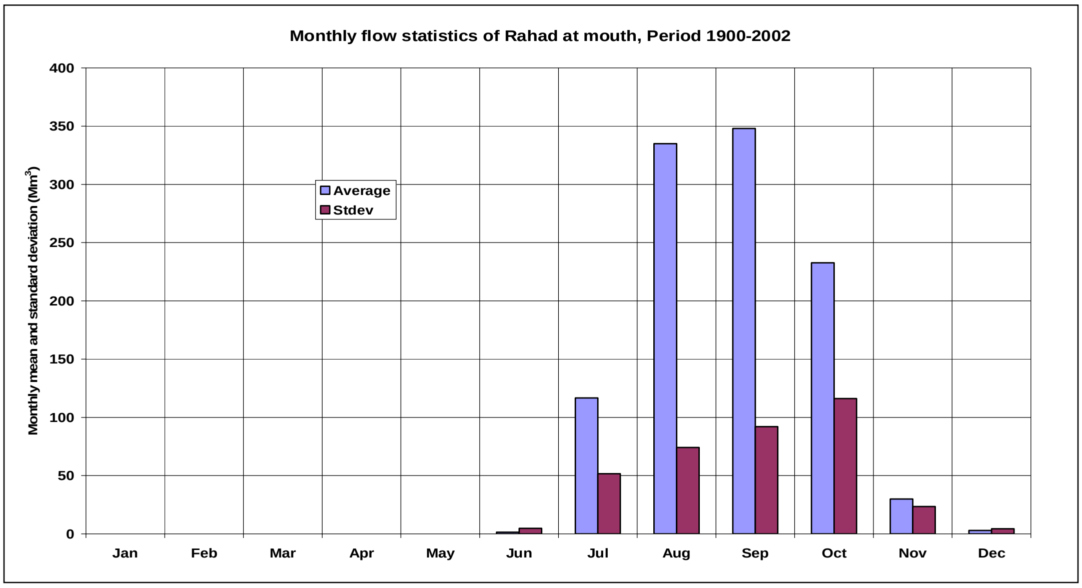

Figure 6.74 Monthly flow statistics of Rahad at mouth, Period 1900-2002

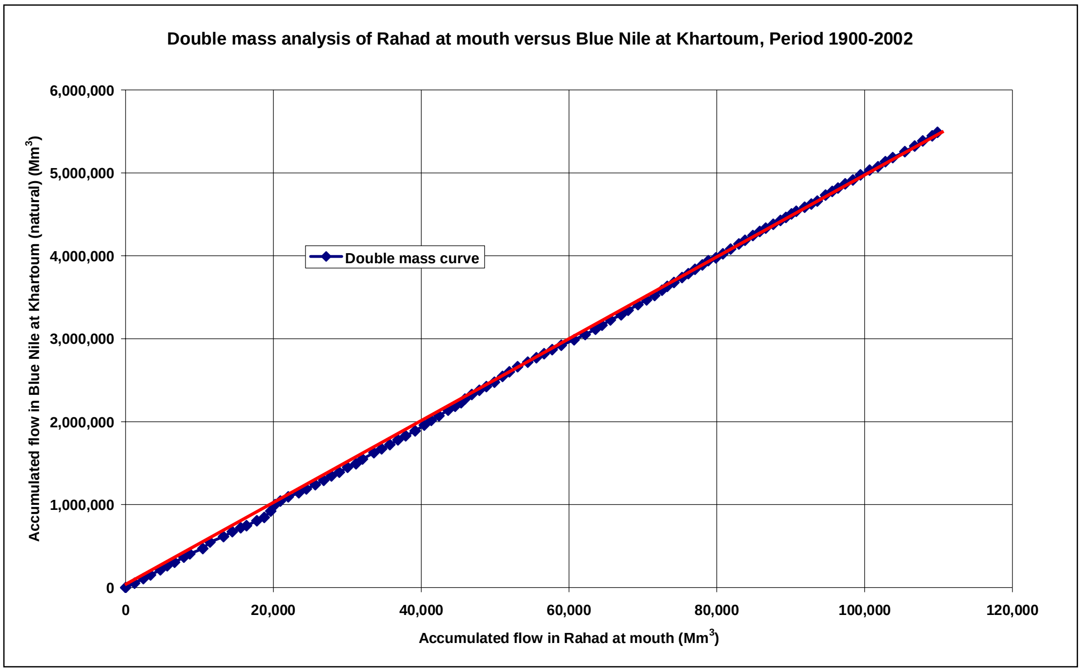

Figure 6.75 Double mass analysis of the flow in Rahad at mouth versus the Blue Nile at Khartoum (natural), Period 1900-2002

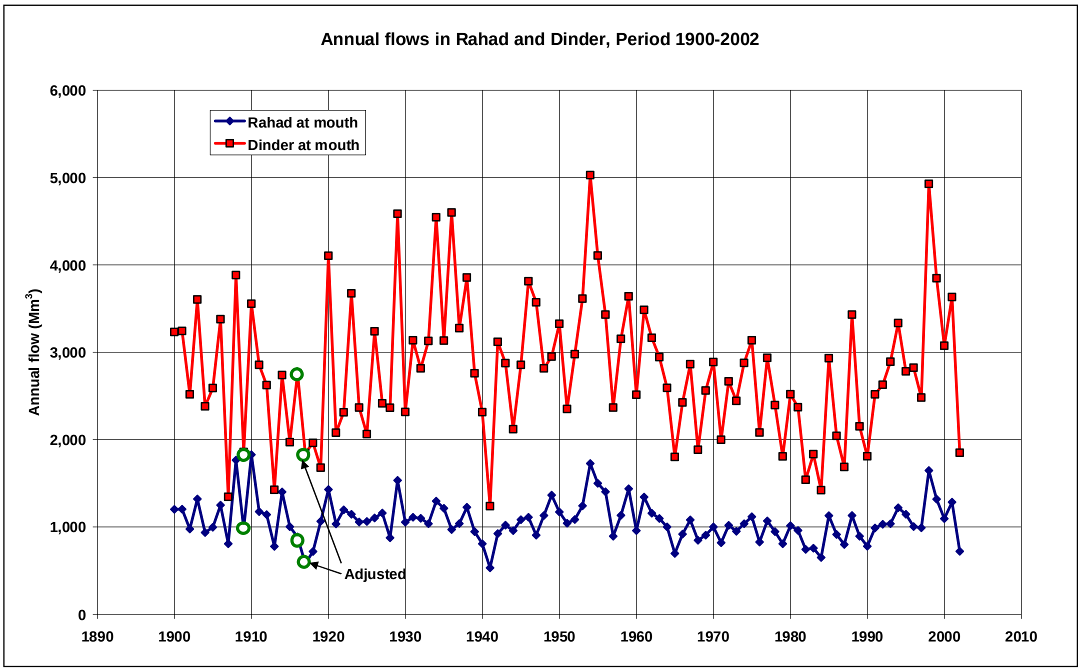

Figure 6.76 Annual flow in Rahad and Dinder at their confluence with the Blue Nile, Period 1900-2002

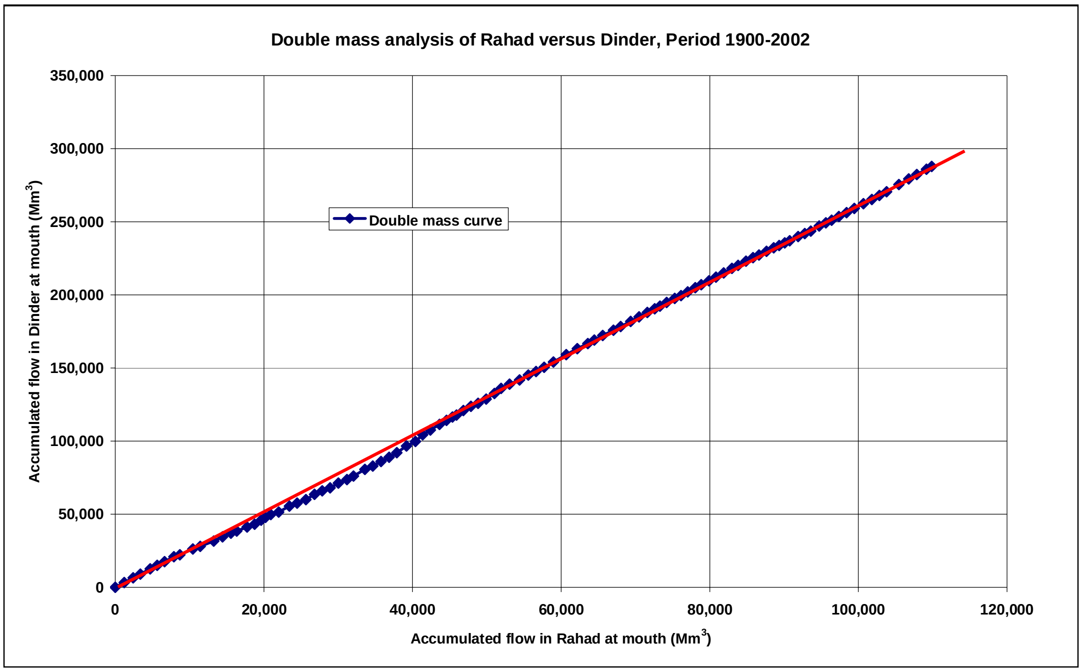

Figure 6.77 Double mass analysis of the flow in Rahad at mouth versus the Dinder at mouth, Period 1900-2002

Note that the flow series of the Dinder, Rahad and Atbara of the years 1909, 1916 and 1917 have been reduced to improve the reproduction of the natural flow series at Aswan for those years.

6.3.11 Blue Nile at Khartoum

The key station on the Blue Nile is Khartoum, which has a complete flow record published by the Nile Control Staff as from 1900 onward till 2002. Particularly for the early years this series has been used to complete series of the Atbara, Dinder, Rahad and Roseires. In the course of time the actual flow at Khartoum has deviated from the natural flow due to water use in the Sudan. Detailed information on irrigation water abstractions and evaporation losses in the Sudan is presented in Sub-section 6.5 when dealing with the natural flow at Aswan. The observed flow and these abstractions in combination with the natural Blue Nile flow at Roseires, in Dinder and Rahad have been used to create the natural flow series for Khartoum. The monthly and annual flow statistics of the natural flow in the Blue Nile at Khartoum are presented in Table 6.28 and Figure 6.94. The peak flows in the natural series generally occur in August-September, with minimum flows in March-April.

Table 6.29 Monthly and annual flow statistics of the natural flow in the Blue Nile at Khartoum, Period 1900-2002

Khartoum	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Average	824.2	478.8	357.6	309.2	527.5	1568.2	6850.9	16527.1	13896.4	7604.6	2860.8	1483.3	53288.5
Stdev	293.4	192.4	166.0	172.6	312.0	663.6	2150.9	3267.3	3211.6	2860.3	972.6	496.8	10367.6
Cvar	0.36	0.40	0.46	0.56	0.59	0.42	0.31	0.20	0.23	0.38	0.34	0.33	0.19
Min	290.0	168.0	90.0	58.0	150.0	466.0	1880.0	7520.0	7300.0	2655.0	969.0	546.0	25693.0
Max	1950.0	1350.0	1050.0	1239.0	1829.0	4249.0	13925.0	26731.0	22900.0	16100.0	6050.0	3160.0	79158.0

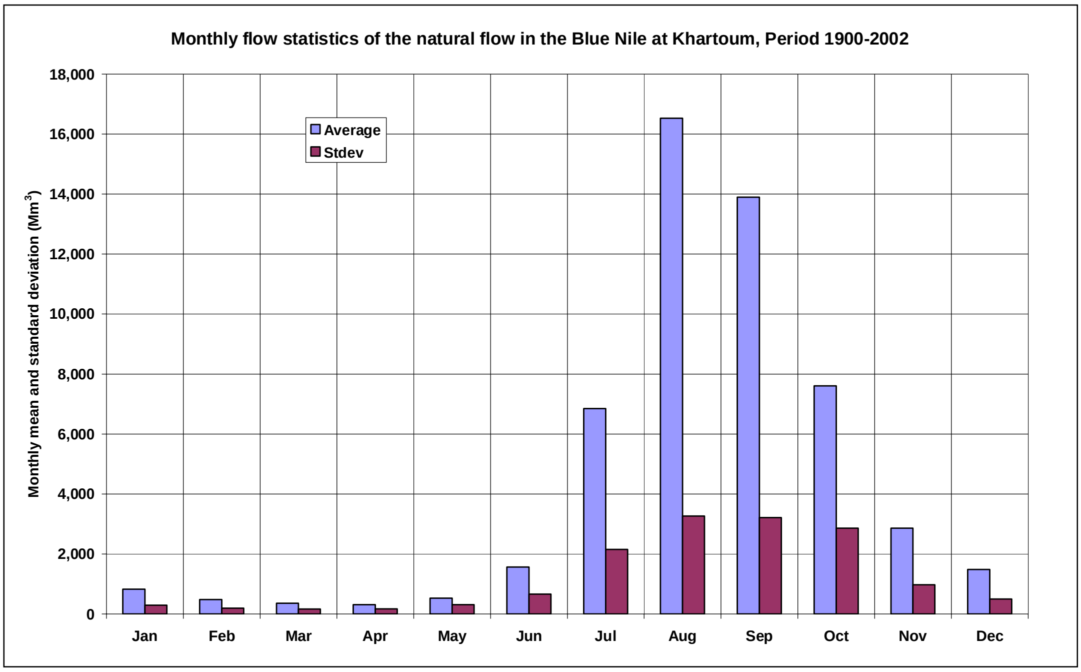

Figure 6.78 Monthly flow statistics of the natural flow in the Blue Nile at Khartoum, Period 1900-2002

The annual natural and observed flows in the Blue Nile at Khartoum are presented in Figure 6.95. It is observed that since the min-twentieths of the last century, with the construction of Sennar reservoir abstractions have taken place. The abstractions since 1975 amounted on average 10.3 Bm^3/year. The abstractions are also clearly visible in Figure 6.96, which shows the double mass curve of the natural and observed flow at Khartoum. The natural annual flow with the 11-year moving average is presented in Figure 6.97. From this figure the prolongued dry period in the seventies and eighties is observed. Finally, in Figure 6.98 the double mass curve of the flow at Khartoum and at Deim is shown. The series are seen to be mutually consistent.

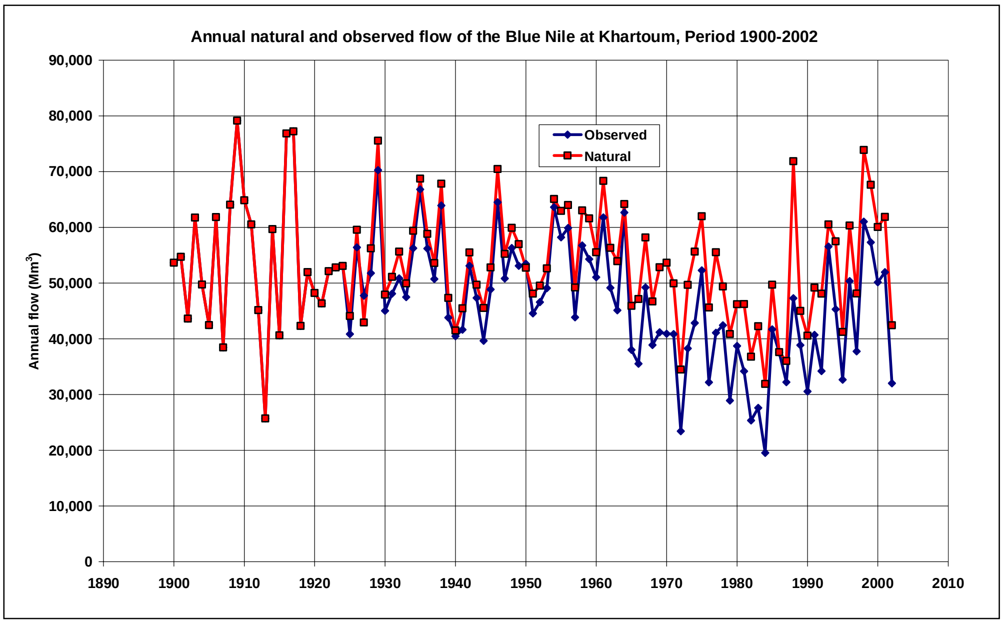

Figure 6.79 Annual natural and observed flow in the Blue Nile at Khartoum, period 1900-2002.

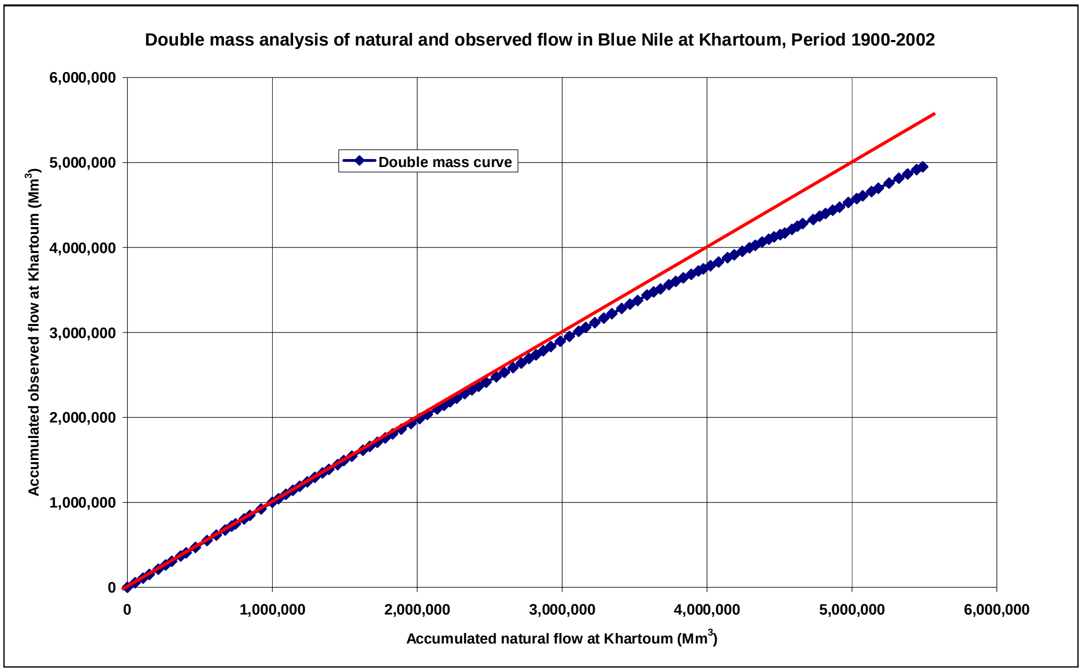

Figure 6.80 Double mass analysis of the natural and observed flow in Blue Nile at Khartoum, Period 1900-2002

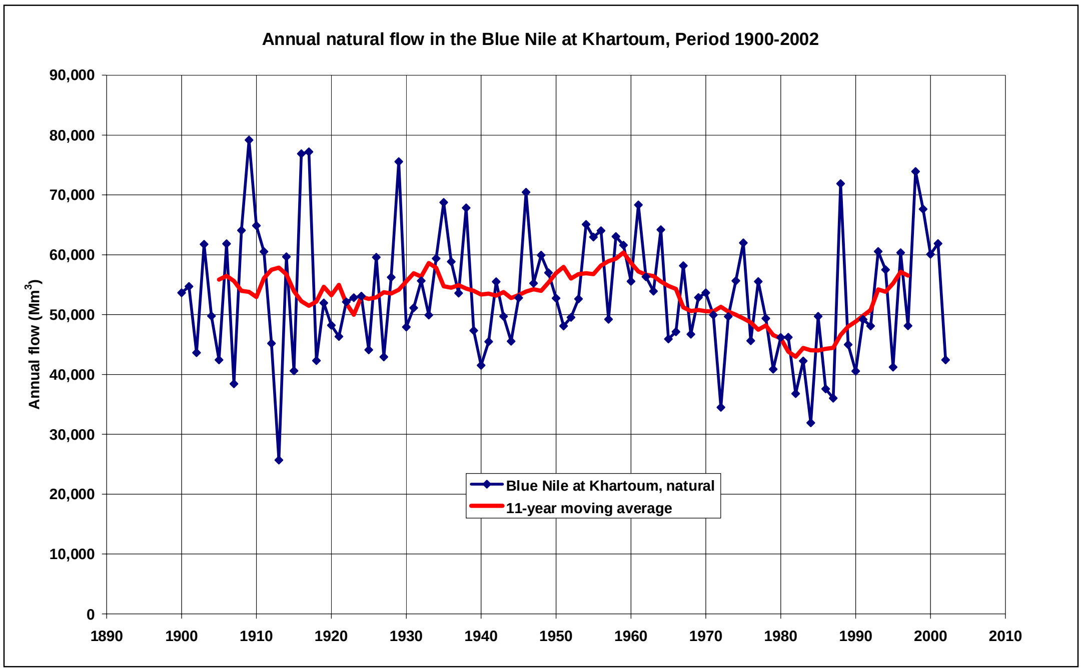

Figure 6.81 Annual natural flow in the Blue Nile at Khartoum with 11-year moving average, Period 1900-2002

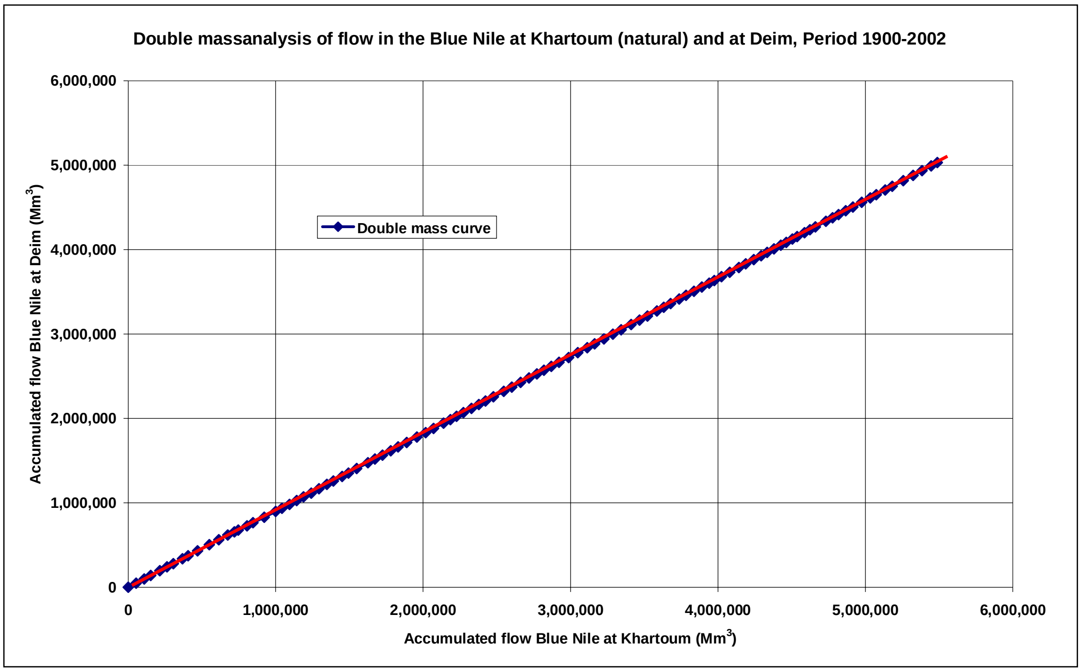

Figure 6.82 Double mass analysis of the natural fow in Blue Nile at Khartoum versus Deim. Period 1900- 2002

6.4 Tekeze-Setit-Atbara sub-basin

6.4.1 Overview of flow extension/completion procedure for the sub-basin

The Eastern Nile Watershed Management Project (2012) recently reviewed the hydrometric infrastructure in the ENTRO basins and lists for Ethiopia in the Tekeze basin some 31 hydrometric stations. Reliable, useful data for ENSWM development only exists for Embamadre for the period 1967-1976. Master Plan and feasibility studies during the last decades made use of this data and extended the series with flow data from Tana and Kessie on Abay (e.g. Howard Humphreys et al., 1997) or with rainfall (NEDECO, 1998). In Sudan historically at 4 and since 2007 at 7 hydrometric stations on Atbara and Setit flow data are collected. The extensive series of K3 near Atbara mouth available from the Nile Control Staff, updated/validated with Khashm el Girba data, have been corrected for irrigation water abstractions and further extended to create a natural flow series for the Atbara covering the full period 1900-2002.

To create natural flow series at the Vif nodes in the Tekeze-Setit-Atbara sub-basin the following strategy has been applied:

- The annual flow in the Tekeze at Embamadre has been correlated with the annual flow in Atbara at K3 and extended to the period 1900-2002
- To obtain a correct monthly flow pattern in the upper river reaches the monthly flows of K3 has been shifted backward with 1/3 month to account for travel time.
- The backward shifted monthly flow of K3 has been partitioned as a fraction of K3 based on best estimates of for the following key sites:
  - On Tekeze-Setit: Yechi, TK5 dam site, Embamadre, Humera and Wad el Heliew.
  - On Goab: Metema.
  - On Angereb: Abderafi.
  - On Atbara: Kubur, Rumela, Khasm el Girba and K3.

The applied procedures are discussed in the following sub-sections.

6.4.2 Tekeze at Embamadre

Station Embamadre is located at the Tekeze bridge in the road from Gondar to Axum, north-west of the Semien Mountains, see Figure 6.99.

Figure 6.83 Hydrmetric satation Embamadre on Tekeze (Sources: Google Earth, C. Staub 2012)

Water level and flow measurements are taken at/from the bridge. The Google Earth image of the site indicates that the low flow cross-section is likely to be unstable, which may hamper accurate assessment of low flows.

For medium and high flows the perpendicular lining of the bridge to a long straight river section is ideal for flow measurements. Some 216 discharge measurements are available for the period 1967-1976. Howard Humphreys et al, (1997) have revised that discharge ratings to the ones presented in Figure 6.100. The ratings show some instability for the low flows, but are remarkably stable for medium and high flows. With these ratings and daily water levels available from 1 June 1967 till 31 December 1976 a reliable flow series for the Tekeze at Embamadre has been created.

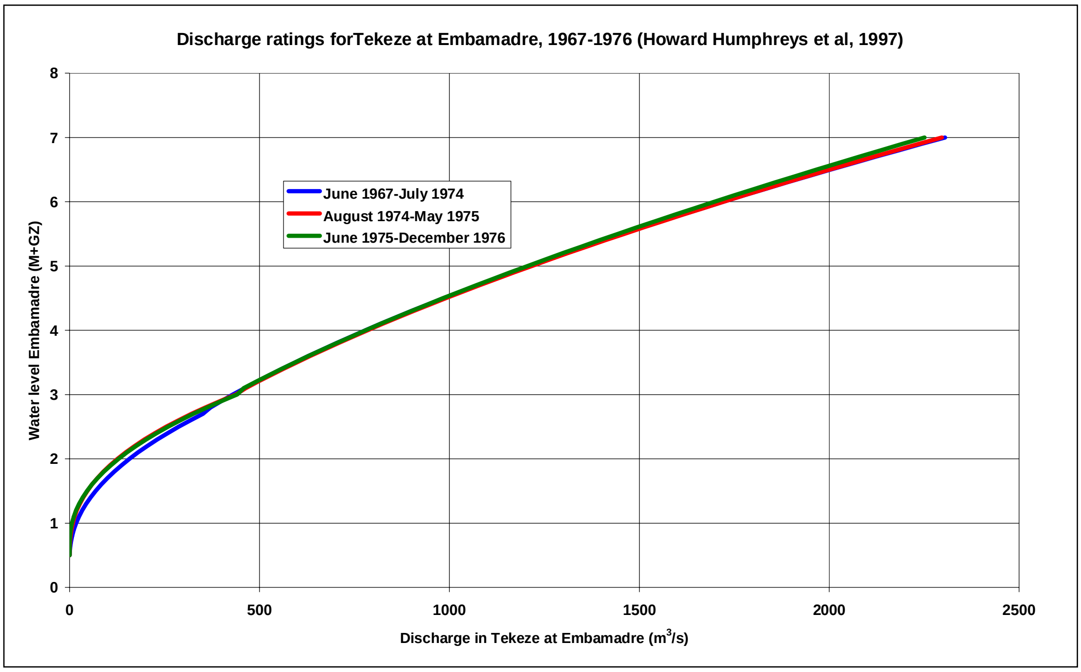

Figure 6.84 Discharge ratings of Tekeze at Embamadre, Period 1967-1976, (Howard Humpreys, 2007)

This flow series has been aggregated to monthly and annual flows covering the period 1967-1976. Howard Humphreys et al. (1997) extended this period to 1956-1995 by regression on Tana inflow and Abay at Kessie. Similarly, the Ethiopian Ministry of Water Resources published annual flows for the period 1967-1998 (with some years missing), presented in Shenkut (2006). Both series have been compared with the natural flow in the Atbara at K3 in Figure 6.85. From the figure it is observed, that, whereas there is a close correlation between the annual flows of 1967-1976 (in red), the flows in the extended periods follow a completely different relationship, leading both to very unrealistic flow ratios for low flows. These extended series have therefore been ignored for further use. In the Tekeze River Basin Integrated Development Master Plan by NEDECO (1998) the series of Embamadre has been extended to the period 1900-1990 by correlation with rainfall, leaning apparently heavily on the long rainfall records of Addis Ababa and Asmara. Instead of using rainfall and flow series from outside the basin, the excellent relationship between the annual flows at Embamadre and K3 (Figure 6.86) has been applied to extend Embamadre to the period 1900-2002. This makes more sense than extension based on regression with rainfall/flows observed in different basins as nearly half of the flow arriving at K3 passed Embamadre.

$$\text{For } Q_{K3} \leq 7{,}000 \text{ Mm}^3\text{/year: } Q_{Embamadre} (Mm^3) = 0.290\, Q_{K3} \qquad (6\text{-}21)$$

$$\text{For } Q_{K3} > 7{,}000 \text{ Mm}^3\text{/year: } Q_{Embamadre} (Mm^3) = 0.685\, Q_{K3} - 2689$$

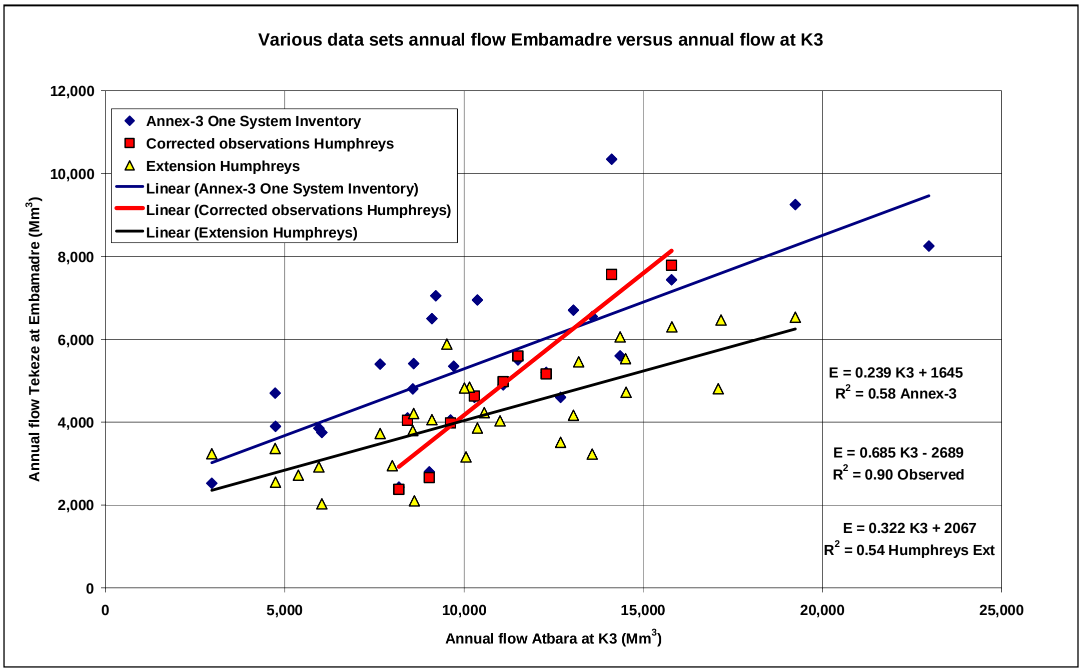

Figure 6.85 Observed and extended flows of Tekeze at Embamadre versus Atbara at K3

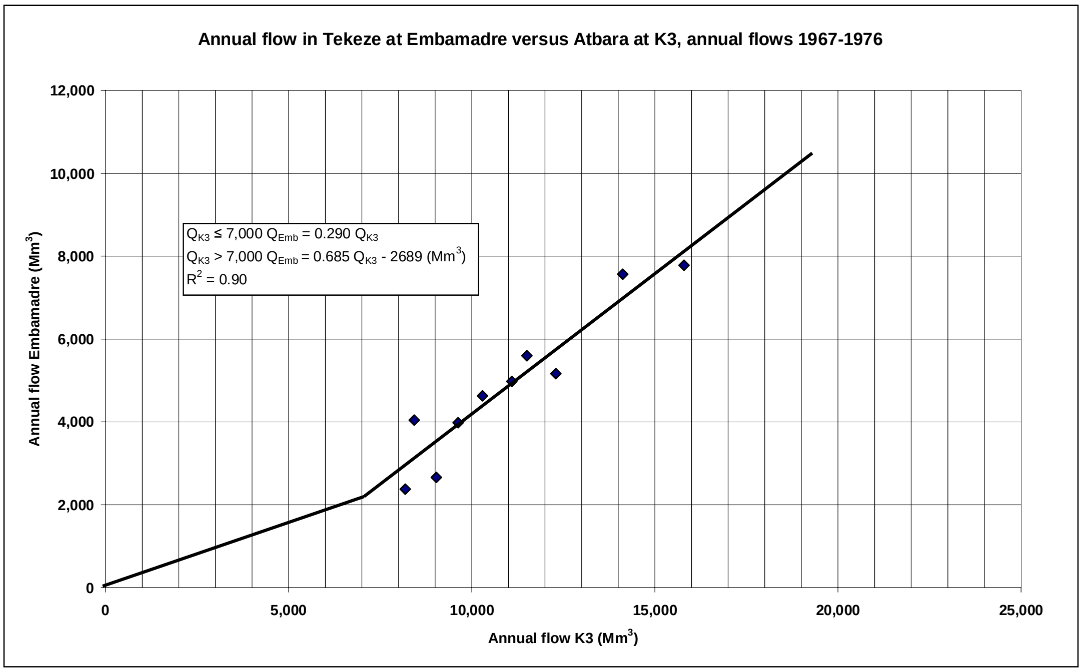

Figure 6.86 Assumed functional relationship of annual flows in Tekeze at Embamadre and Atbara at K3.

To create a monthly flow series of Tekeze at Embamadre the following approach can be used (note: QE = flow in Tekeze at Embamadre, QK3 = flow in Atbara at K3):

- create annual flow series for Embamadre based on K3, see Figure 6.86 and eq. (6-21).
- create wet season series $QE_{Jul\text{-}Oct}$ = 0.955 QE_{annual}, and QE(Jul-Sept) = 0.887 QE_{annual}
- create QE_{July} = $QK3_{July}$ x $(QE/QK3)_{average,\ July}$, etc. for months August and September.

- create $QE_{October} = 0.213\ QE_{Sept} + \sigma_E\sqrt{(1-R^2)} \times \varepsilon_{Normal}(0,1)$.
- adjust monthly flows July-October to the wet season relationships.
- determine rest flow = $QE_{annual} - QE_{Jul\text{-}Oct}$ and partition rest over the remaining months according to the percentages in the period 1967-1976.

The flow statistics are presented in Table 6.29, Figure 6.103 and Figure 6.104.

Table 6.30 Monthly and annual flow statistics (Mm^3) of Tekeze at Embamadre, Period 1900-2002

Embamadre	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Average	21.6	13.3	22.0	30.0	55.9	152.4	1271.0	2482.4	905.1	201.2	61.3	36.3	5252.4
Stdv	10.9	6.6	12.3	15.1	30.2	74.1	616.6	1177.0	511.1	121.6	30.4	18.5	2408.4
Cvar	0.51	0.50	0.56	0.51	0.54	0.49	0.49	0.47	0.56	0.60	0.50	0.51	0.46
Min	2.1	1.3	2.1	2.9	5.0	8.0	194.4	371.8	197.0	3.6	6.0	3.5	860.1
Max	57.0	33.0	80.0	83.0	185.0	361.9	2910.4	6275.8	3293.3	786.0	145.6	99.0	13055.2

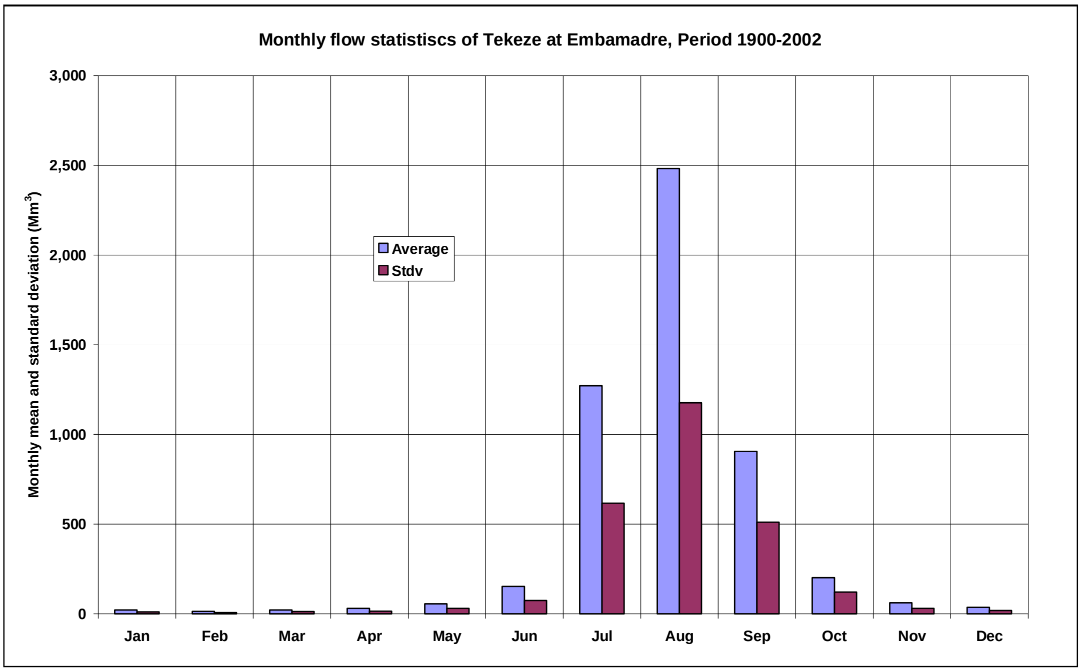

Figure 6.87 Monthly flow statistics of Tekeze at Embamadre, Period 1900-2002

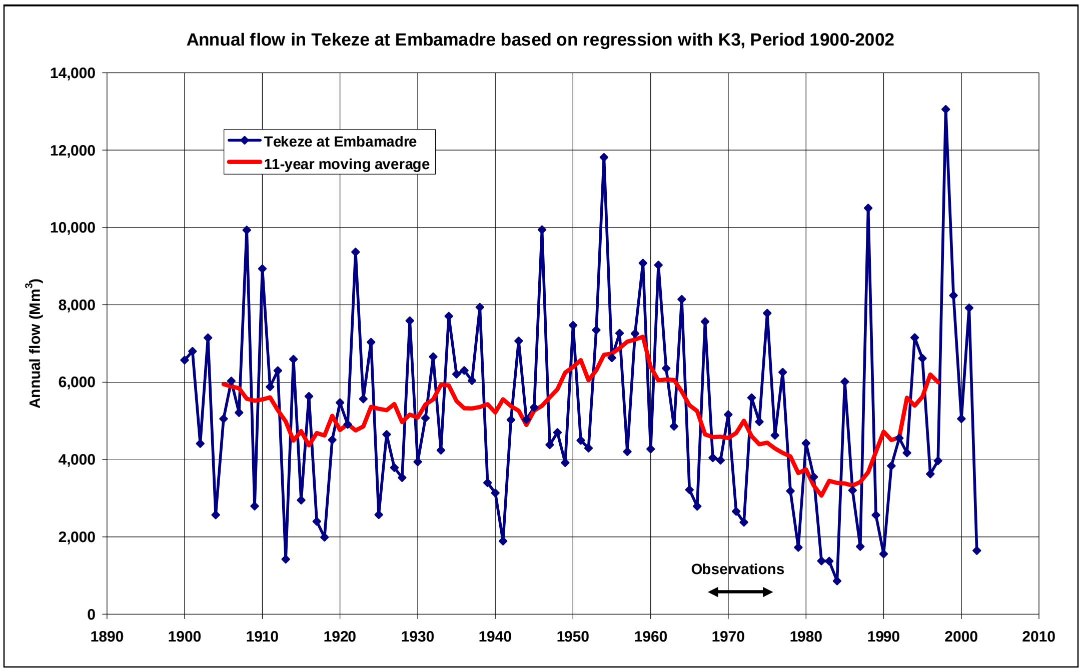

Figure 6.88 Annual flow in Tekeze at Embamadre with 11-year moving average, Period 1900-2002

Flow series Embamadre as fraction of K3 flows

Alternatively, the monthly flows at Embamadre can be derived as a fraction of the monthly flows at K3. Based on the annual flows of the period 1967-1976 the fraction for Embamadre becomes 0.456. For the annual flows the fractional relationship is dispayed in Figure 6.89. However, from Figure 6.90 it is observed that the monthly natural flow distribution at K3 lags somewhat behind the monthly flows at Embamadre, as it takes several days for the flow to travel from one site to the other. To make the monthly flows at K3 transferable to monthly flows at Embamadre a shift has been applied to the flows at K3 to account for this travel time. Best agreement between the distribution at Embamadre and the shifted distribution of K3 is obtained if the flow of K3 is shifted 1/3 month (≈10 days) see Figure 6.91. It is observed that the monthly flow distribution particularly after the flow maximum in August improves considerably by this adjustment. This is particularly of importance for irrigation water supply. The flow in June is overestimated by this approach. The resulting flow statistics are presented in Table 6.31. Compared to Table 6.30 it is observed that dry flow period variability increased but the wet season and annual variability decreased. The latter effect is also observed from Figure 6.92.

Table 6.31 Monthly and annual flow statistics in Tekeze at Embamadre as fraction of shifted K3, Period 1900-2002

Embamadre	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Average	4.2	1.3	1.0	5.8	89.4	571.0	1537.6	1846.9	930.9	217.3	35.4	11.6	5252.4
Stdev	8.4	3.6	4.3	12.2	53.7	221.4	496.5	610.9	377.1	113.2	33.0	13.8	1665.8
Cvar	1.99	2.82	4.32	2.10	0.60	0.39	0.32	0.33	0.41	0.52	0.93	1.19	0.32
Min	0.0	0.0	0.0	0.0	0.0	129.1	339.8	449.9	317.0	49.4	0.0	0.0	1353.8
Max	60.9	27.4	31.9	70.8	314.9	1221.3	2835.8	4040.4	2744.7	694.0	160.9	57.9	10485.6

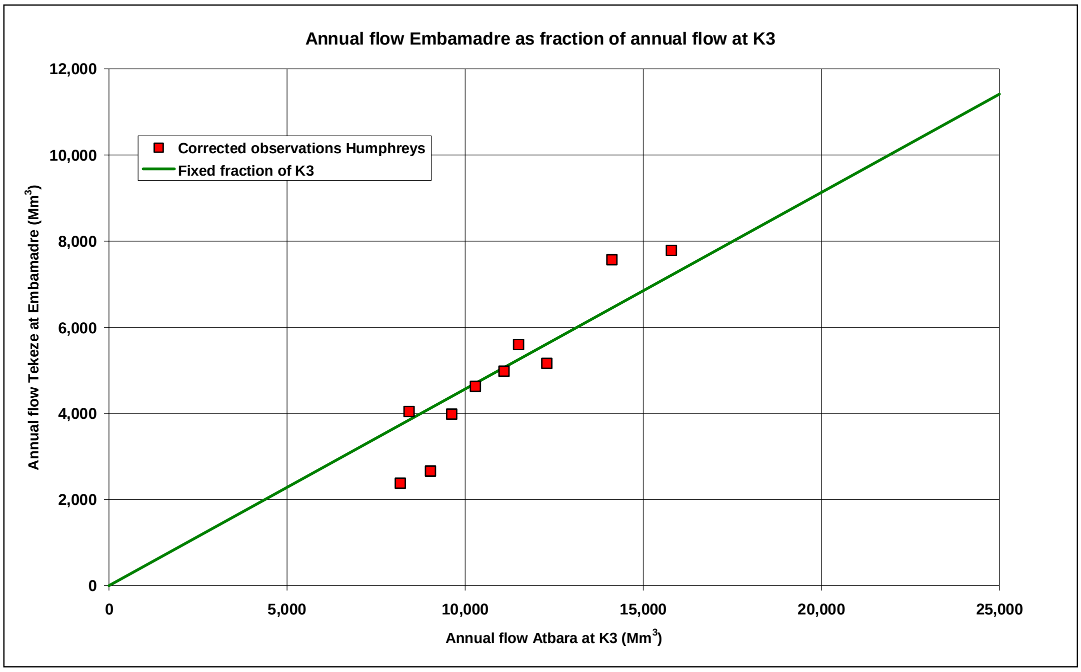

Figure 6.89 Annual flow in Tekeze at Embamadre as fraction of the Atbara at K3, Period 1967-1976

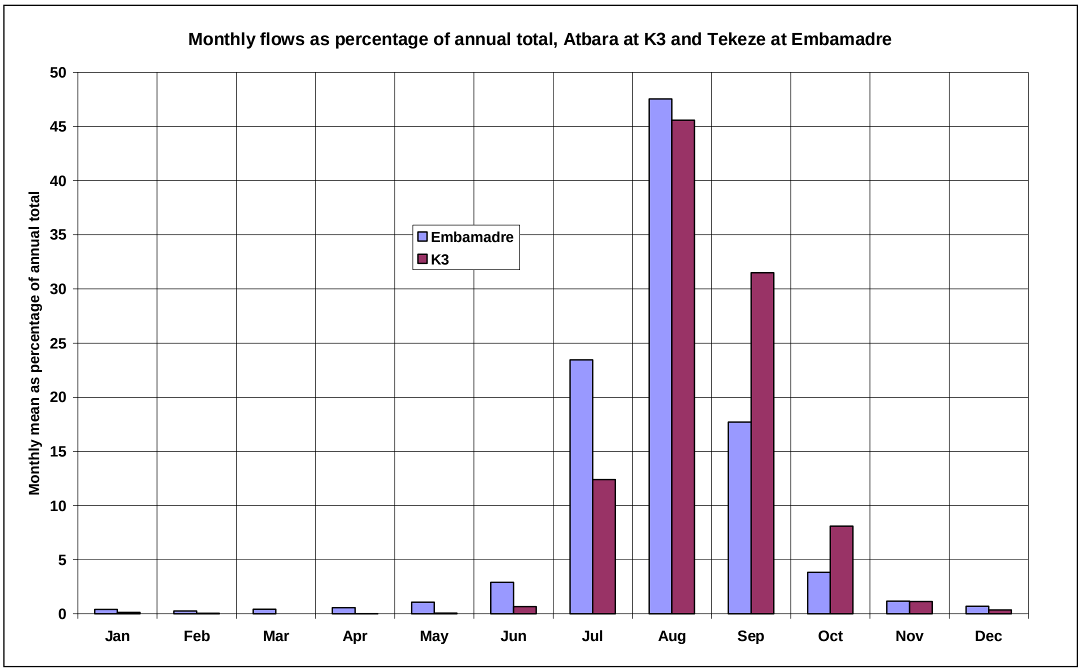

Figure 6.90 Average monthly flows in Tekeze at Embamadre and Atbara at K3 as percentage of annual total

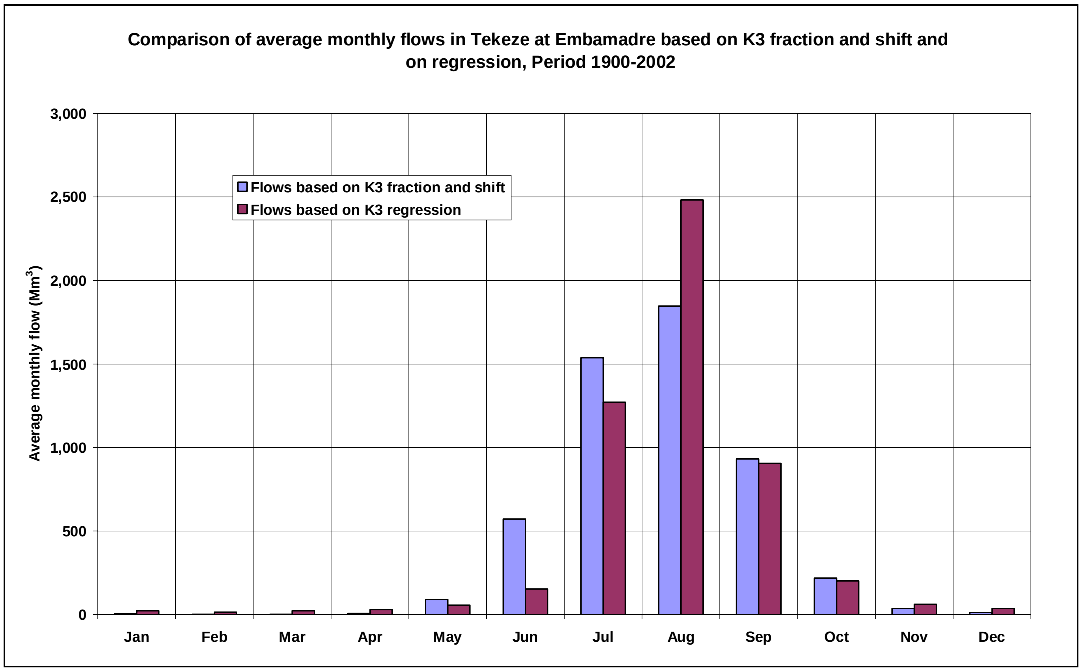

Figure 6.91 Average monthly flows in Tekeze at Embamadre derived from K3 fractin and shift and from regression on K3, Period 1900-2002

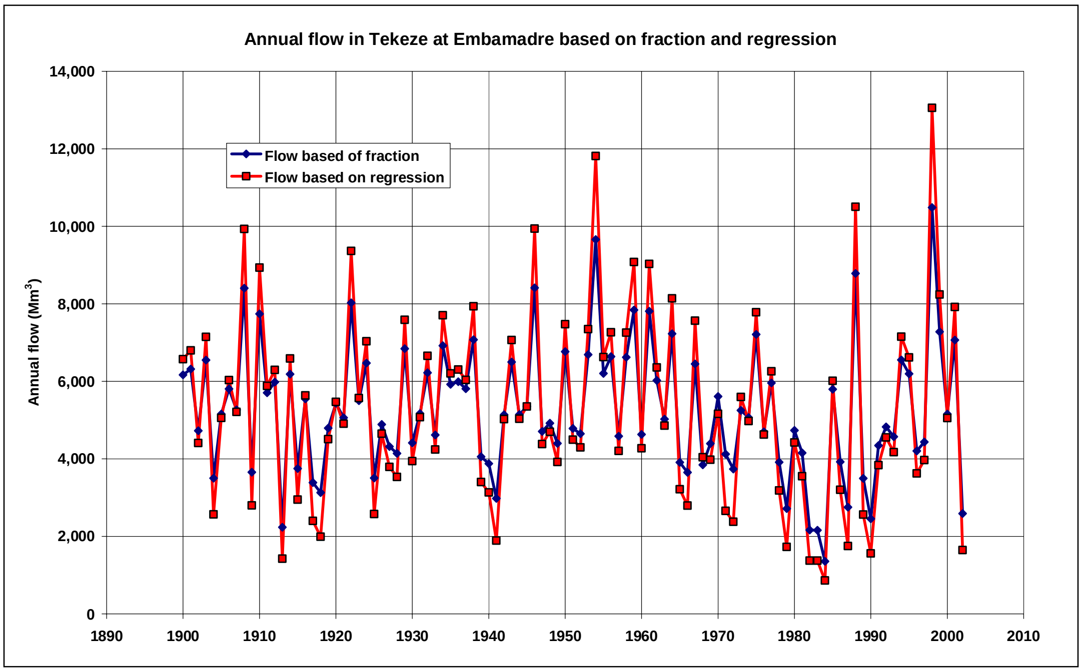

Figure 6.92 Annual flow estimates for Tekeze at Embamadre based on K3 fraction and regression, Period 1900-2002

6.4.3 Partitioning of flow values upstream of K3

The flow values at the stations and Vif's upstream of Embamadre (Yechi, TK5), downstream of Embamadre (Humera and Wad el Heliew) and in the rest of the basin (Metema, Abederafi, Rumela and Khashm el Girba) have been derived from the series of Embamadre and K3. In the regression approach (first method presented in Sub-section

6.4.2) the monthly distribution has either been determined as a fraction of Embamadre (stations upstream) or adapted from NEDECO (1998) as follows:

- For the locations Yechi and TK5 on Tekeze the monthly flows have been taken as a fraction of Embamadre, based on the product of area and average annual rainfall ratio's, respectively 0.485 and 0.695.
- For the locations Humera (Tekeze), Metema (Goang) and Abederafi (Angereb) the average monthly flow ratio's at the stations relative to Embamadre as presented in the Master Plan Study by NEDECO (1998) has been taken. Annual values for Metema and Abederafi have been adjusted to obtain a realistic distribution along Upper Atbara.
- The flow series of Humera has been transferred to Wad el Heliew on Setit by applying the area ratio.
- The difference between K3 and the sum of the flows at at Metema, Abederafi and Wad el Heliew after shifting the sum by 1/3 month foreward has been determined and after elimination of the negative flows and adjustment of the remaining positive flows to the correct annual value has been attributed to the downstream area as follows: 8/11 to the reach Metema-Rumela and 3/11 to the reach Rumela-Khashm el Girba.

The monthly and annual flow statistics of this procedure for the key locations have been presented in Table 6.32.

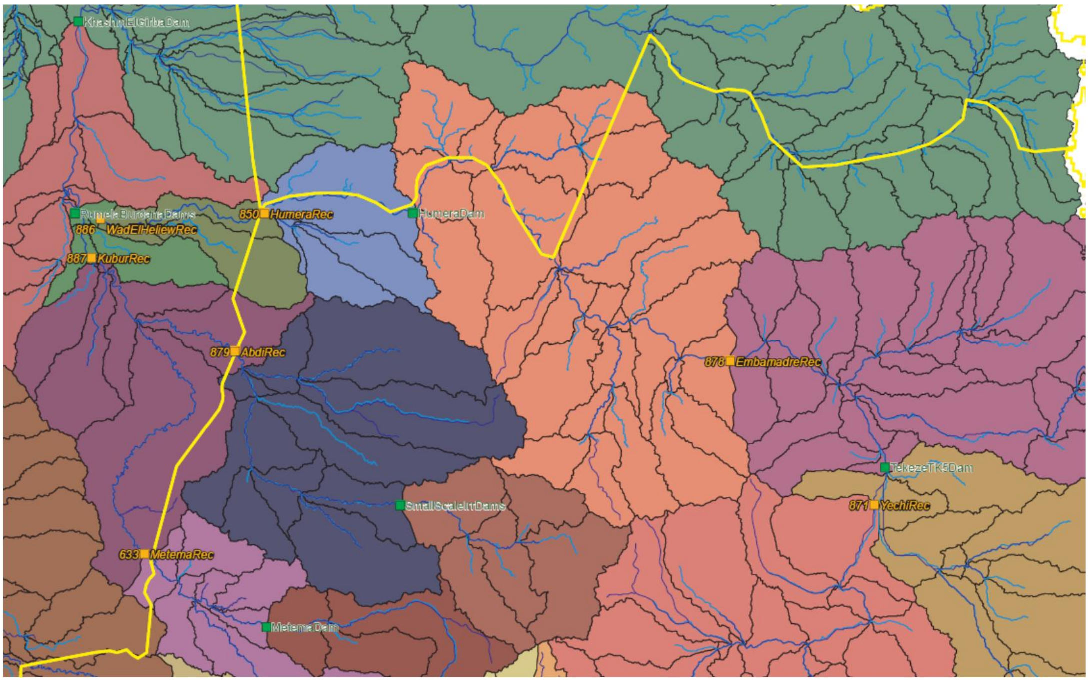

Figure 6.93 Hydrometric stations in Tekeze-Setit-Atbara sub-basin

Table 6.32 Monthly and annual flow statistics of key locations in Tekeze-Setit-Atbara basin upstream of K3, Period 1900-2002

Yechi	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Average	10.5	6.4	10.7	14.5	27.1	73.9	616.5	1204.1	439.0	97.6	29.7	17.6	2547.8
Stdv	5.3	3.2	6.0	7.3	14.6	36.0	299.1	570.9	247.9	59.0	14.7	9.0	1168.3
Cvar	0.51	0.50	0.56	0.51	0.54	0.49	0.49	0.47	0.56	0.60	0.50	0.51	0.46
Min	1.0	0.6	1.0	1.4	2.4	3.9	94.3	180.3	95.6	1.8	2.9	1.7	417.2
Max	27.6	16.0	38.8	40.3	89.7	175.5	1411.7	3044.2	1597.4	381.3	70.6	48.0	6332.6
TK5													
Average	15.0	9.2	15.3	20.8	38.9	105.9	883.7	1725.9	629.3	139.9	42.6	25.2	3651.7
Stdv	7.6	4.6	8.5	10.5	21.0	51.5	428.7	818.3	355.3	84.5	21.1	12.8	1674.5
Cvar	0.51	0.50	0.56	0.51	0.54	0.49	0.49	0.47	0.56	0.60	0.50	0.51	0.46
Min	1.5	0.9	1.5	2.0	3.5	5.6	135.2	258.5	137.0	2.5	4.1	2.5	598.0
Max	39.6	22.9	55.6	57.7	128.6	251.6	2023.5	4363.3	2289.6	546.5	101.2	68.8	9076.7
Embamadre													
Average	21.6	13.3	22.0	30.0	55.9	152.4	1271.0	2482.4	905.1	201.2	61.3	36.3	5252.4
Stdv	10.9	6.6	12.3	15.1	30.2	74.1	616.6	1177.0	511.1	121.6	30.4	18.5	2408.4
Cvar	0.51	0.50	0.56	0.51	0.54	0.49	0.49	0.47	0.56	0.60	0.50	0.51	0.46
Min	2.1	1.3	2.1	2.9	5.0	8.0	194.4	371.8	197.0	3.6	6.0	3.5	860.1
Max	57.0	33.0	80.0	83.0	185.0	361.9	2910.4	6275.8	3293.3	786.0	145.6	99.0	13055.2
Humera-station													
Average	32.1	19.7	32.7	44.5	83.1	226.4	1615.0	3154.2	1361.0	299.1	91.1	53.9	7012.9
Stdv	16.2	9.8	18.3	22.5	44.9	110.2	783.5	1495.5	768.5	180.7	45.2	27.4	3222.9
Cvar	0.51	0.50	0.56	0.51	0.54	0.49	0.49	0.47	0.56	0.60	0.50	0.51	0.46
Min	3.1	1.9	3.2	4.3	7.4	11.9	247.1	472.4	296.3	5.4	8.9	5.2	1159.6
Max	84.7	49.0	118.9	123.3	274.9	537.8	3698.1	7974.3	4952.1	1168.2	216.4	147.1	17672.9
Wad el Heliew													
Average	32.9	20.2	33.6	45.7	85.2	232.3	1657.0	3236.3	1396.4	306.9	93.5	55.3	7195.4
Stdv	16.6	10.1	18.7	23.1	46.0	113.0	803.9	1534.4	788.5	185.4	46.3	28.2	3306.7
Cvar	0.51	0.50	0.56	0.51	0.54	0.49	0.49	0.47	0.56	0.60	0.50	0.51	0.46
Min	3.2	2.0	3.3	4.4	7.6	12.2	253.5	484.7	304.0	5.5	9.1	5.4	1189.8
Max	86.9	50.3	122.0	126.5	282.1	551.8	3794.3	8181.8	5081.0	1198.6	222.1	151.0	18132.8
Metema													
Average	4.2	2.6	4.2	5.8	10.8	29.4	264.2	517.5	168.5	38.8	11.8	7.0	1064.8
Stdv	2.1	1.3	2.4	2.9	5.8	14.3	126.1	228.7	83.2	23.5	5.9	3.6	453.9
Cvar	0.51	0.50	0.56	0.51	0.54	0.49	0.48	0.44	0.49	0.60	0.50	0.51	0.43
Min	0.4	0.2	0.4	0.6	1.0	1.5	40.9	78.9	38.0	0.7	1.1	0.7	176.5
Max	11.0	6.4	15.4	16.0	35.7	69.8	612.1	1017.9	441.2	151.6	28.1	19.1	1973.0
Abederafi													
Average	6.5	4.0	6.6	9.0	16.7	45.5	441.4	857.8	262.9	59.9	18.3	10.8	1739.3
Stdv	3.1	1.9	3.6	4.4	8.8	21.3	200.0	356.9	125.4	34.1	8.7	5.3	699.7
Cvar	0.49	0.48	0.54	0.49	0.52	0.47	0.45	0.42	0.48	0.57	0.48	0.49	0.40
Min	0.7	0.4	0.7	0.9	1.5	2.4	74.5	142.4	63.9	1.1	1.9	1.1	312.2
Max	17.3	10.0	24.3	25.3	56.3	100.4	954.3	1550.2	686.5	219.0	43.1	29.8	3007.8
Rumela													
Average	11.5	7.1	11.0	15.4	30.6	185.2	1103.9	1786.8	548.1	115.7	32.2	18.4	3865.9
Stdv	7.9	5.1	6.0	9.0	19.1	90.9	281.5	371.5	201.8	55.4	17.1	8.9	623.1
Cvar	0.69	0.72	0.55	0.59	0.62	0.49	0.25	0.21	0.37	0.48	0.53	0.48	0.16
Min	1.1	0.7	1.1	1.5	2.5	20.9	343.3	521.2	178.4	17.6	3.1	1.8	1410.4
Max	68.8	44.9	39.8	70.0	122.5	487.0	1932.3	2511.2	1125.8	370.7	97.7	49.0	4995.7

Monthly flows using fraction of K3

As presented in Sub-section 6.4.2 instead of using regression relations a simpler procedure is obtained by taking the flows as a fixed percentage of the flow at K3. The fraction is based on the basin area ratio corrected for areal rainfall ratios. To account for travel time a backward shift of the flow at K3 of 1/3 month has been applied for the stations in Ethiopia and Wad el Heliew and a shift of 1/6 month downstream.

Rainfall values have been taken from Howard Humpreys et al. (1997) (used on Tekeze and Setit in transferring Embamadre flows) and average annual flow values as presented by Assefa Guchie DELTA DMCS, Data Collection and compilation on Environment and related issues in Eastern Nile Sub-Basin in Ethiopia, ENTRO, 2006 in transferring Embamadre flows to Metema and Abederafi.

The flow at K3 has been partitioned over the Atbara upstream of Khashm el Girba as shown in Table 6.33 in relation to contributing area and rainfall.

Table 6.33 Fraction of flow in Atbara at K3 attributed to locations upstream after shifting K3 flows backward in time by resp 1/3 and 1/6 month

Station	River	Percentage of K3
Yechi	Tekeze	22.14
TK5	Tekeze	31.74
Embamadre	Tekeze	45.65
Humera	Tekeze	62.74
Wad el Heliew	Setit	64.23
Abederafi	Angereb	15.53
Metema	Goang	9.21
Metema-Rumela	Atbara	8.00
Rumela-Khashm el Girba	Atbara	3.04
K3	Atbara	100.00

Above procedure is more approximate than the regression based method, but in view of the non-availability of the reliable flow values for all stations except a short period for Embamadre both procedures have their weaknesses and advantages. Nevertheless, based on a better reproduction of the monthly flow distribution in the simulated results the regression approach is advocated.

6.4.4 Atbara at K3

The flow in the Atbara is based on the record of station K3, which has published flow data (Nile Control Staff, 2007) for the period 1903-2002. These series have been adjusted for the period 1903-1924 based on instructions presented in Nile Volume IV. The blank fields in the discharge record have been checked on missing or zero values, based on water levels and records of discharge measurements.

To arrive at natural series, observed flows as from 1964 onward have been corrected for abstractions and evaporation losses at Khashm El Girba reservoir, according to annual abstraction figures from the Nile Water Sector, see Figure 6.94. The distribution of the correction (= abstraction + evaporation losses) over the months has been done according to standard reservoir filling curve of 50 days duration, starting on 25 August: i.e = 6/50 of the annual correction added to August, 30/50 to September and 14/50 to October.

Completion of series of the period 1900-1902 has been based on correlation with annual flow from Blue Nile series of Khartoum (see Figure 6.95), using the average monthly percentages for the flow distribution within the year.

A comparison of the natural and observed annual flow of the Atbara at K3 is given in Figure 6.96. The long term average annual flow series of the Atbara at K3 as applied in ENSWM amounts 11,506 Mm^3/yr with a standard deviation of 3,647 Mm^3/yr. This includes the reductions made for the flow in the years 1909, 1916 and 1917, to improve the calibration of ENSWM for the Nile at Aswan. The natural annual flow at K3 with the 11-year moving average is shown in Figure 6.97. It shows that simulation periods shorter than 1003 years have to be selected with care to include climatic features.

The statistics of the monthly flows are presented in Table 6.34 and Figure 6.98. It is observed that the Atbara carries only substantial amounts of water in the months July to October, similar to the Dinder and Rahad.

Table 6.34 Monthly and annual flow statistics (Mm3) of the Atbara at K3, Period 1900-2002

K3	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Average	11.9	3.6	1.2	4.0	30.4	526.6	2699.7	4705.6	2726.9	663.9	100.2	32.2	11506.2
Stdev	22.4	11.0	5.6	17.9	55.1	291.6	948.3	1542.4	1093.8	349.4	91.7	36.5	3647.4
Cvar	1.88	3.05	4.49	4.50	1.82	0.55	0.35	0.33	0.40	0.53	0.92	1.13	0.32
Min	0.0	0.0	0.0	0.0	0.0	0.0	598.4	1036.6	883.5	150.7	0.0	0.0	2965.8
Max	155.0	90.0	42.7	124.3	325.7	1511.3	5160.0	9337.1	7879.0	2280.3	457.3	142.7	22970.3

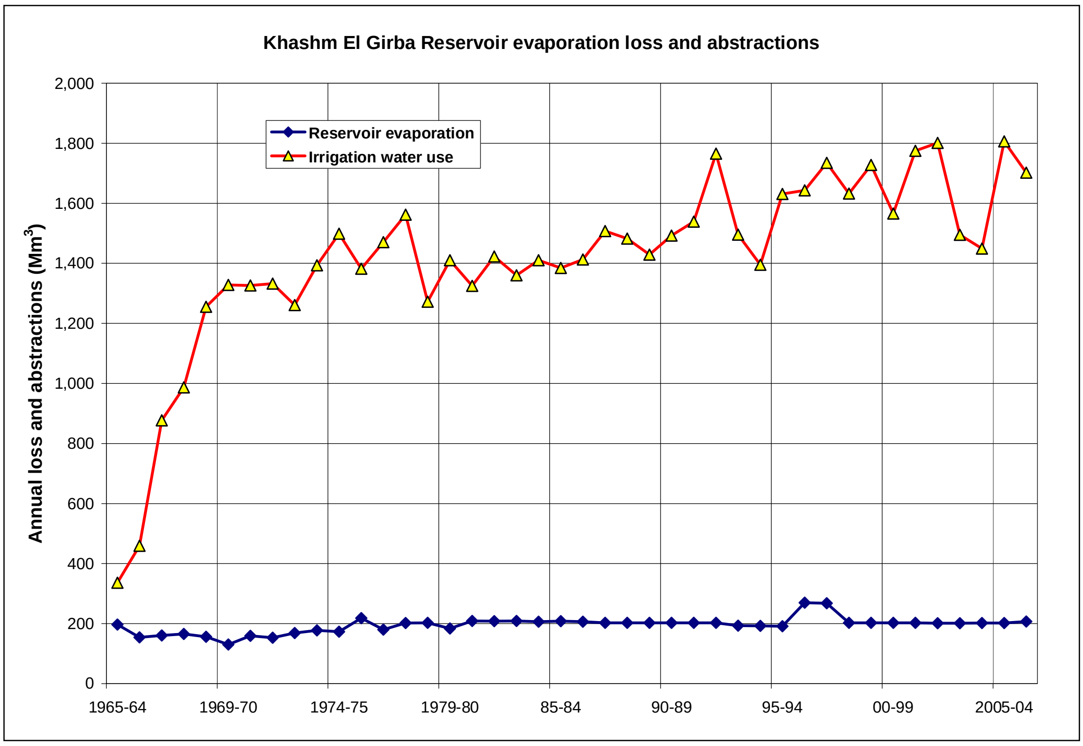

Figure 6.94 Annual evaporation loss and irrigation abstractions at Khashm el Girba reservoir

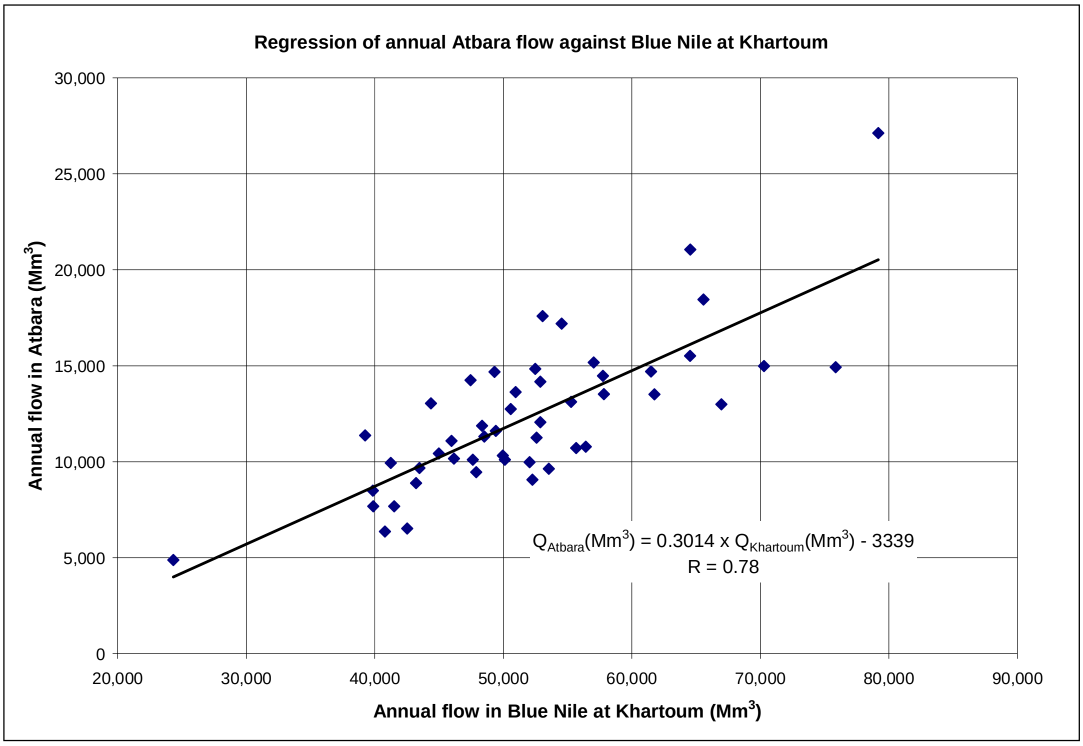

Figure 6.95 Regresion of annual Atbara flow against the Blue Nile at Khartoum

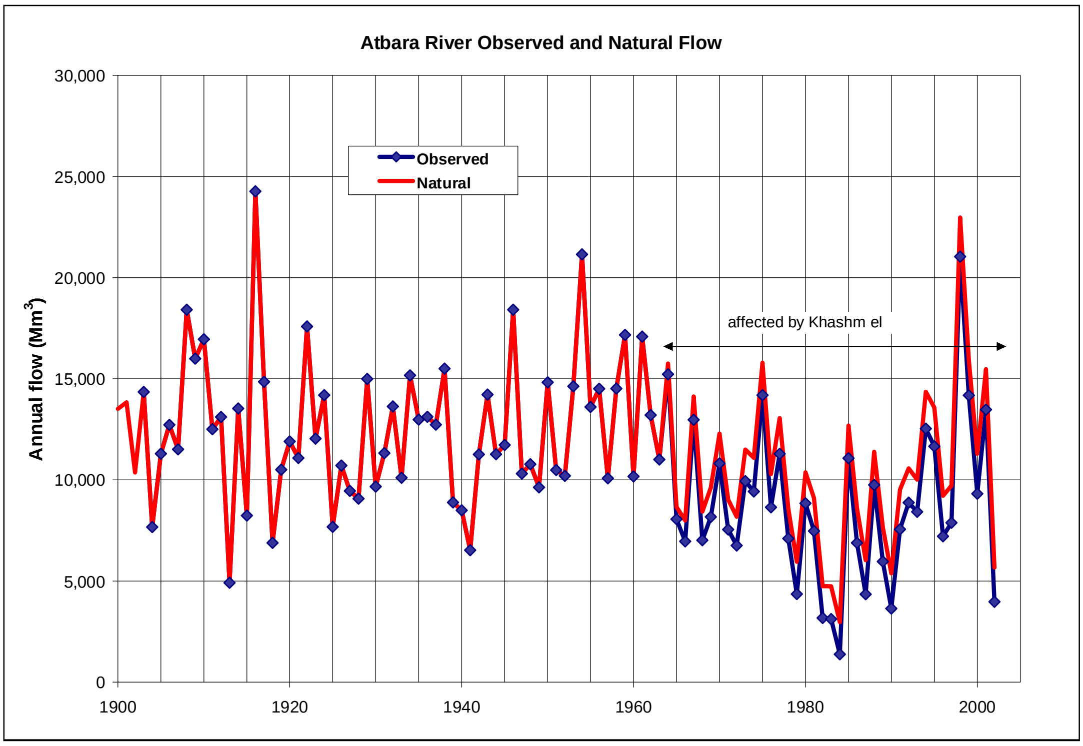

Figure 6.96 Annual natural and observed flow in the Atbara at K3, period 1900-2002

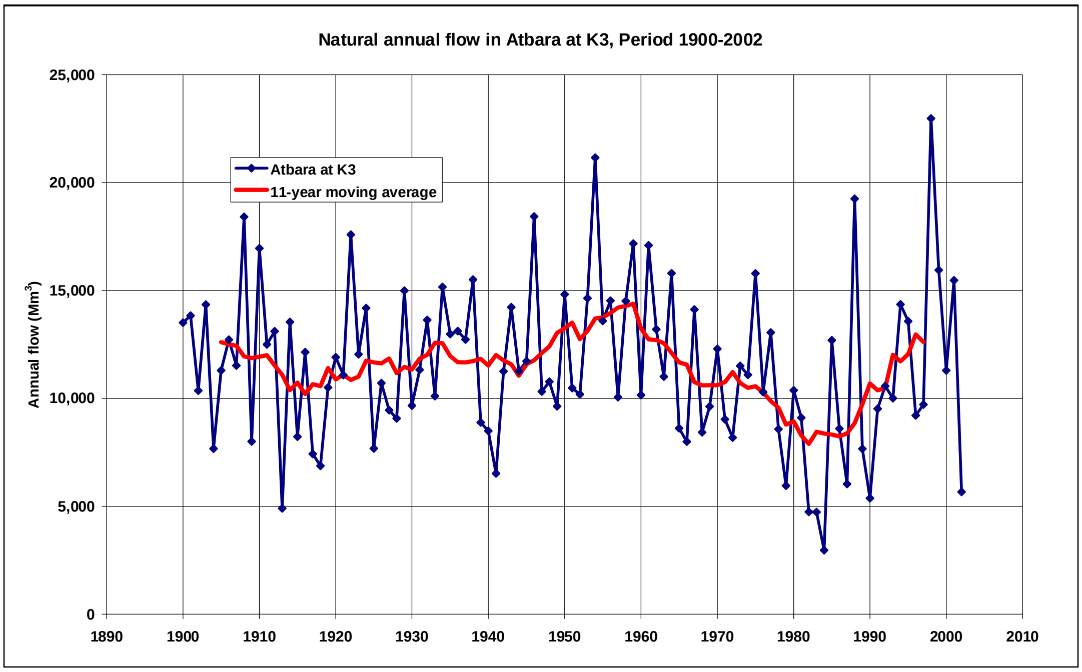

Figure 6.97 Natural annual flow in Atbara at K3 with 11-year moving average, Period 1900-2002

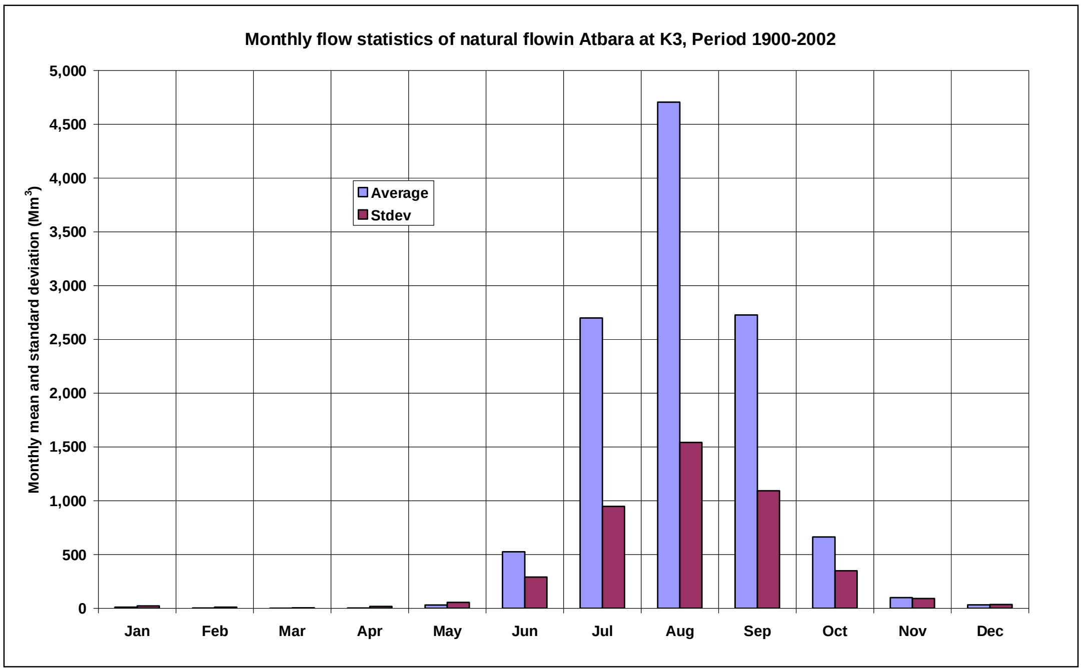

Figure 6.98 Statistics of the natural monthly flow of the Atbara at K3, period 1900-2002

Consistency checks for the natural flow in the Atbara at K3 have been made with double mass analyses versus the Blue Nile at Khartoum, Figure 6.99, and the Rahad at mouth in Figure 6.100. It is observed that the long term variation of the natural K3 series is very similar to those of the flows in the Blue Nile and Rahad rivers. The series can considered to be mutually consistent.

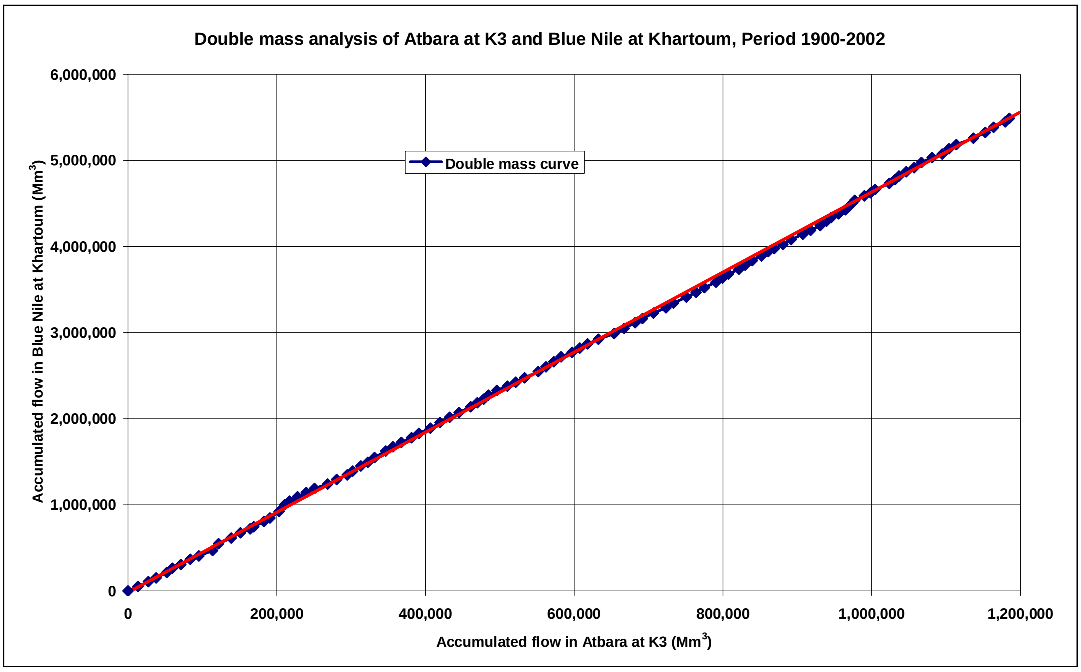

Figure 6.99 Double mass analysis of natural flows in Atbara at K3 versus Blue Nile at Khartoum, Period 1900-2002

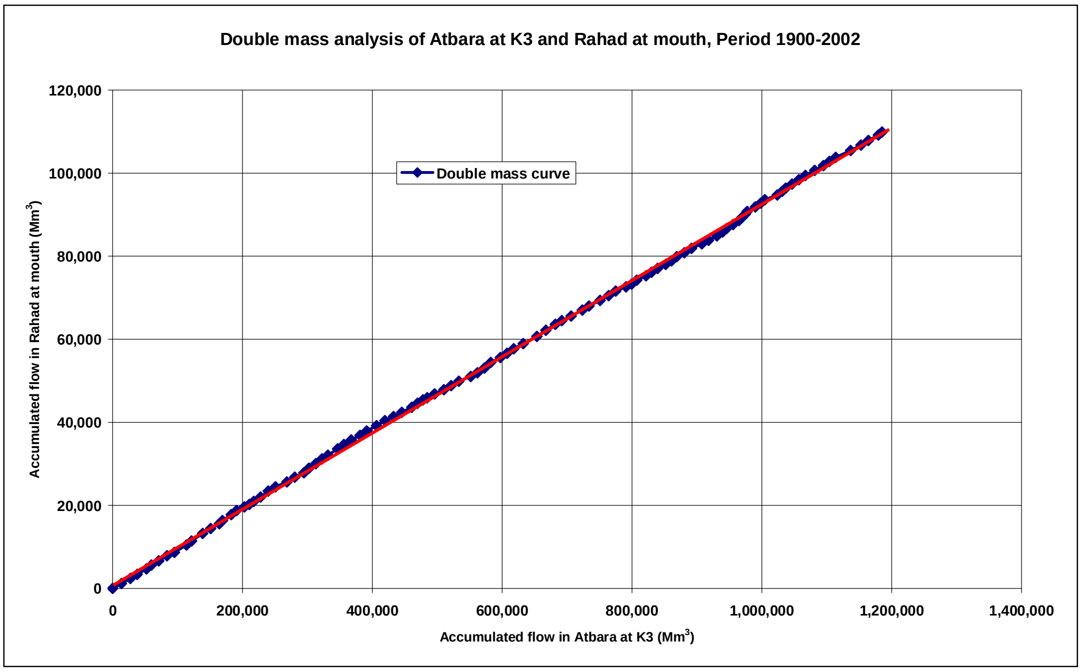

Figure 6.100 Double mass analysis of natural flows in Atbara at K3 versus Rahad at mouth, Period 1900-2002

6.5 Main Nile sub-basin

Main Nile at Aswan

The natural Nile flow at Aswan as used in ENSWM is based on the procedure used by the Nile Forecast Centre and is computed from (6-22):

$$Q_{natural} = HAD_{release} + \Delta S_{LakeNasser} + Loss_{LakeNasser} + Spill_{Toshka} + \Delta S_{Sennar} + \Delta S_{Roseires} + \Delta S_{KhasmelGirba} + Loss_{JebelAulia} + Sudan_{Abstractions}$$

where:

$Q_{natural}$ = natural Nile flow
$HAD_{release}$ = release from High Aswan Dam
$Loss_{Lake\ Nasser}$ = evaporation loss from Lake Nasser = lake area x evaporation rate
Spill Toska = spillage to Toshka
ΔS_{Sennar} = change in storage in Sennar reservoir
$\Delta S_{Roseires}$ = change in storage in Roseires reservoir
$\Delta S_{Khasm\ el\ Girba}$ = change in storage in Khasm el Girba reservoir
$oss_{Jebel\ Aulia}$ = losses from Jebel Aulia reservoir
$Sudan_{abstractions}$ = Sudan abstractions

The procedures used for the various components of (6-22) are discussed in the following. The computational procedure has been reviewed by WL|Delft Hydraulics (2007).

HAD release

The release to the Nile as a function of the water level downstream of OAD (Old Aswan Dam) can be described by the following rating equation:

$$HAD_{release} = c(H_{OAD\,d/s} + a)^b \qquad (6\text{-}23)$$

with: $H_{OAD\,d/s}$ = water level d/s of Old Aswan Dam

The releases to the Nile d/s Aswan are derived from the sluice discharges of OAD. The discharge rating is regularly updated.

Storage-elevation and surface area-elevation of Lake Nasser

The storage-elevation curve for Lake Nasser reads:

$$\Delta S_{HAD} = S_{HAD}(t+1) - S_{HAD}(t)$$
$$S_{HAD} = \left[1465 - 20.52 H_{HAD} + 0.0734 H_{HAD}^2\right] x1000 \quad [MCM] \qquad (6\text{-}24)$$

Lake evaporation

The loss at Lake Nasser comprises the evaporation loss computed from an evaporation rate times the surface area of Lake Nasser:

$$Loss_{LakeNasser} = A_{HAD} x E_{HAD} \quad [MCM]$$
$$A_{HAD} = 37,300 - 546.7\overline{H}_{HAD} + 2.075\overline{H}^{2}_{HAD} \quad [10^6 m^2] \qquad (6\text{-}25)$$
$$\overline{H}_{HAD} = \frac{1}{2}\left(H_{HAD}(t+1) + H_{HAD}(t)\right) \quad [m + MSL]$$

The Lake Nasser evaporation rates as used in the computation of natural flow series are shown in and Table 6.35. As is observed from the table an annual total of 2706 mm is assumed.

Table 6.35 Figures for evaporation from Lake Nasser, evaporation losses from Jebel Aulia reservoir and Sudan abstractions

Month	**E_{HAD} (m)**	**$Loss_{Jebel\ Aulia}$ (MCM)**	**$Sudan_{abstractions}$ (MCM)**
January	0.168	284.11	1,172.650
February	0.150	337.26	829.050
March	0.178	364.65	708.403
April	0.190	222.39	503.909
May	0.220	67.34	556.860
June	0.230	19.18	887.750
July	0.280	30.91	1,328.390
August	0.300	112.84	1,689.290
September	0.310	170.22	1,961.375
October	0.270	287.27	1,769.675
November	0.220	209.50	1,452.880
December	0.190	269.81	1,263.810
Year	2.706	2,374.48	14,124.042

Jebel Aulia losses

Loss from Jebel Aulia reservoir (LossJebel Aulia) is presented in Table 6.35. It includes only evaporation losses. Change in storage is not taken into account.

Spill to Toshka

The Toshka depression is connected with Lake Nasser via Toshka Khor and Canal, with a weir at the end. The spillway was originally designed to convey 215 MCM/day at a level of 182 m+MSL. In reality the capacity appeared to be about 60% of the design capacity (135 MCM per day at 182 m+MSL). The capacity of the spillway is being upgraded in a number of pases as presented in Table 6.36. In 2004 the conditions according to Phase 1 were applied at Toshka. It is observed that with the full implementation the capacity will almost be doubled relative to Phase 1.

Sennar, Roseires, Sennar and Khasm el Girba reservoirs

Table 6.36 Toshka spillway rating curves

Phase	Capacity (m³/s) at level (m+MSL)			
	178	180	181	182
Original	0	500	1050	1600
Phase 1	162	961	1620	2407
Phase 2	394	1400	2153	3044
Phase 3	428	1516	2315	3264
Phase 4	589	1961	3013	4282

Sennar storage change

The change in storage of Sennar reservoir is computed from:

$$\Delta S_{Sennar} = S_{Sennar}(t+1) - S_{Sennar}(t)$$
$$S_{Sennar} = 1,310,812 - 6,378.59 H_{Sennar} + 7.76 H_{Sennar}^2 \qquad (6\text{-}26)$$

Roseires storage change

The change in storage of Roseires reservoir is computed from:

$$\Delta S_{Roseires} = S_{Roseires}(t+1) - S_{Roseires}(t)$$
$$S_{Roseires} = 1,771,230 - 7,659.19 H_{Roseires} + 8.28 H_{Roseires}^2 \qquad (6\text{-}27)$$

Khasm el Girba storage change

The change in storage of Khasm el Girba reservoir:

$$\Delta S_{Khashm\,el\,Girba} = S_{Khashm\,el\,Girba}(t+1) - S_{Khashm\,el\,Girba}(t)$$
$$S_{Khashm\,el\,Girba} = 511,640 - 2,268.065 H_{Khashm\,el\,Girba} + 2.514 H_{Khashm\,el\,Girba}^2 \qquad (6\text{-}28)$$

From the storage-elevation curves and the standard filling curves it can be deduced that the storage change in the month of September for Roseires, Sennar and Khashm el Girba is respectively in the order of 3100, 700 and 900 MCM. These values are subtracted for the same months, without making corrections for travel time.

Sudan abstractions

he abstractions for irrigation in the Sudan, as applied in the computation of the natural flow at Aswan, is presented in Table 6.37. Note that the total abstractions at Aswan are taken as 90% of the summed abstractions.

Table 6.37 Annual abstractions for irrigation in the Sudan (years 1960-2006) in Mm^3 (Source: NFC)

Year	Total abstraction at Aswan	Total water abstraction	Basins abstractions	Pumps	Sugar Kena-na	Assa-lya	Abu Namad	Suki	Rahad	West Sennar Sugar	Geneid	Khashm res Evap	KEG canal abstraction	Rosei-res res evap	Sennar res evap	Gezira &Managil
1961-60	5,542	6,122	462	1,695	-	-	-	-	-	-	-	-	-	-	245	3,720
1962-61	5,790	6,395	488	1,964	-	-	-	-	-	-	-	-	-	-	234	3,709
1963-62	5,562	6,143	472	1,950	-	-	-	-	-	-	-	-	-	-	244	3,477
1964-63	6,182	6,833	457	2,084	-	-	-	-	-	-	-	-	-	-	236	4,056
1965-64	6,699	7,444	375	2,423	-	-	-	-	-	-	-	197	336	-	289	3,824
1966-65	7,148	7,942	112	2,485	-	-	-	-	-	-	-	154	459	-	309	4,422
1967-66	8,844	9,826	180	2,612	-	-	-	-	-	-	-	161	877	272	324	5,401
1968-67	9,082	10,091	352	2,638	-	-	-	-	-	-	-	166	987	373	339	5,238
1969-68	8,703	9,670	352	1,821	-	-	-	-	-	-	-	156	1,255	319	304	5,462
1969-70	10,187	11,319	338	2,284	-	-	-	-	-	-	-	131	1,328	196	317	6,725
1971-70	10,504	11,672	439	3,016	-	-	-	-	-	-	-	160	1,326	365	307	6,059
1972-71	10,738	11,932	225	3,258	-	-	-	-	-	-	-	153	1,333	375	299	6,288
1973-72	10,437	11,597	3.00	3,332	-	-	-	-	-	-	-	169	1,261	386	315	6,131
1974-73	11,231	12,478	185	3,076	-	-	-	-	-	-	-	177	1,393	373	344	6,931
1974-75	11,304	12,560	243	2,944	-	-	-	-	-	-	-	173	1,499	414	347	6,940
1976-75	11,259	12,510	338	3,608	-	-	-	-	-	-	-	218	1,382	424	361	6,180
1977-76	11,304	12,560	187	3,039	-	-	-	-	-	-	-	180	1,471	397	343	6,944
1978-77	12,287	13,653	156	2,300	-	-	198	336	439	245	398	202	1,562	384	349	7,084
1979-78	11,054	12,282	162	2,500	-	42.9	90.8	253	433	285	314	202	1,273	407	318	6,001
1979-80	12,093	13,436	159	2,400	-	57.4	25.0	303	1,141	285	369	184	1,410	423	330	6,349
1981-80	11,466	12,741	159	2,760	-	77.4	32.8	234	918	250	308	209	1,325	422	322	5,722
1982-81	12,597	13,997	159	2,760	532	168	35.5	267	1,057	239	344	208	1,423	420	333	6,052
1983-82	12,624	14,027	6.00	2,582	679	173	48.9	320	977	363	247	209	1,360	501	319	6,243
1984-83	13,002	14,446	120	2,111	801	190	57.3	1,082	275	415	301	206	1,411	420	325	6,731
1985-84	12,732	14,147	164	2,491	875	222	53.1	357	1,240	283	249	208	1,385	412	322	5,885
1986-85	12,596	13,996	189	2,501	912	203	65.9	260	930	302	270	206	1,413	411	331	6,002
1987-86	12,006	13,340	181	2,059	882	191	43.7	317	1,165	304	314	203	1,508	416	342	5,414
1988-87	12,678	14,087	131	2,061	897	230	44.3	313	1,192	278	341	203	1,483	427	344	6,144
1989-88	12,118	13,465	180	2,108	825	206	76.6	339	1,099	255	288	203	1,429	468	368	5,620
1990-89	13,376	14,862	150	2,491	897	191	49.6	679	1,164	286	395	203	1,493	457	349	6,059
1991-90	13,471	14,968	150	2,328	868	201	60.6	381	1,173	367	453	203	1,539	402	325	6,518
1992-91	13,766	15,296	150	2,323	867	201	58.7	245	1,154	341	412	203	1,766	436	350	6,790
1993-92	12,651	14,056	150	2,371	869	224	61.4	283	1,019	292	347	193	1,496	440	348	5,963
1994-93	13,860	15,400	150	2,380	871	237	64.5	162	2,227	276	428	192	1,396	419	346	6,251
1995-94	13,585	15,095	150	2,290	880	249	65.2	294	2,145	276	428	192	1,631	389	361	5,745
1996-95	13,073	14,526	150	2,072	772	148	915	270	842	252	191	270	1,643	439	371	6,192
1997-96	14,021	15,579	150	2,074	744	154	515	458	904	238	194	268	1,735	432	358	7,355
1998-97	13,271	14,746	150	2,582	816	231	15.1	256	1,054	318	485	203	1,632	460	351	6,192
1999-98	11,979	13,310	150	2,317	775	224	7.5	168	847	295	454	203	1,728	492	365	5,285

2000-99	13,214	14,682	150	2,332	784	238	0.7	497	977	283	424	203	1,566	454	365	6,409
2001-00	13,543	15,048	150	2,360	793	236	6.3	215	1,034	319	488	203	1,775	464	355	6,651
2002-01	14,153	15,725	150	2,424	852	258	0.0	677	968	250	422	201	1,801	397	361	6,964
2003-2	13,855	15,394	150	2,451	884	290	0.0	641	956	248	436	201	1,495	433	321	6,887
2004-3	12,831	14,257	150	2,424	980	308	0.0	275	886	341	374	202	1,449	431	346	6,091
2005-04	14,857	16,508	150	2,493	929	315	0.0	412	1,158	277	494	202	1,806	431	346	7,495
2006-5	14,002	15,558	160	2,543	813	326	0.0	350	1,036	287	320	207	1,702	433	346	7,035
95-03	13,532	15,036	151	2,364	835	248	127	376	1,067	282	392	213	1,664	438	354	6,525
61-03	11,463	12,733	207	2,459	452	126	56.3	231	661	184	228	178	1,294	357	329	5,970
Max	14,857	16,508	488	3,608	980	326	915	1,082	2,227	415	494	270	1,806	501	371	7,495
Min	5,542	6,122	3.00	1,695	0.0	0.0	0.0	162	275	238	191	184	336	196	234	3,477

The total annual abstractions in the Sudan are displayed in Figure 6.101. It is observed that since the nineties hardly any increase of the abstractions is noticed.

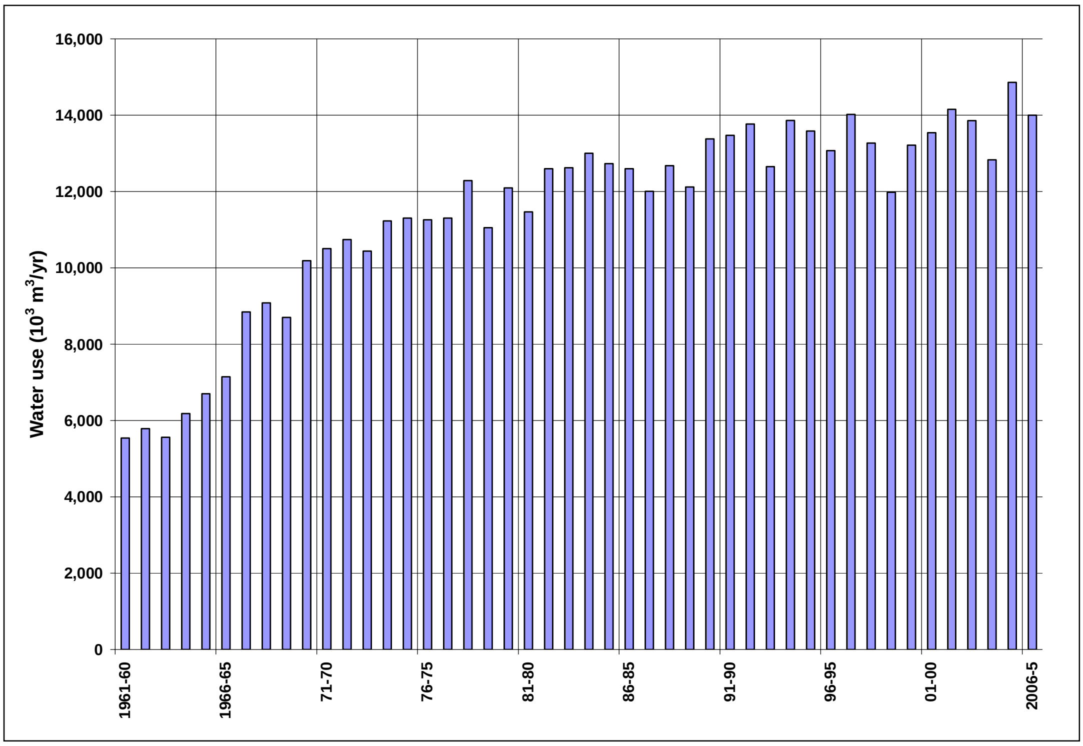

Figure 6.101 Annual abstractions for irrigation in the Sudan, since 1960

The monthly and annual statistics of the natural flow in the Main Nile at Aswan as derived by above procedure are presented in Table 6.38 and Figure 6.102. The annual natural flow series with 11-year moving average is shown in Figure 6.103. The natural flow series of the Main Nile at Aswan are consistent with the sum of the flows in the White Nile at Malakal, the Blue Nile at Khartoum and the Atbara at K3 as can be observed from Figure 6.104.

Table 6.38 Monthly and annual statistics (Mm^3) of the natural flow in the Main Nile at Aswan, 1900-2002

Aswan natural	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Average	4009.6	2989.9	2655.1	2584.5	2434.7	2282.8	4923.0	18125.9	20443.6	13406.0	7521.8	5072.4	86449.4
Stdev	743.3	763.7	750.6	1066.8	1050.4	868.4	1642.9	4144.0	4763.2	3794.2	1941.1	860.3	13682.8
Cvar	0.19	0.26	0.28	0.41	0.43	0.38	0.33	0.23	0.23	0.28	0.26	0.17	0.16
Min	1720.0	1150.0	1070.0	950.0	800.0	900.0	1740.0	6500.0	7311.0	5967.0	4062.0	2830.0	45630.0
Max	6570.0	6043.0	5813.0	5259.0	4715.0	4905.0	11029.0	29659.0	30209.0	22800.0	13300.0	7880.0	119967.0

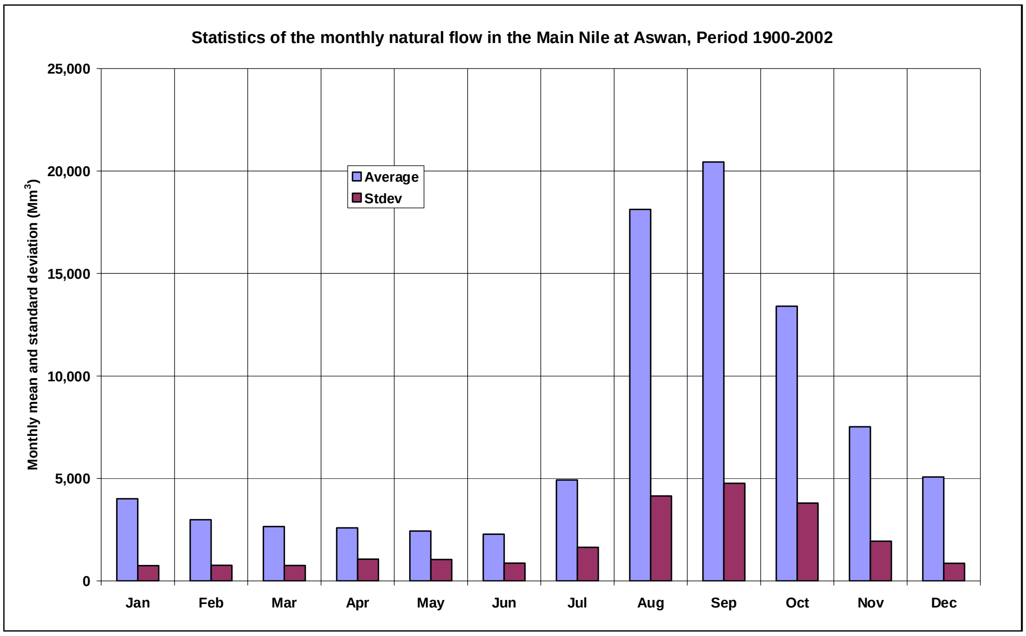

Figure 6.102 Monthly natural flow statistics of the Main Nile at Aswan, Period 1900-2002

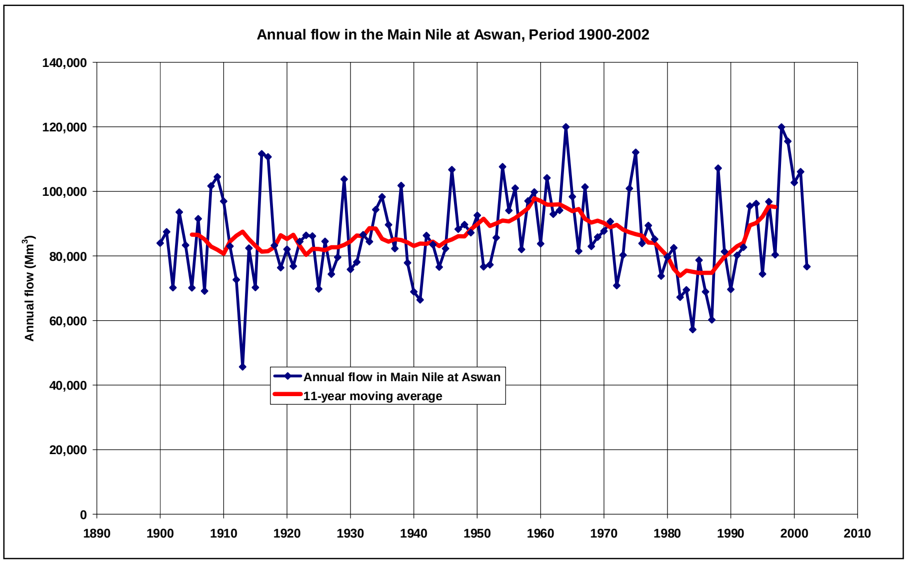

Figure 6.103 Annual natural flow in the Main Nile at Aswan with 11-year moving average, Period 1900-2002

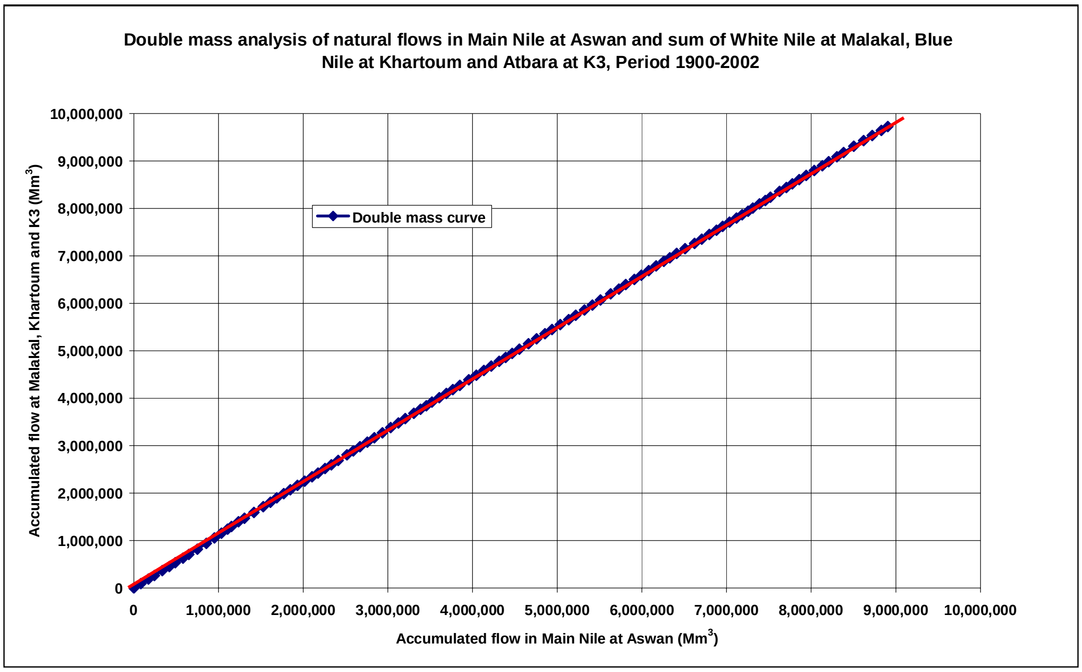

Figure 6.104 Double mass analysis of the natural flow in the Main Nile at Aswan with the sum of the flows in the White Nile at Malakal, the Blue Nile at Khartoum and the Atbara at K3, Period 1900-2002

6.6 Summary of flow statistics along the Nile

Based on the procedures discussed in the sub-sections 6.2 to 6.5 in Table 6.39 an overview is given of the average monthly and annual natural flows at key locations in the Nile Basin between Mongalla and Aswan. The averages are based on the observed, extended and adjusted flow series of the years 1900-2002. Such a long period was shown to be needed to cope with the non-stationarities present on the series. If a shorter period is considered the period has to be carefully selected to avoid unwanted biasses. Furthermore, due to the long term variations in the series, the use of generated data which do not deal with these variations is dissuaded.

The series presently available in ENSWM system are mutually consistent. For large scale projects on the main streams the series also are sufficient. However, for detailed irrigation studies taking water from upstream tributaries further partitioning of the data will generally be required. Such refinements are easily included in the model. The results from various Master Plan studies, referenced in this report, can be taken as a starting point. It is stressed that it will be required to properly validate those data, as in many occasions such information is missing, and reported data often differ considerably and are not consistent with the published isohyets.

Table 6.39 Average natural monthly and annual flow in Mm^3 at key locations in the Nile basin from Mongalla to Aswan, period 1900-2002

River	Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Baro-Akobo-Sobat-White Nile sub-system														
Baro	Baro-I	32.9	19.6	30.9	50.4	118	275	432	540	441	315	109	53.0	2,416
Baro	Baro-II	33.9	20.2	31.9	52.0	121	284	445	557	455	326	112	54.7	2,493
Genji	Genji	22.7	13.2	20.0	36.0	69.4	138	220	284	256	196	72.7	36.1	1,365
Birbir	Birbir	190	121	93.7	92.1	226	639	1,220	1,721	2,163	1,440	598	322	8,825
Baro	Gambela	246	156	146	178	417	1,062	1,886	2,563	2,874	1,962	783	413	12,685
Baro	Baro-mouth	246	155	146	180	410	922	1,398	1,646	1,698	1,408	726	411	9,345
Alwero	Abobo	17.8	9.3	8.6	12.4	42.1	66.1	84.8	105	94.6	85.9	43.5	24.9	595
Gilo	Pugnido	109	66	151	114	278	368	397	518	473	412	233	179	3,297
Pibor	Gilo US	241	137	103	32.7	31.6	49.4	96.3	242	375.6	387.2	376.1	271.7	2,343
Sobat	Hillet Doleib	950	406	246	211	388	829	1,285	1,570	1,732	1,936	1,920	1,674	13,147
W. Nile	Mongalla	2,699	2,428	2,506	2,569	2,956	2,883	3,145	3,534	3,525	3,460	3,177	2,925	35,805
Ghazal	Bahr el Gh.	54.3	10.2	5.1	10.9	164	485	1,108	2,070	3,111	2,979	1,347	318	11,663
Jebel	Sudd outfl.	1,463	1,348	1,433	1,345	1,357	1,288	1,352	1,415	1,413	1,478	1,364	1,393	16,650
W.Nile	Malakal	2,491	1,772	1,675	1,525	1,694	2,055	2,558	2,911	3,099	3,384	3,311	3,150	29,626
Abay-Blue Nile sub-system														
L.Tana	Tana inflow	97.4	71.2	88.6	59.6	38.2	137	1,059	2,050	1,230	444	109	48.6	5,432
Abay	Bahir Dar	231	146	107	80	49.9	39.1	105	449	992	874	557	379	4,009
Abay	Kessie	347	220	211	186	181	203	2,449	6,305	3,350	1,500	845	534	16,331
Abay	Guder DS	439	277	270	230	219	258	3,039	7,852	4,382	1,861	997	651	20,475
Abay	Beko Abo	483	302	284	244	262	413	3,429	8,676	5,284	2,420	1,194	741	23,731
Abay	Shogole	731	444	364	321	504	1,293	5,639	13,350	10,403	5,590	2,307	1,252	42,197
B.Nile	Deim	820	495	387	348	588	1,619	6,434	15,032	12,245	6,731	2,708	1,436	48,842
Dinder	Dinder	0.0	0.0	0.0	0.0	0.0	7.8	353	1,017	982	371	52.8	10.9	2,795
Rahad	Rahad	0.0	0.0	0.0	0.0	0.0	1.5	117	335	348	233	29.9	2.9	1,067
B.Nile	Khartoum	824	479	358	309	528	1,568	6,851	16,527	13,896	7,605	2,861	1,483	53,289
Tekeze-Setit-Atbara sub-system														
Tekeze	Yechi	10.5	6.4	10.7	14.5	27.1	73.9	617	1,204	439	97.6	29.7	17.6	2,548
Tekeze	TK5	15.0	9.2	15.3	20.8	38.9	106	884	1,726	629	140	42.6	25.2	3,652
Tekeze	Embamadre	21.6	13.3	22.0	30.0	55.9	152	1,271	2,482	905	201	61.3	36.3	5,252
Tekeze	Humera-dam	30.7	18.9	31.3	42.5	79.4	216	1,544	3,015	1,301	286	87.1	51.6	6,704
Tekeze	Humera stn	32.1	19.7	32.7	44.5	83.1	226	1,615	3,154	1,361	299	91.1	53.9	7,013
Goang	Metema	4.2	2.6	4.2	5.8	10.8	29.4	264	517	169	38.8	11.8	7.0	1,065
Angereb	Abederafi	6.5	4.0	6.6	9.0	16.7	45.5	441	858	263	59.9	18.3	10.8	1,739
Atbara	Rumela	11.5	7.1	11.0	15.4	30.6	185	1,104	1,787	548	116	32.2	18.4	3,866
Atbara	Met.-Rumela	0.8	0.5	0.2	0.7	3.2	110	398	412	117	17.0	2.0	0.5	1,062
Setit	W. Heliew	32.9	20.2	33.6	45.7	85.2	232	1,657	3,236	1,396	307	93.5	55.3	7,195
Atbara	Rum.-Girba	0.3	0.2	0.1	0.3	1.3	47.3	170	171	46.6	6.9	0.9	0.2	445
Atbara	K3	12.0	3.6	1.2	4.0	30.4	527	2,700	4,706	2,727	664	100	32.2	11,506
Main Nile sub-system														
M. Nile	Aswan	4,010	2,990	2,655	2,585	2,435	2,283	4,923	18,126	20,444	13,406	7,522	5,072	86,449

7 Model validation

7.1 General

The ENSWM has been validated based on the reproduction of the natural flow conditions as derived in the previous chapter. In a number of cases the partitioned flow upstream of a measuring station has been derived as a fraction of the flow at the \measuring station. In such case the observed/natural flow should exactly be reproduced by the model provided that the routing component in the model is not switched on; if switched on deviations may occur due to attenuation. In other cases the functioning of hydraulic infrastructure like swamps and lakes, which is only approximately simulated by the model, prohibits an exact reproduction of the observed/natural flow conditions. An approximate result is acceptable provided that the differences between the simulated and observed flows are small. In this chapter the reproduction of the monthly flow statistics, annual flow and consistency checks between model results and observations by mean of double mass analysis is discussed.

7.2 Baro-Akobo-Sobat-White Nile sub-basin

In the Baro-Akobo-Sobat-White Nile sub-basin at all locations consistency checks have been carried out. Except for the Sobat at Hillet Doleib and the White Nile at Malakal, the validation is no more than a check on full reproduction of the original as a closed water balance of flows has been the basis for partitioning. In the Sobat, however, muskingum routing is applied, whereas Malakal on the White Nile is located directly downstream of the Sudd swamps, modelled by a linear reservoir above a threshold inflow. The ENSWM validation results for the Sobat at Hillet Doleib and the White Nile at Malakal are presented in Figure 7.1 to Figure 7.6. It is observed that the monthly flow statistics and annual flow series are properly reproduced by the model and that the simulated flows are fully consistent with the observations at both sites. Hence, the variable inflows as applied in the ENSWM for the Baro-Akobo-Sobat-White Nile sub-system correctly simulate the observed and extended flows developed in the previous chapter.

For projects on Birbir and in the upper regions of Alwero, Gilo and Akobo further partitioning of the currently assumed flows is required.

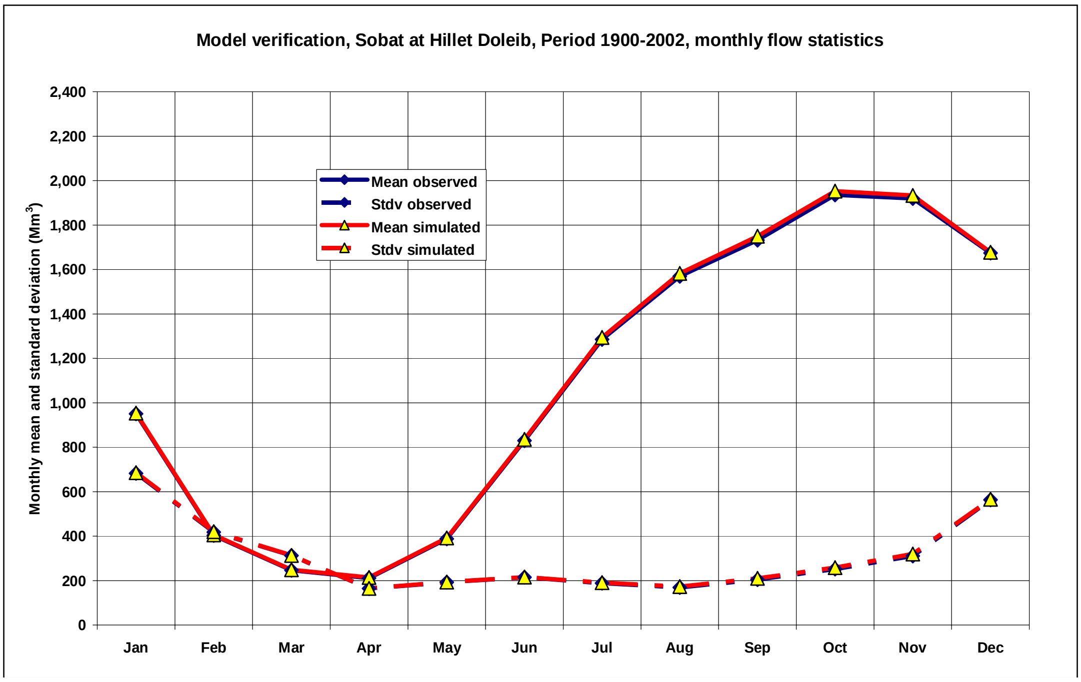

Figure 7.1 Model verification of the Sobat at Hillet Doleib, Period 1900-2002, monthly flow statistics

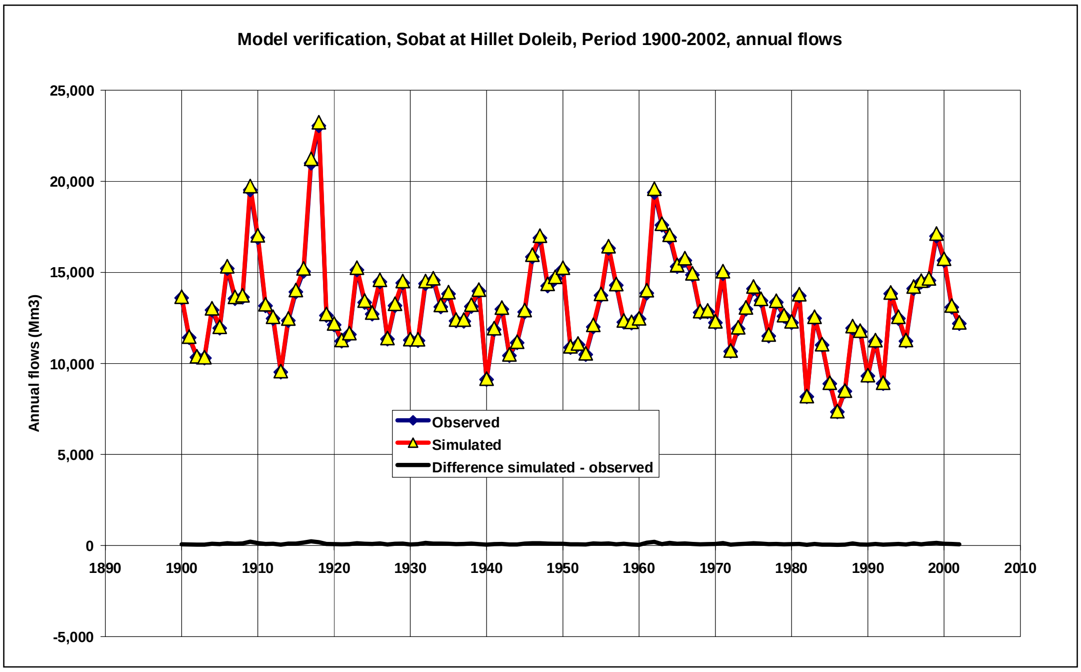

Figure 7.2 Model verification of the Sobat at Hillet Doleib, Period 1900-2002, annual flows

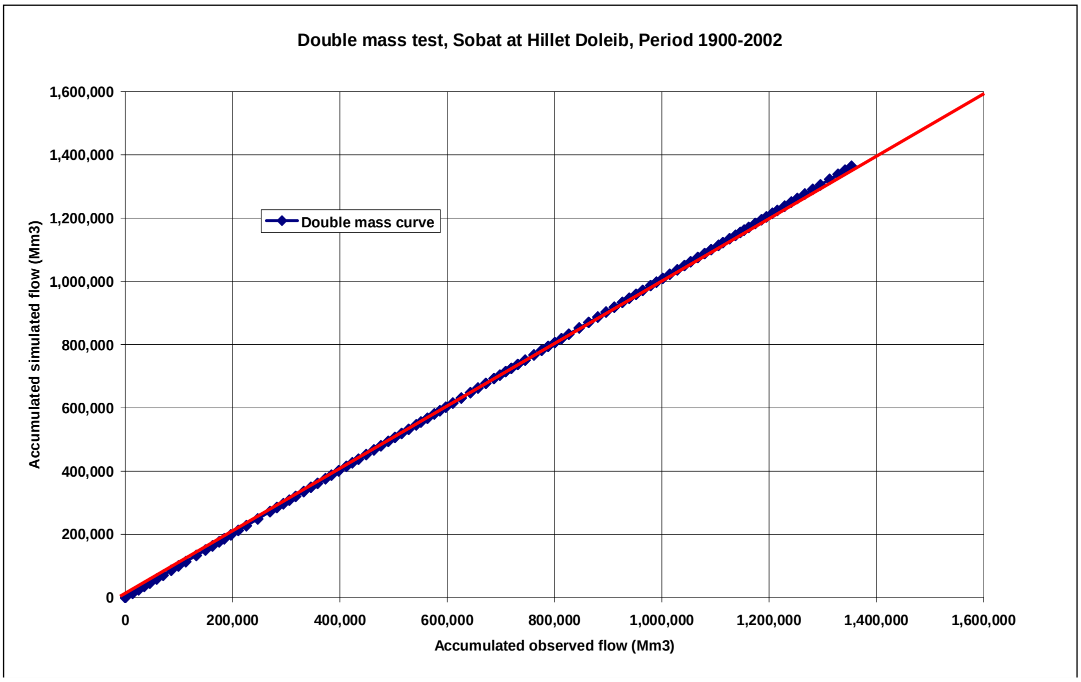

Figure 7.3 Consistency check on observed and simulated flow in the Sobat at Hillet Doleib by double mass analysis, Period 1900-2002

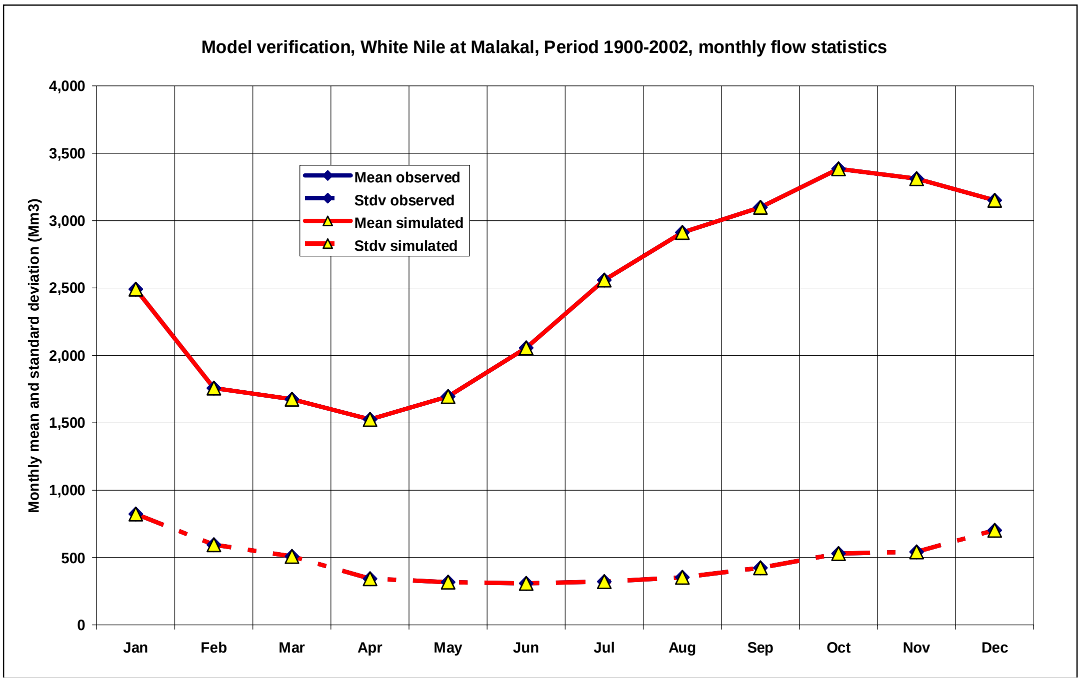

Figure 7.4 Model verification of the White Nile at Malakal, Period 1900-2002, monthly flow statistics

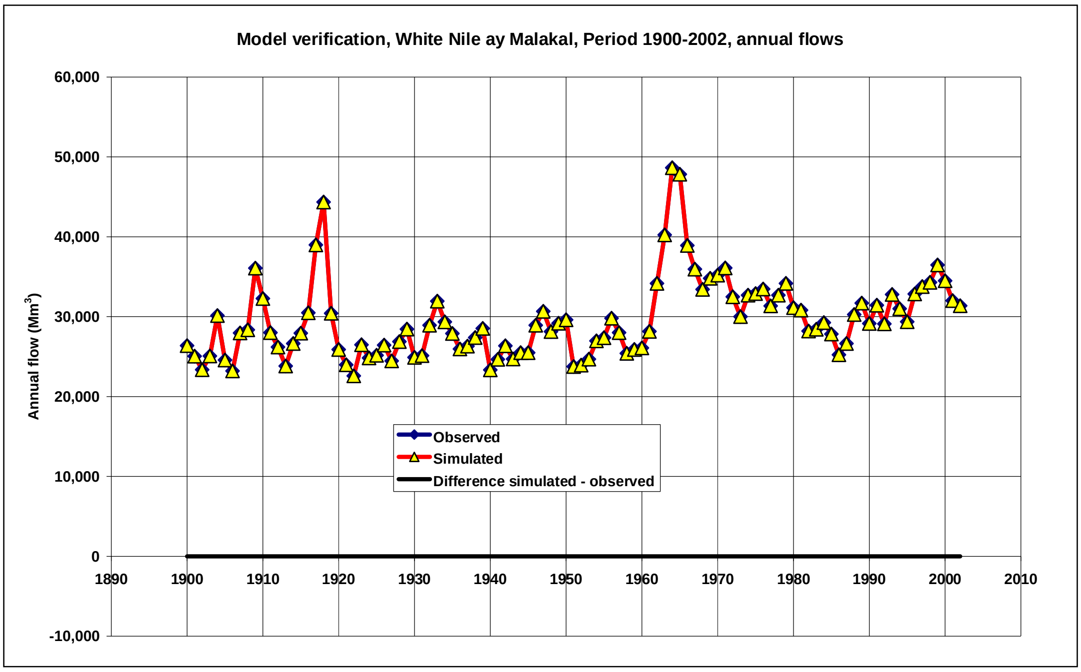

Figure 7.5 Model verification of the White Nile at Malakal, Period 1900-2002, annual flows

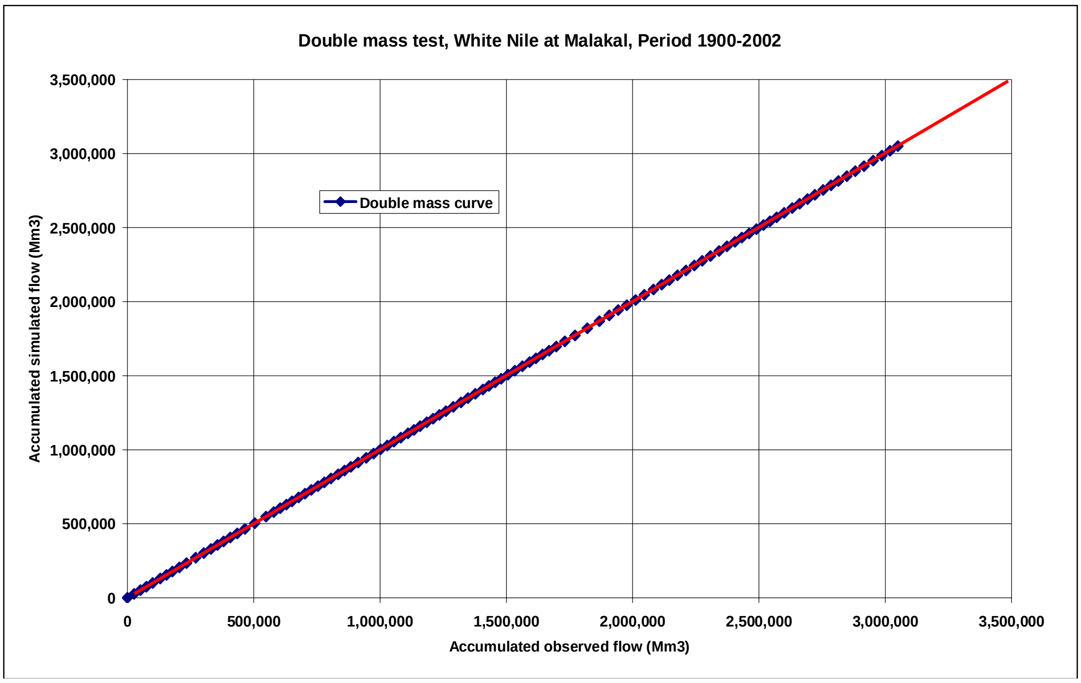

Figure 7.6 Consistency check on observed and simulated flow in the White Nile at Malakal by double mass analysis, Period 1900-2002

7.3 Abay-Blue Nile sub-basin

The ENSWM validation for the Abay and Blue Nile has been carried out for the Lake Tana outflow at Bahir Dar and further downstream hydrometric stations on Abay and Blue Nile at Kessie, Guder DS, Bure or Beko Abo, Shogole, Deim and Khartoum. The results are presented in Figure 7.7 to Figure 7.27.

For all locations an acceptable reproduction of the observed/normalised monthly flow statistics and annual flow series obtained with the model. The small differences observed in between the normalised and simulated flow in the Blue Nile at Khartoum in the first decades of the last century are due to a reduction in the flow of Rahad and Dinder introduced to improve simulation result at Aswan; if these corrections had not been made the results for Khartoum for these decades would have been closer.

The excellent reproduction at the key stations does not mean that for upstream locations in the sub-basins the inflows will be acceptable due to the applied flow partitioning based on the main stream flows; local adjustment will be required to arrive at unbiased results. Note further that ENSWM exactly reproduces the flow series assumed for Rahad and Dinder.

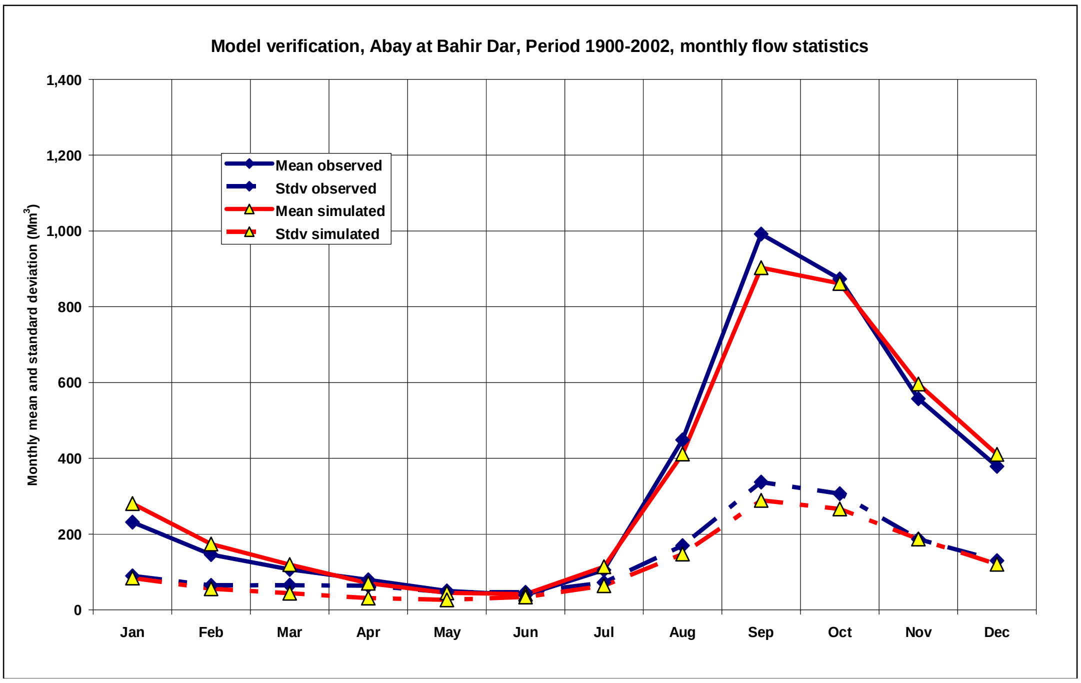

Figure 7.7 Model verification of the Abay at Bahir Dar, Period 1900-2002, monthly flow statistics

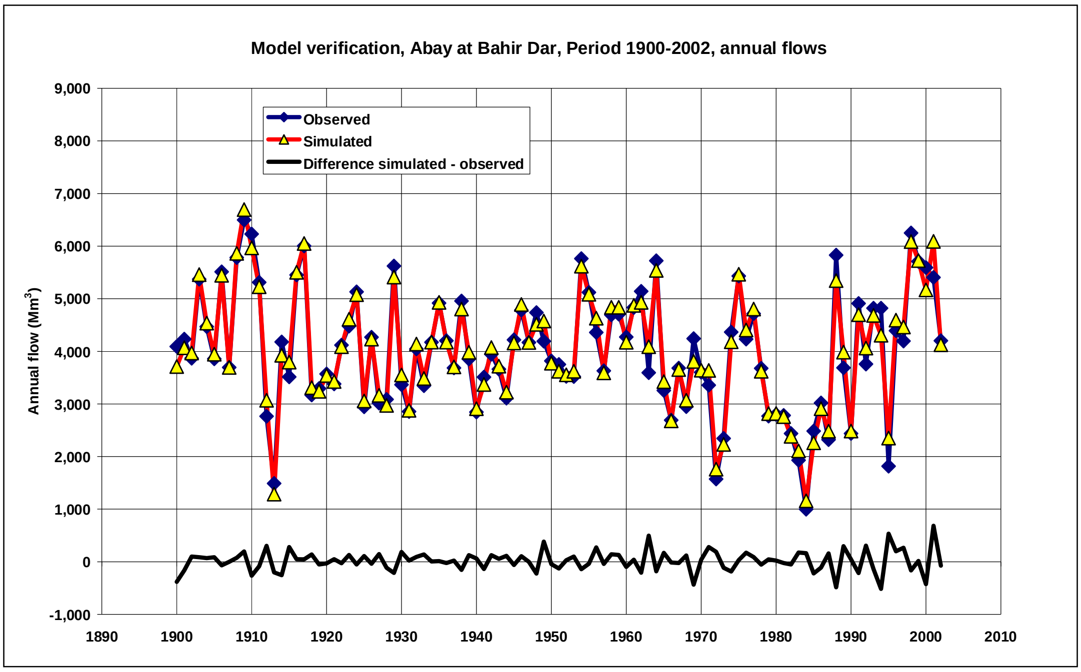

Figure 7.8 Model verification of the Abay at Bahir Dar, Period 1900-2002, annual flows

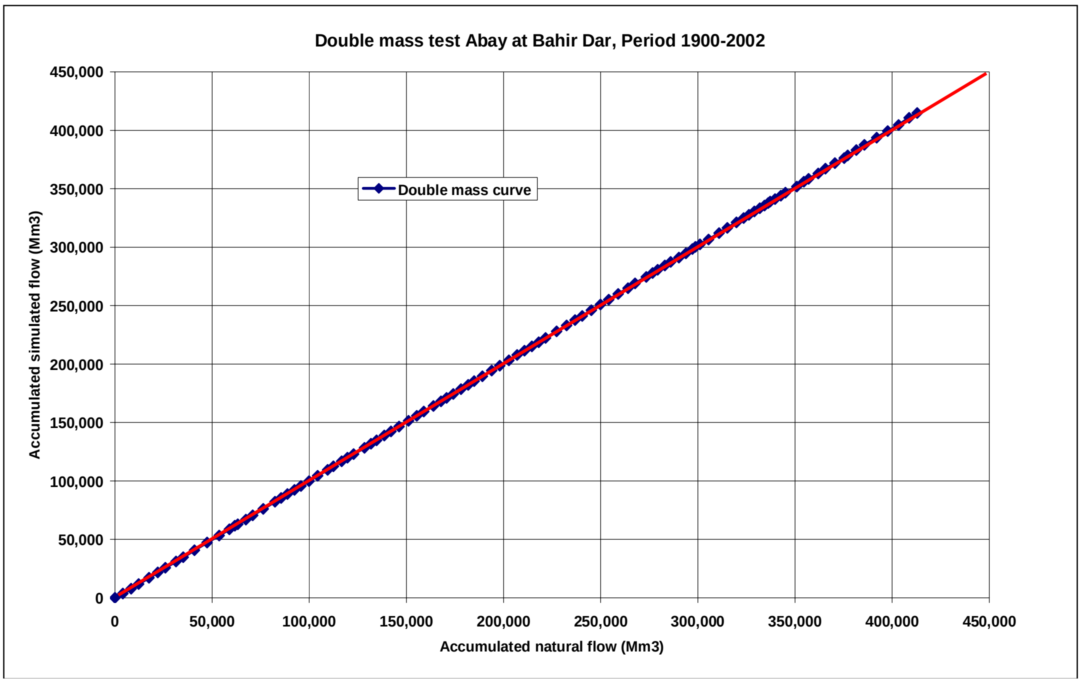

Figure 7.9 Consistency check on observed and simulated flow in the Abay at Bahir Dar by double mass analysis, Period 1900-2002

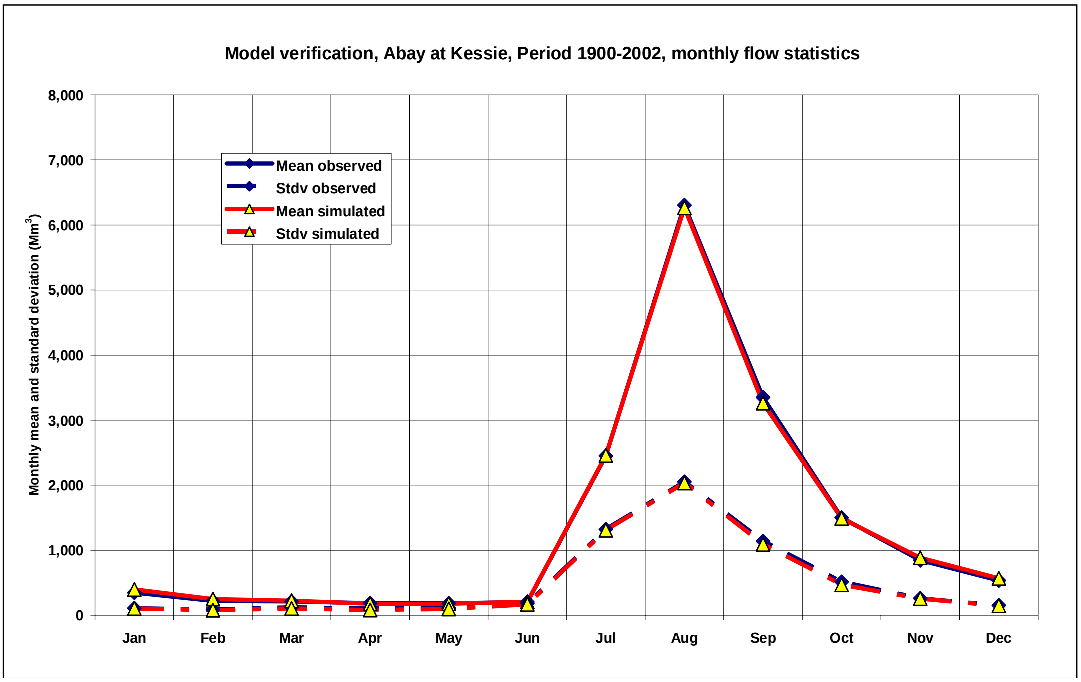

Figure 7.10 Model verification of the Abay at Kessie, Period 1900-2002, monthly flow statistics

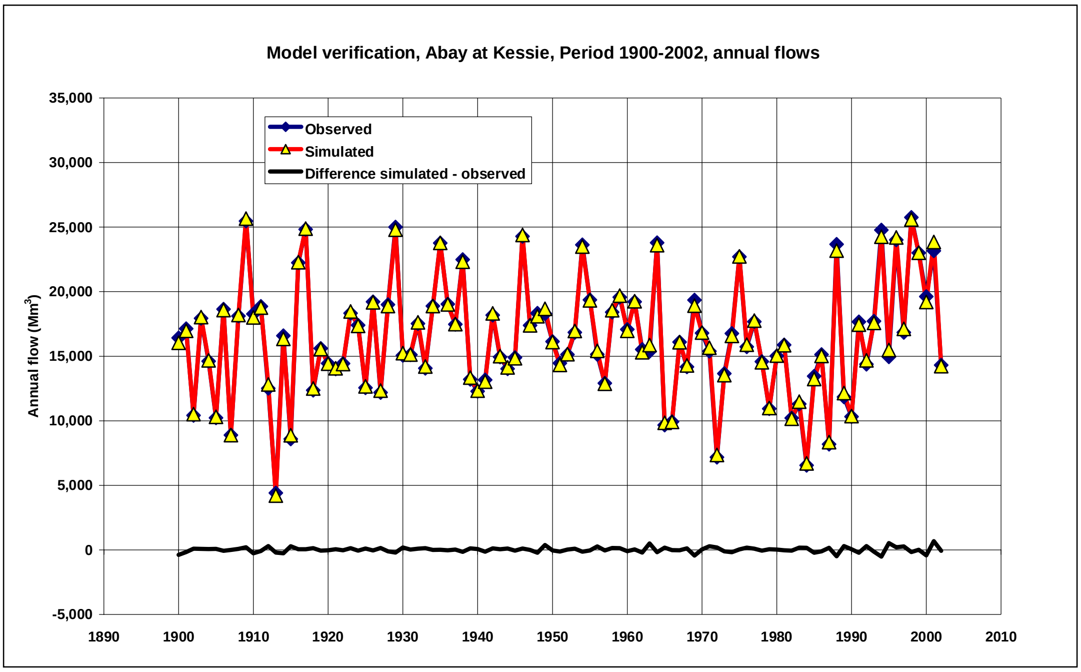

Figure 7.11 Model verification of the Abay at Kessie, Period 1900-2002, annual flows

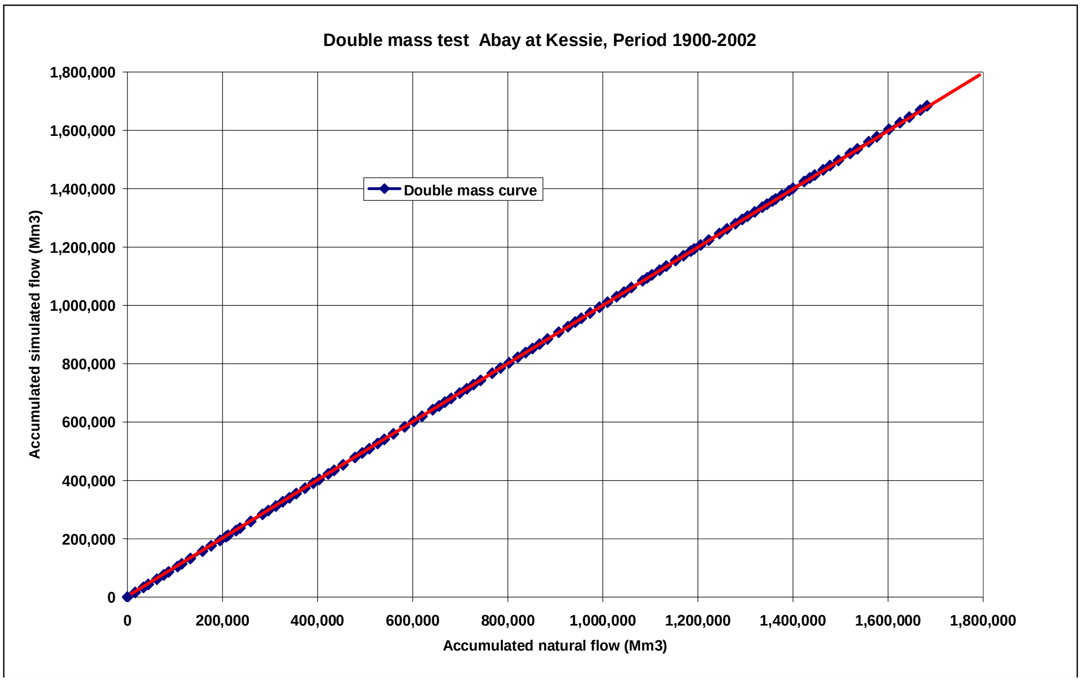

Figure 7.12 Consistency check on observed and simulated flow in the Abay at Kessie by double mass analysis, Period 1900-2002

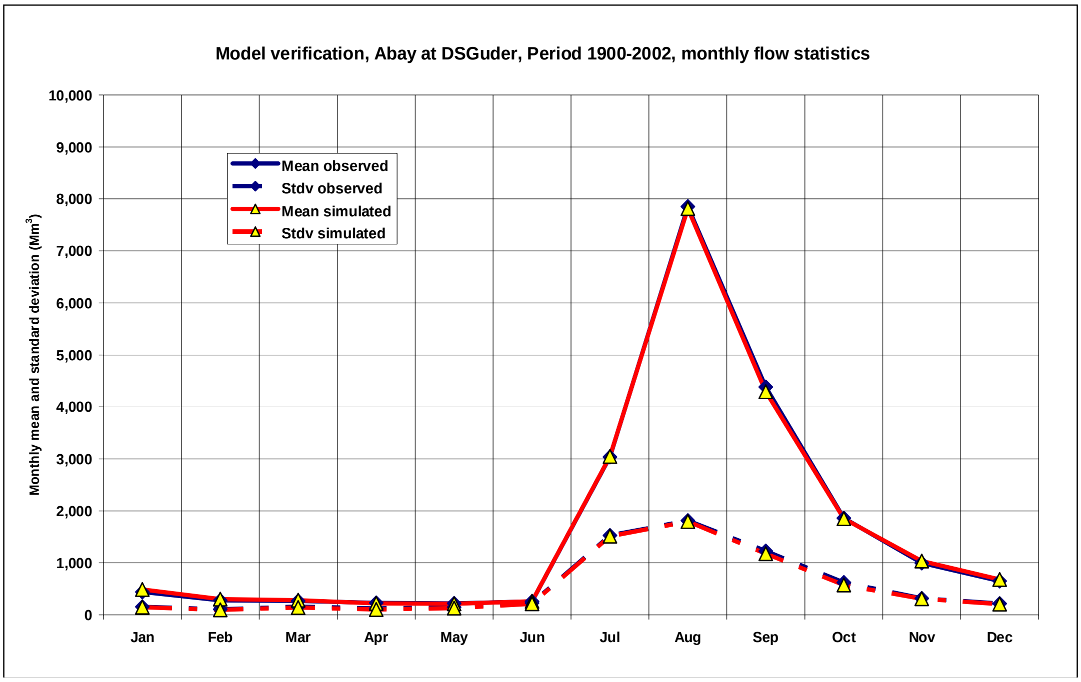

Figure 7.13 Model verification of the Abay at Guder DS, Period 1900-2002, monthly flow statistics

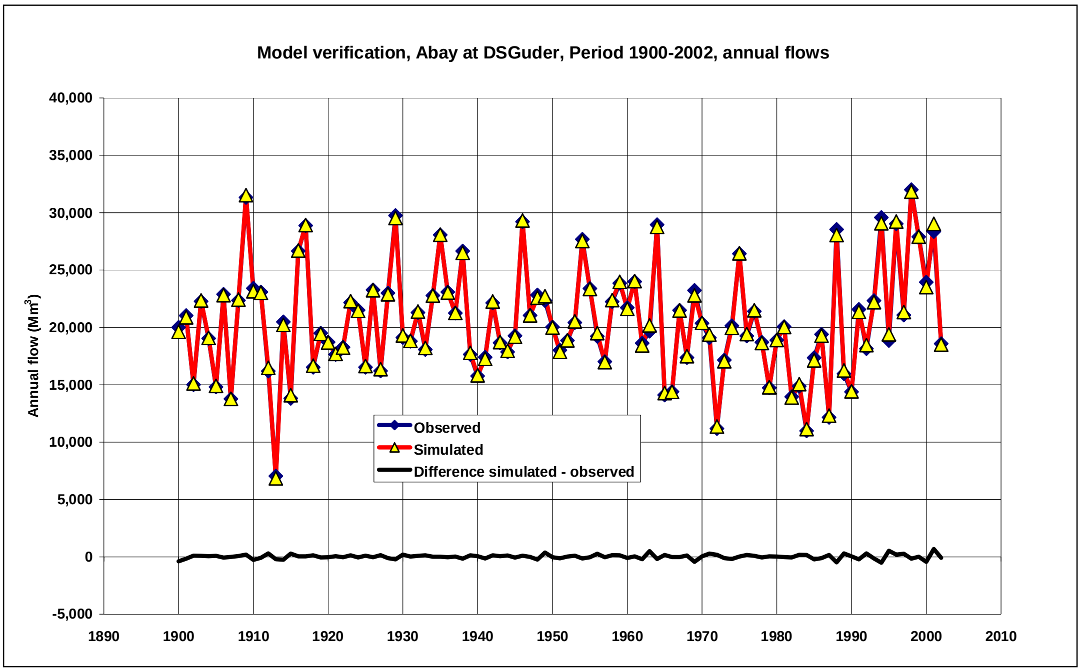

Figure 7.14 Model verification of the Abay at Guder DS, Period 1900-2002, annual flows

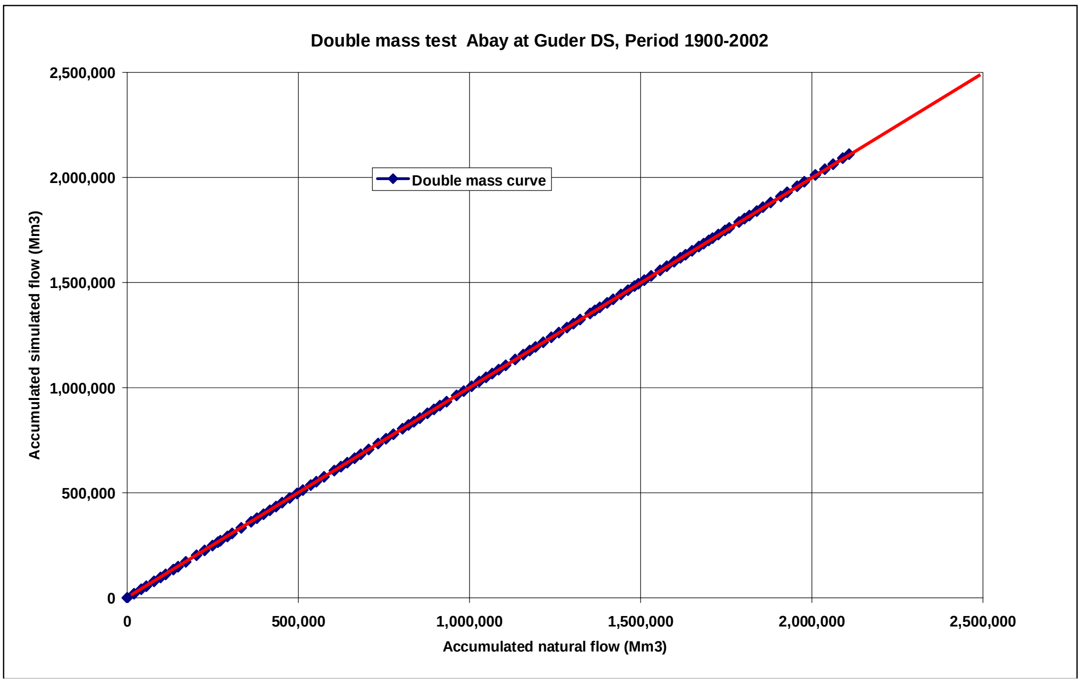

Figure 7.15 Consistency check on observed and simulated flow in the Abay at Guder DS by double mass analysis, Period 1900-2002

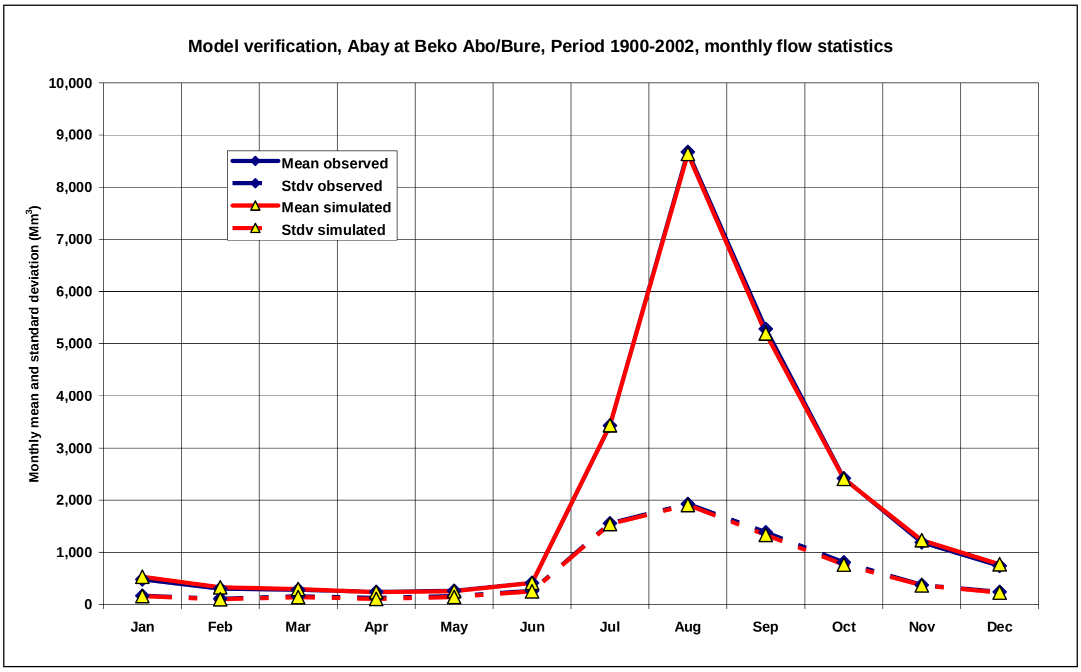

Figure 7.16 Model verification of the Abay at Beko Abo/Bure, Period 1900-2002, monthly flow statistics

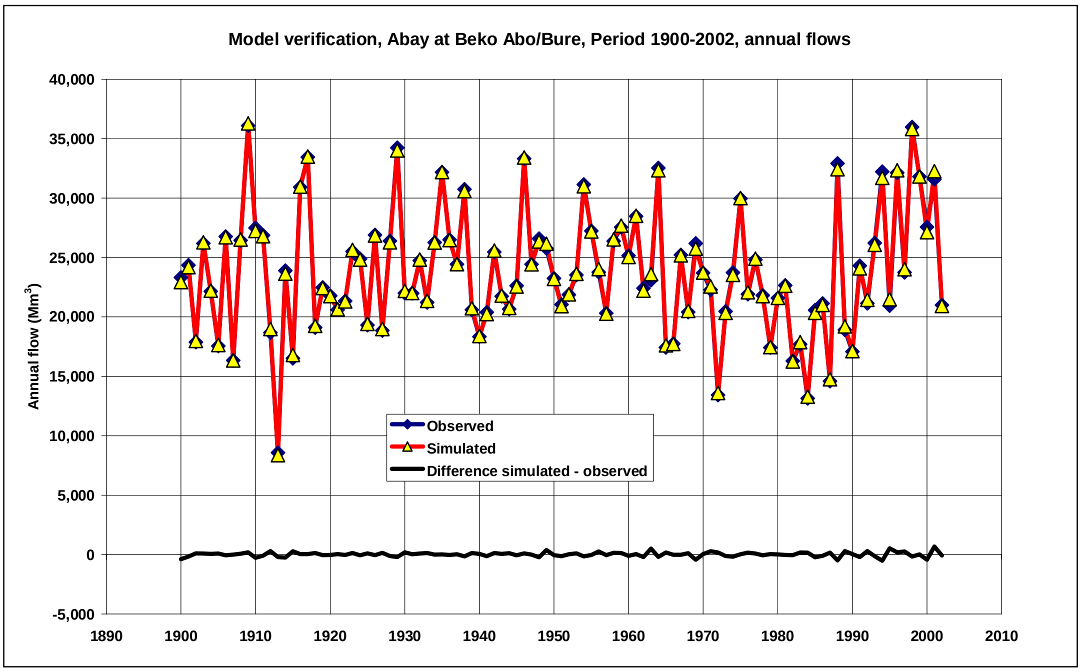

Figure 7.17 Model verification of the Abay at Beko Abo/Bure, Period 1900-2002, annual flows

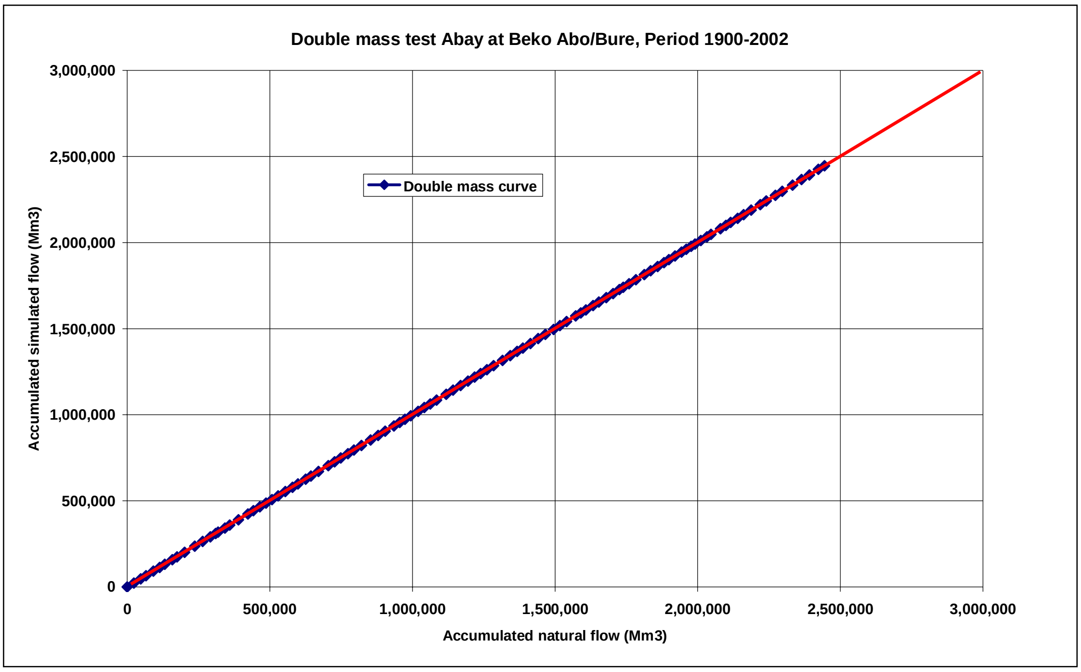

Figure 7.18 Consistency check on observed and simulated flow in the Abay at Beko Abo/Bure by double mass analysis, Period 1900-2002

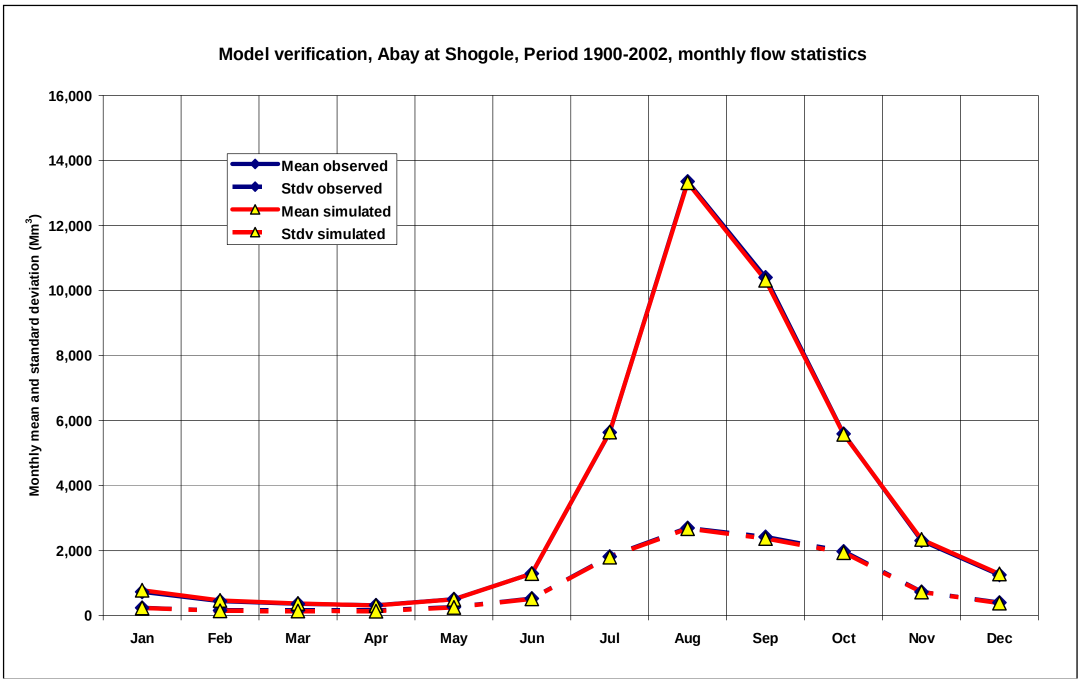

Figure 7.19 Model verification of the Abay at Shogole, Period 1900-2002, monthly flow statistics

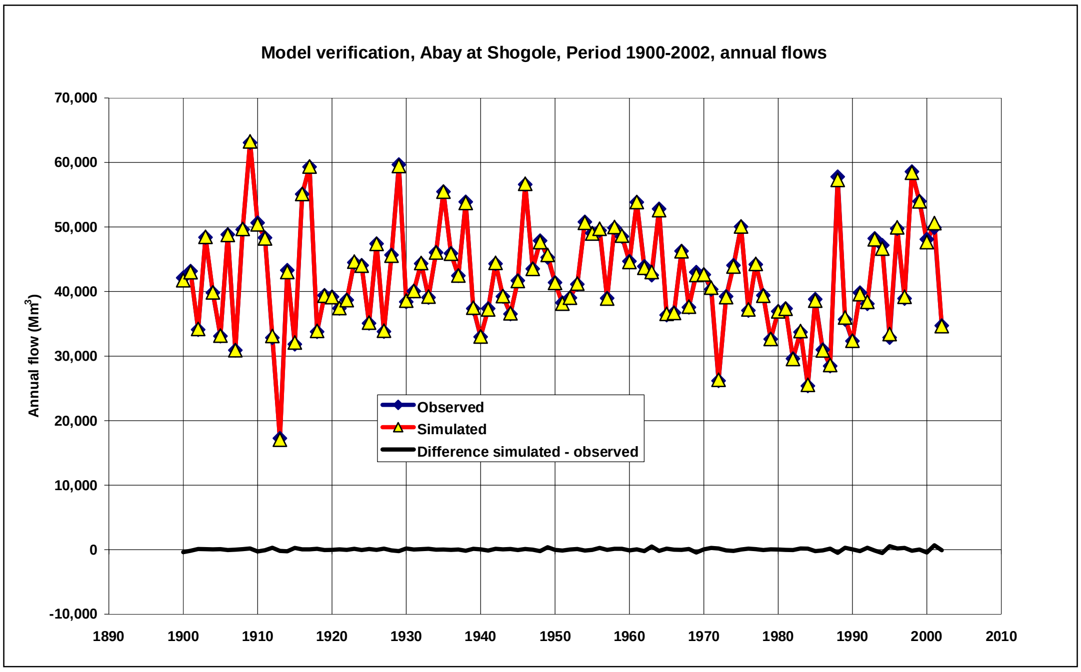

Figure 7.20 Model verification of the Abay at Shogole, Period 1900-2002, annual flows

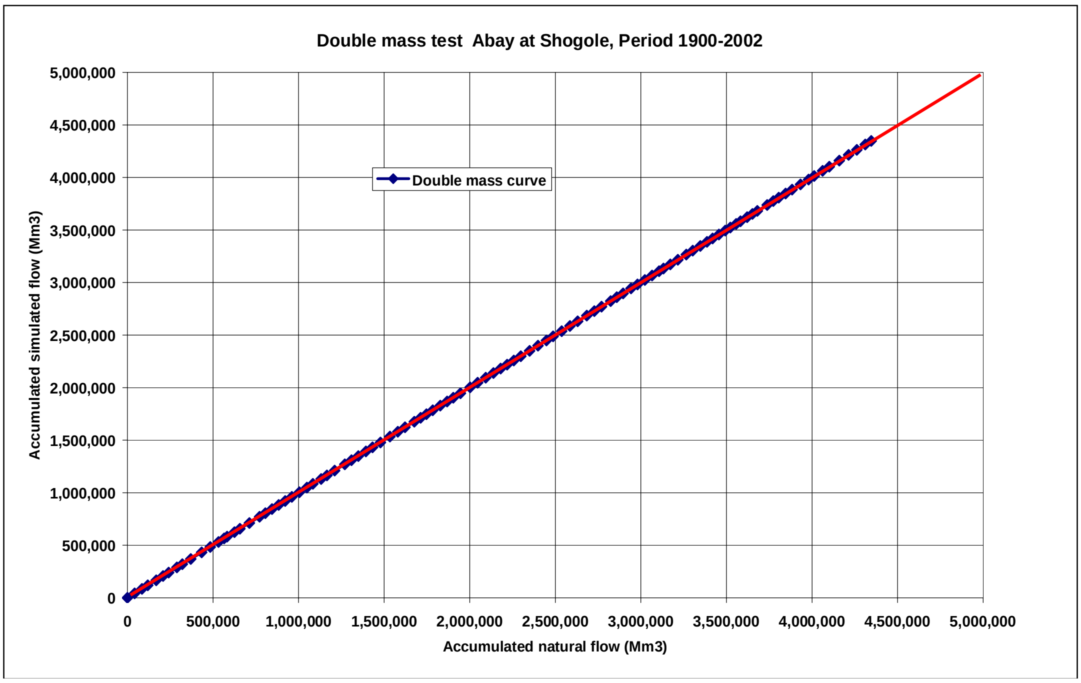

Figure 7.21 Consistency check on observed and simulated flow in the Abay at Shogole by double mass analysis, Period 1900-2002

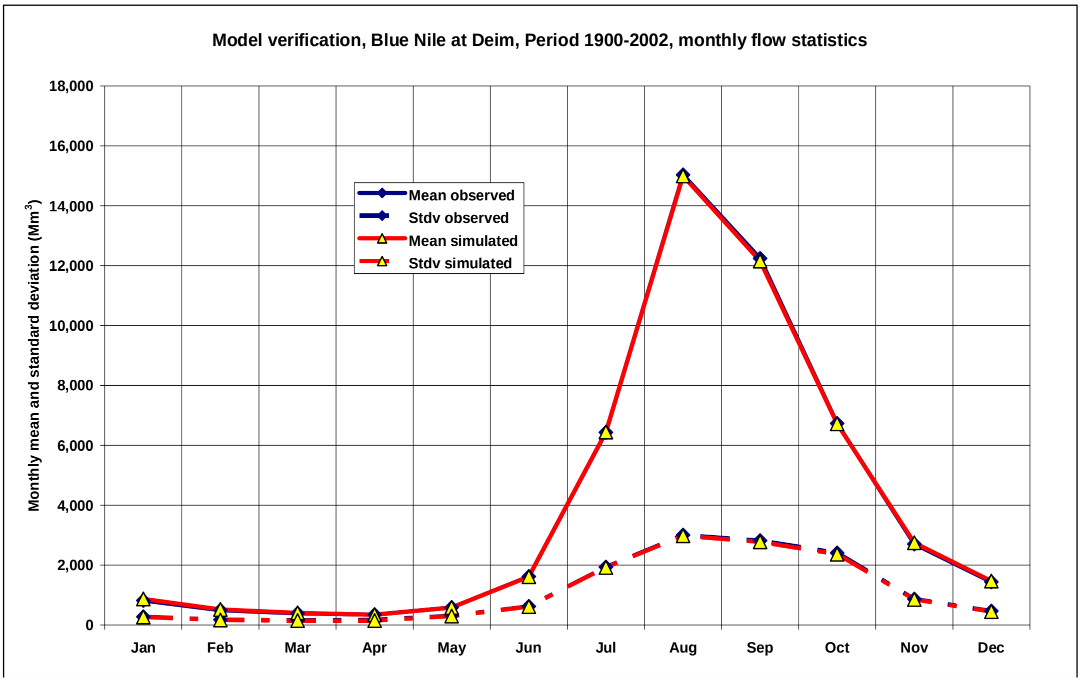

Figure 7.22 Model verification of the Bue Nile at Deim, Period 1900-2002, monthly flow statistics

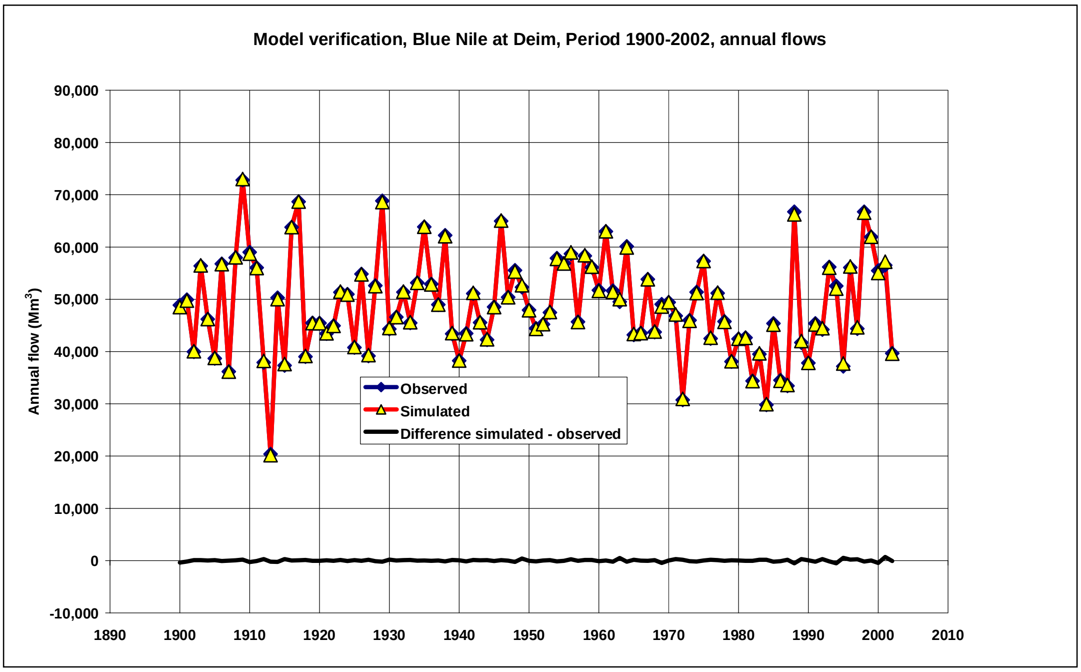

Figure 7.23 Model verification of the Bue Nile at Deim, Period 1900-2002, annual flows

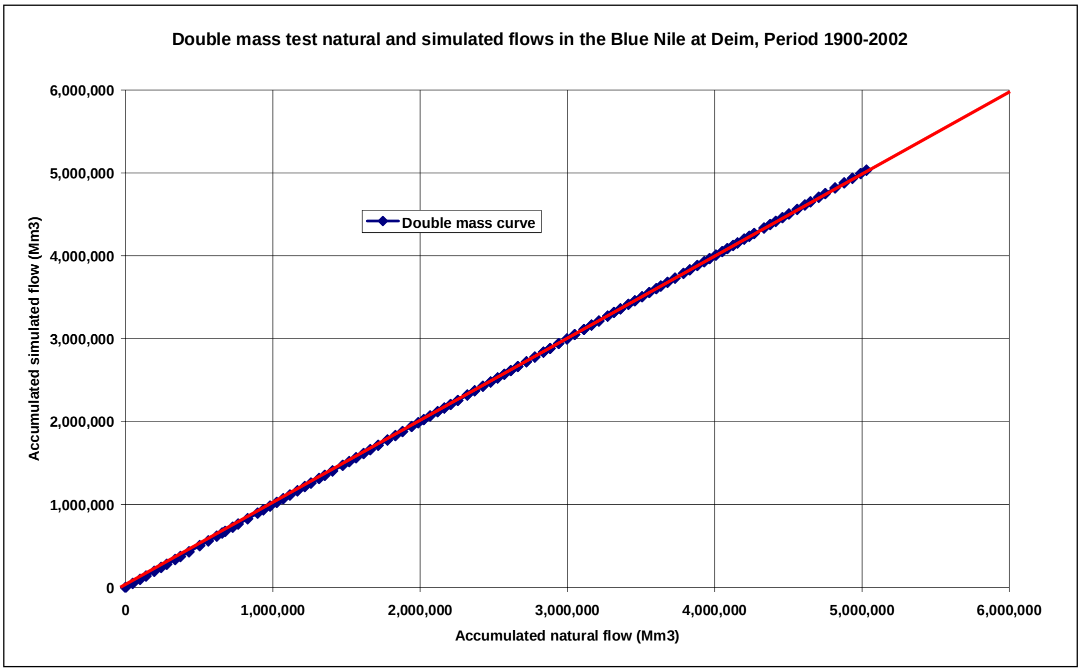

Figure 7.24 Consistency check on observed and simulated flow in the Bue Nile at Deim by double mass analysis, Period 1900-2002

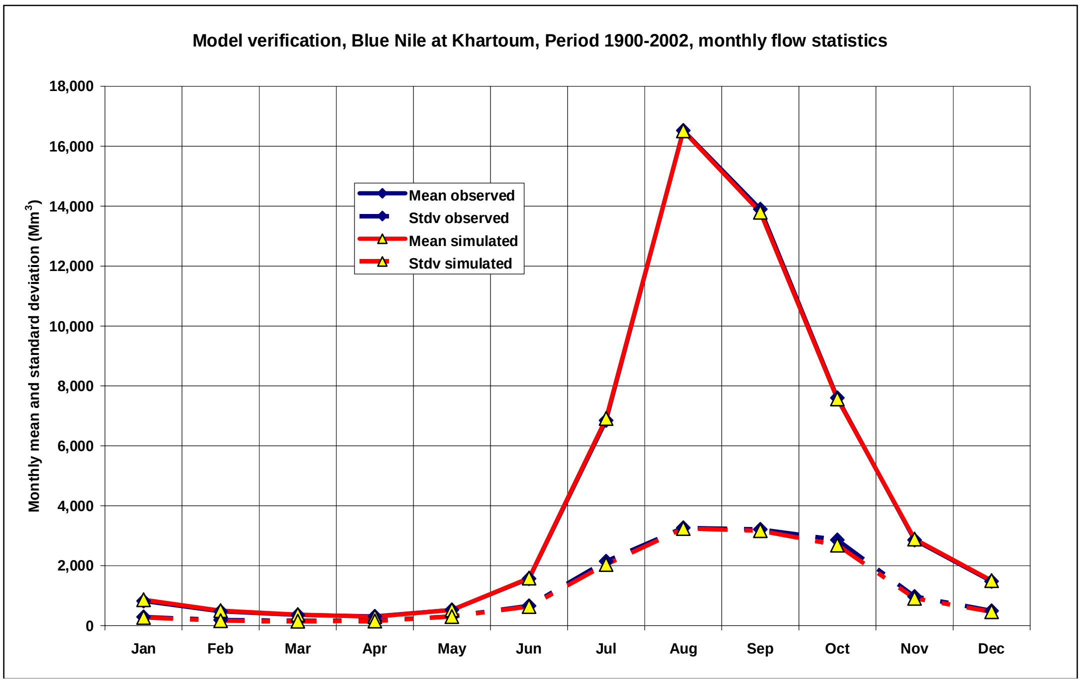

Figure 7.25 Model verification of the Bue Nile at Khartoum, Period 1900-2002, monthly flow statistics

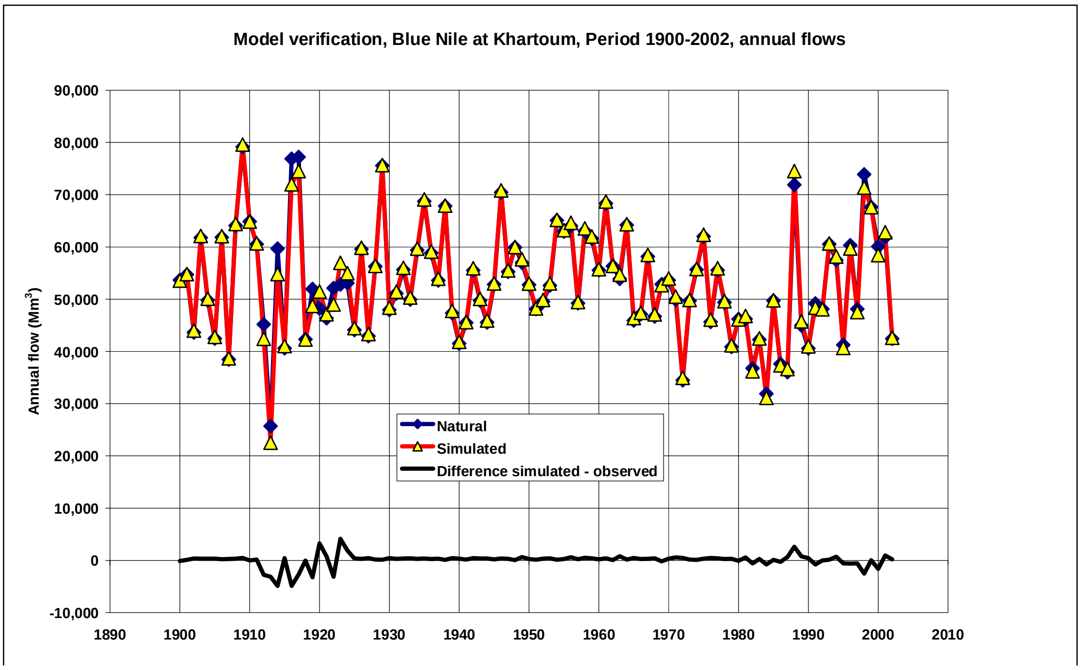

Figure 7.26 Model verification of the Bue Nile at Khartoum, Period 1900-2002, annual flows

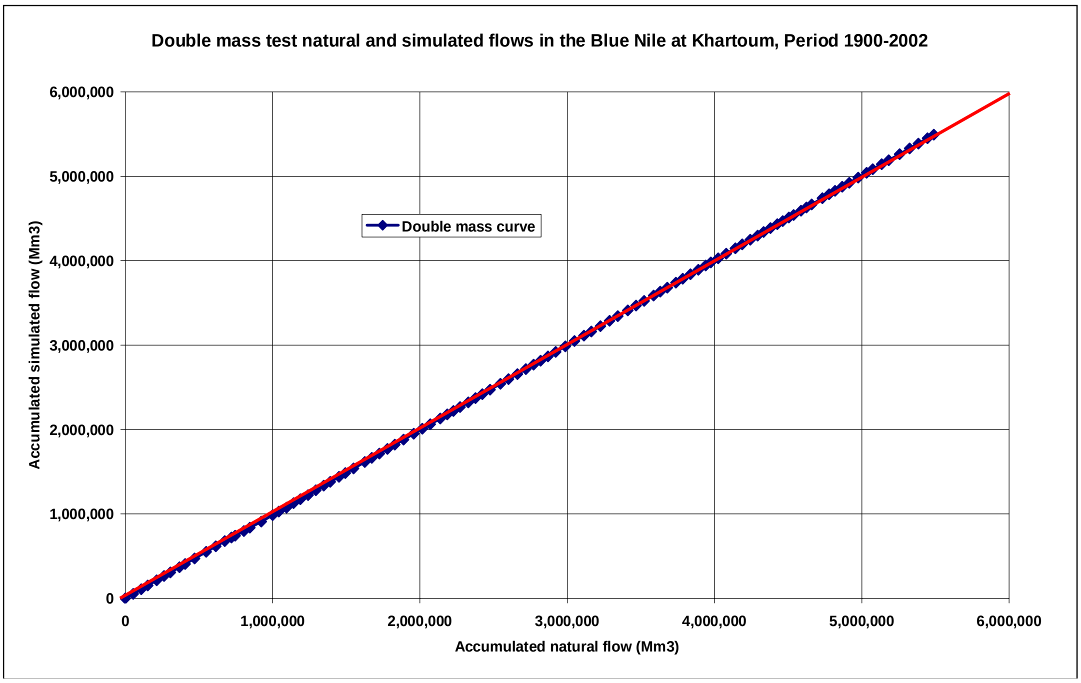

Figure 7.27 Consistency check on observed and simulated flow in the Bue Nile at Khartoum by double mass analysis, Period 1900-2002

7.4 Tekeze-Setit-Atbara sub-basin

The ENWSM validation for Tekeze-Setit-Atbara has been carried out for station K3 near the mouth of the Atbara. For the partitioning of the flow in the basin two approaches have been used:

- flows are fractions of the shifted monthly flows at K3

- flows are based on the observations at Embamadre and K3 using regression relations.

The simulation results with the fraction approach are presented in Figure 7.28 to Figure 7.30. The annual flows are seen to be properly reproduced, but the simulated monthly distribution at K3 is flatter than the original one. This is due to the applied shift of 1/3 and 1/6 month of the series of K3 prior to the partitioning of the flows. This shifting creates a smoothening of the series increasing the low flows and decreasing the high flows.

The simulation results of the regression approach are shown in Figure 7.31 to Figure 7.33. It is observed that the annual flows are nearly exactly reproduced. With respect to the monthly flow distribution, this procedure leads to a closer reproduction of the natural flow statistics than the fraction method. Since this method exactly reproduces the flow statistics in the Tekeze-Setit and Upper Atbara this method is to be preferred above the fraction method.

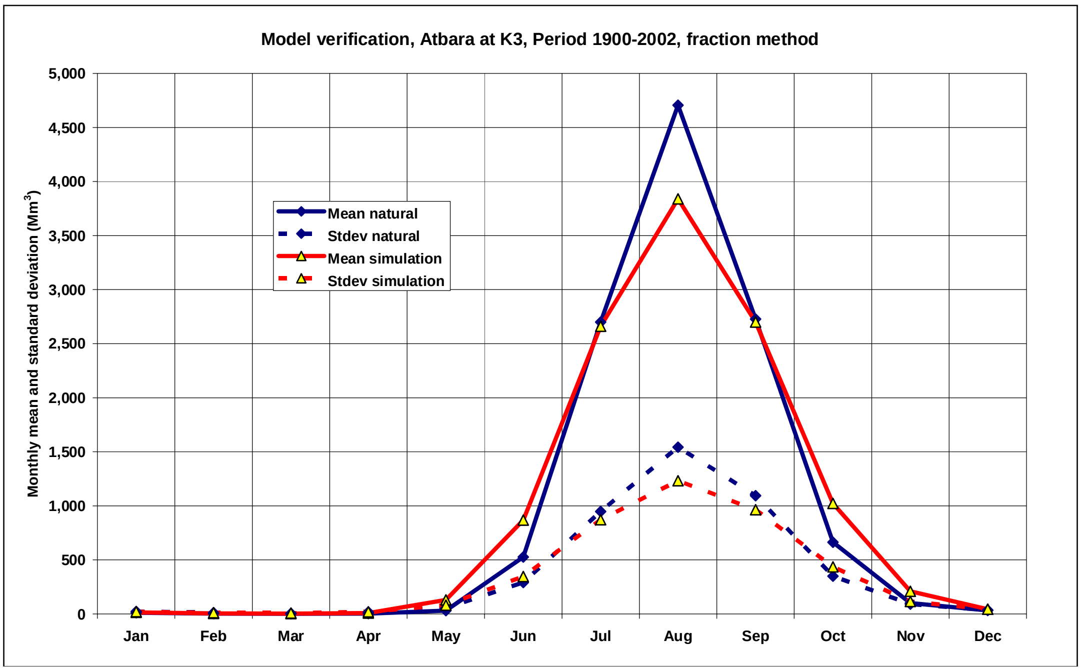

Figure 7.28 Model verification of the Atbara at K3, Period 1900-2002, monthly flow statistics, fraction approach

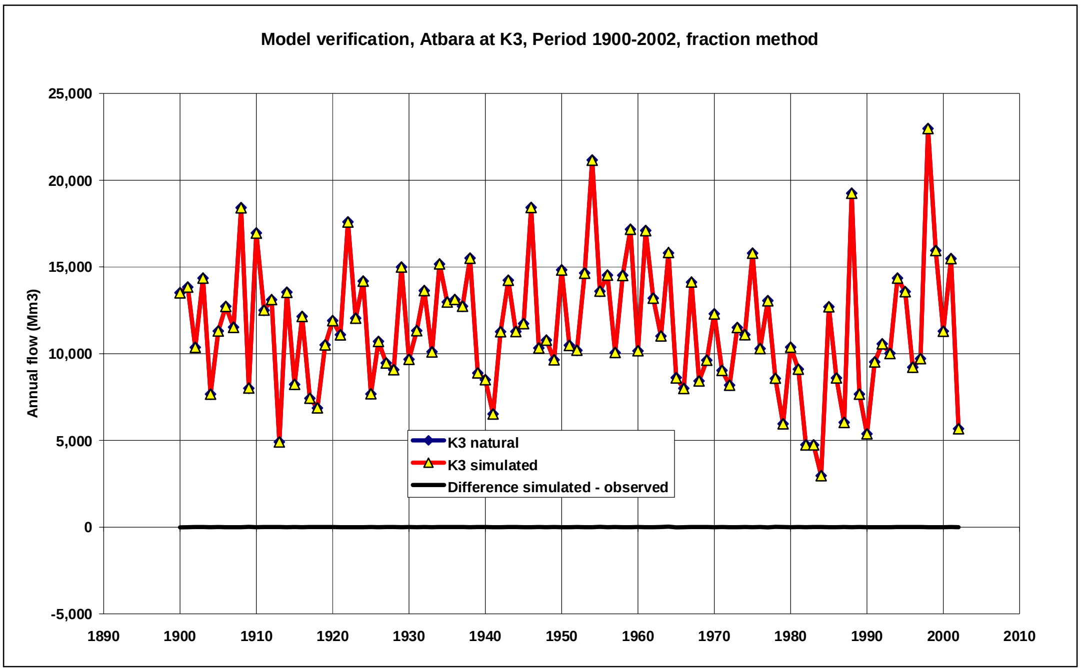

Figure 7.29 Model verification of the Atbara at K3, Period 1900-2002, annual flows, fraction approach

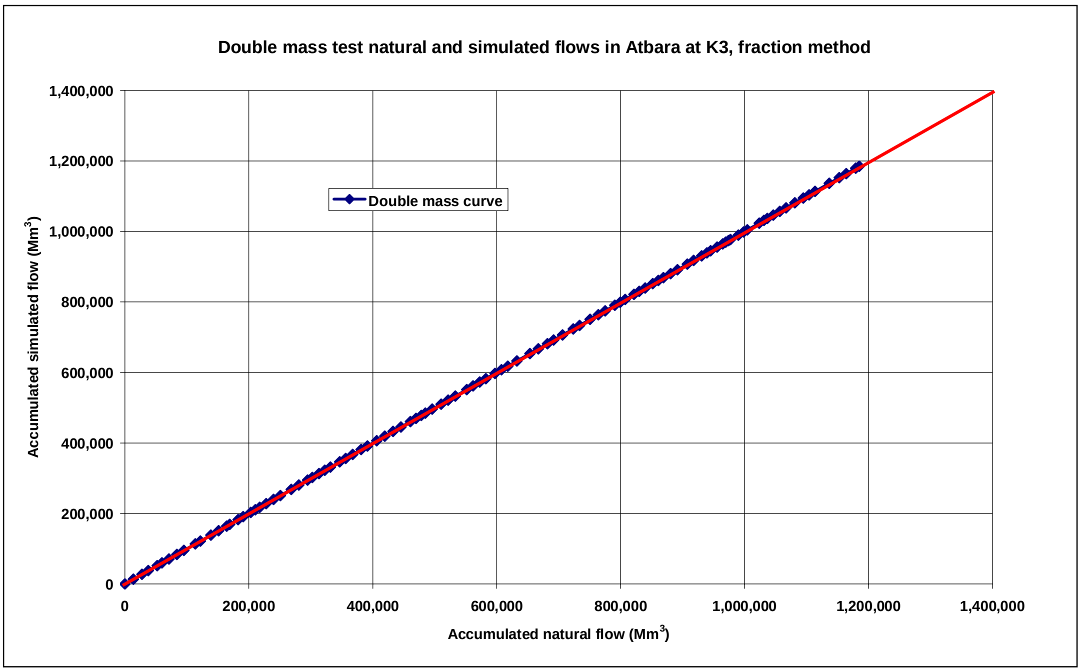

Figure 7.30 Consistency check on observed and simulated flow in the Atbara at K3by double mass analysis, Period 1900-2002, fraction approach

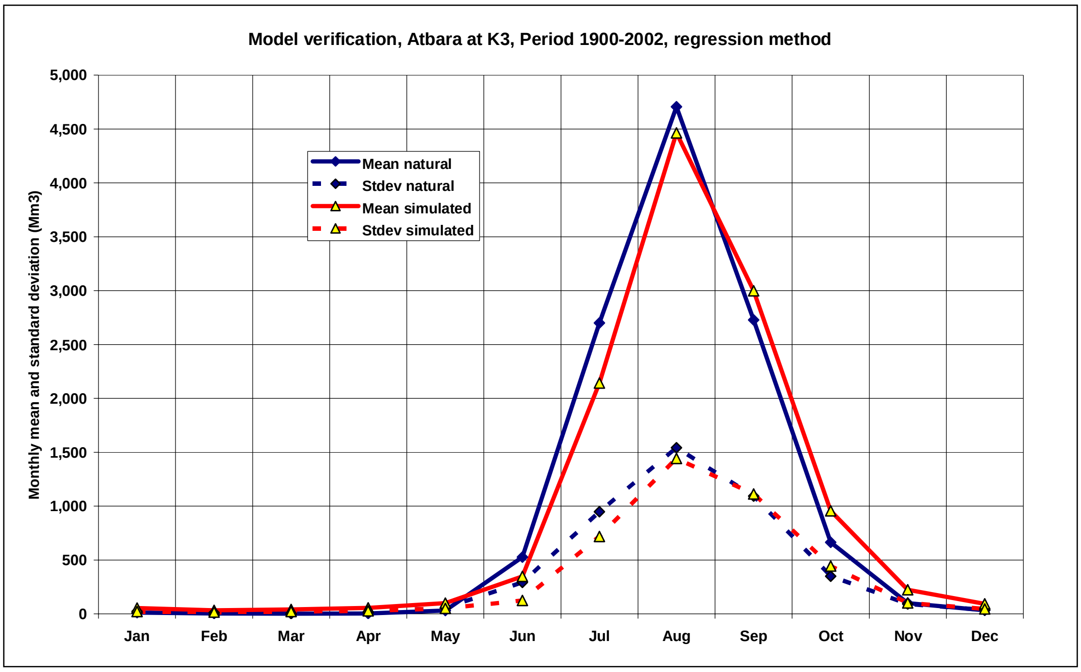

Figure 7.31 Model verification of the Atbara at K3, Period 1900-2002, monthly flow statistics, regression approach

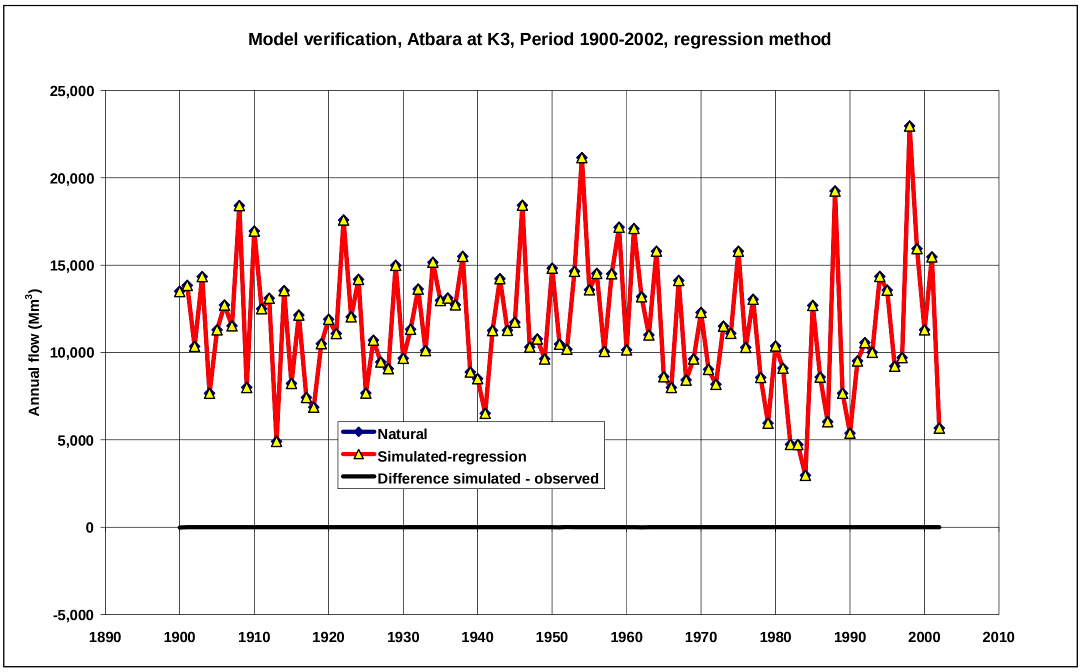

Figure 7.32 Model verification of the Atbara at K3, Period 1900-2002, annual flows, regression approach

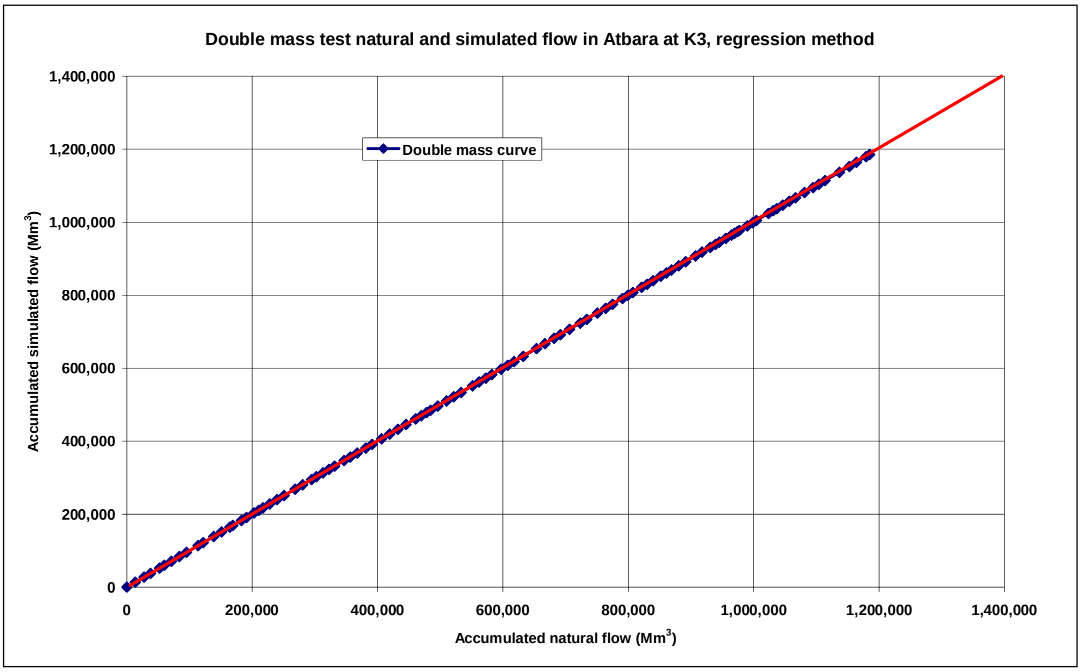

Figure 7.33 Consistency check on observed and simulated flow in the Atbara at K3by double mass analysis, Period 1900-2002, regression approach

7.5 Main Nile sub-basin

The above determined flows and incremental flows with the evaporation losses in the rivers in the natural case should add up to the natural flow at Aswan. First simulations carried out with ENSWM for the natural state of the river basin revealed that the flows in the years 1909, 1916 and 1917 based on the upstream contributions exceeded the natural flow record of Aswan. Therefore, the flows of the Atbara, Dinder and Rahad were adapted to improve the result. Subsequently, the evaporation losses in the model have tuned to arrive at a close match with the natural flow at Aswan at an annual basis; the overall difference is 0.026%.

The results of the model validation are presented in Figure 7.34 to Figure 7.36. The figures show an acceptable reproduction of the flow at Aswan based on the incremental inflows discussed in the previous sub-sections. To obtain a proper reproduction of the within year variation the Muskingum routing component has been switched on to correctly delay the White Nile, Blue Nile and Atbara flows on the Main Nile. The reproduction of the monthly distribution of the flow at Aswan is presented in Figure 7.34. It is observed that ENSWM satisfactory simulates the monthly distribution.

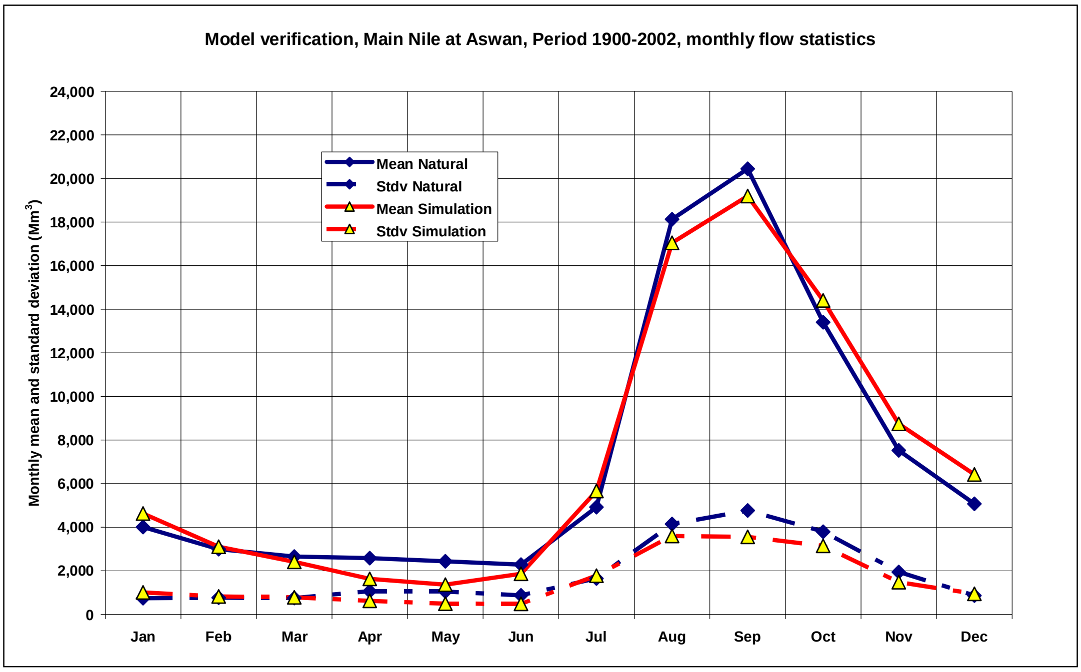

Figure 7.34 Average natural monthly flow of the Nile at Aswan, recorded and simulated by ENWSM, period 1900-2002

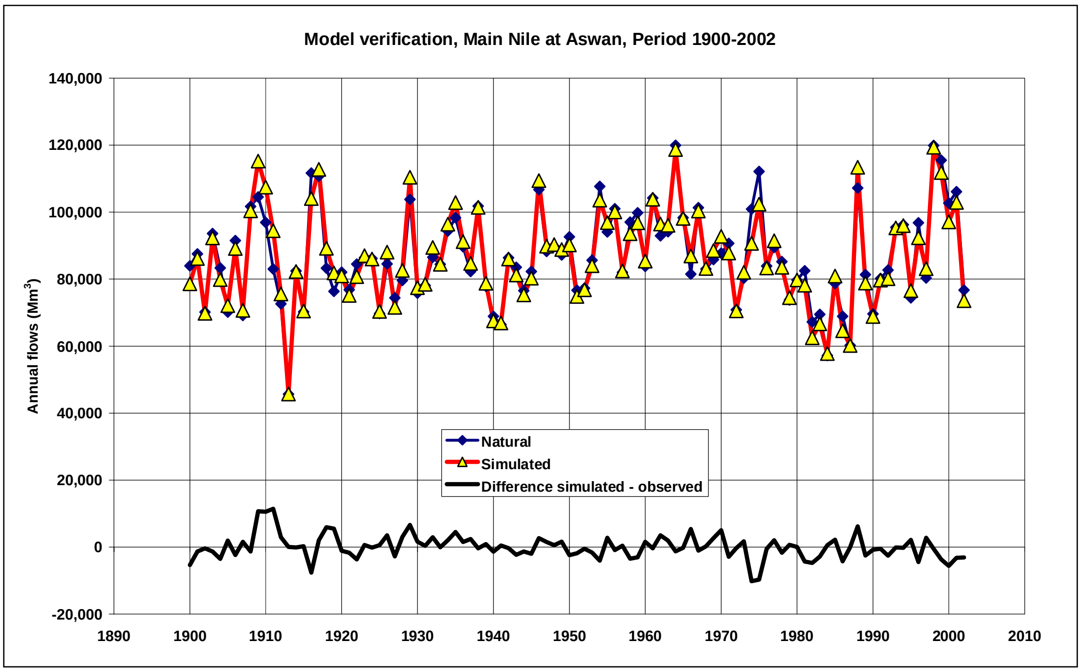

Figure 7.35 Comparison of annual river flow at Aswan simulated by ENSWM for natural basin and the natural flow record, period 1900-2002

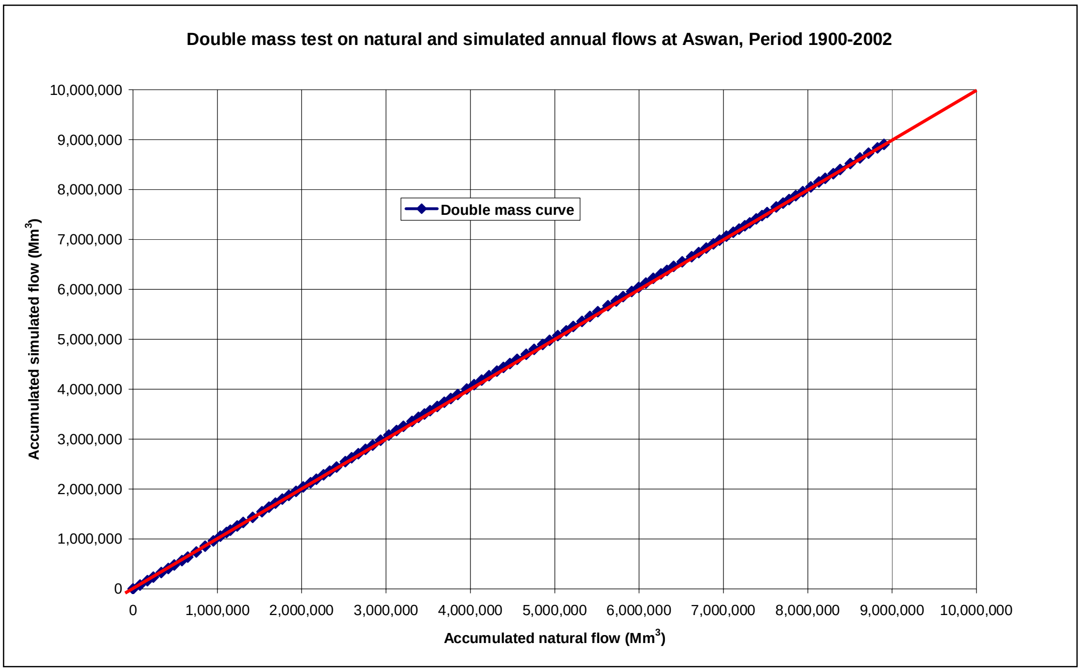

Figure 7.36 Consistency check on observed and simulated flow in the Main Nile at Aswan by double mass analysis, Period 1900-2002

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