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Independent Review

of the Environmental Impact Assessment

for the Merowe Dam Project

(Nile River, Sudan)

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1. Executive summary

The Merowe Dam, presently under construction 800 km downstream of Khartoum on the Nile River in Sudan, will submerge the fourth cataract of the Nile and form a 200 km long artificial lake. With a surface area of 800 km^2, the lake will inundate 55 km^2 of irrigated land and 11 km^2 of farmland used for flood recession agriculture. Merowe represents the current largest hydropower project in Africa. The main purpose of the 67 m high Merowe Dam is hydropower production. The capacity of 1'250 MW will be almost twice the current hydropower capacity in Sudan. The project includes an irrigation component but there are still uncertainties as to whether it will be implemented.

The total cost of the Merowe Dam Project is estimated to reach $1.2 billion. Beside the Sudanese Government, the project is financially supported by the China Export Import Bank, the Arab Fund for Economic and Social Development, and the Development Funds of Saudi Arabia, Kuwait, Abu Dhabi, and the Sultanate of Oman. The dam and the transmission lines are mainly being constructed by Chinese companies. Sudanese contractors are involved in building the dam and the resettlement sites. Several European companies are participating in the project: Lahmeyer International (Germany) manages the construction of the project; Alstom (France) is supplying electro-mechanic equipment; and ABB (Switzerland) is building transmission substations.

At the planning stage of dam constructions on major rivers, a full consideration of the environmental impacts is required according to international standards. The project participants are therefore required to prepare or contract an environmental impact assessment report (EIAR) in accordance with specific guidelines that address three major topics:

- **Social issues -** consequences of people resettlement from future flooded area;
- **Archeological issues -** resulting from destruction or submerging important archeological sites or places of high cultural value;
- **Environmental issues -** effect of large scale hydrological alteration of the natural river system with major impacts on the environment and water quality.

In April 2002, Lahmeyer International prepared the EIAR for the Merowe Dam Project. The document focuses on the complex resettlement issues involving about 7'500 families. Among the environmental impacts it discusses are the hydrological changes, the erosion of the river bed and its banks, greenhouse gas emissions and changes in the aquatic ecosystem. The 150 page report was far from meeting European or international standards, such as the guidelines of the World Commission on Dams (WCD, 2000). No serious attempt was made to use the vast scientific knowledge base on environmental effects of large dams, although four decades of research on the Aswan High Dam (Lake Nasser in Egypt, Lake Nubia in Sudan) have revealed a dramatic sediment accumulation in the upper part of the reservoir, problematic water quality issues and detrimental downstream effects such as river bed erosion or water level fluctuations.

This independent review of the Lahmeyer EIAR (2002) was motivated by the mission of Eawag to use our competence in the assessment of surface water systems and their management in relevant contexts. In addition, Eawag has an intrinsic interest as man-made alterations of aquatic system are part of its core business. International Rivers Network (IRN) encouraged Eawag to carry out this review, and provided inputs by sharing documents and other information. IRN did not influence the contents nor the topics addressed in this review in any way. In preparing this review we worked towards achieving three objectives:

- to **review the relevant literature** concerning the environmental effects of the Aswan High Dam as a suitable reference system for large dam projects on the main reach of the Nile River,
- to **identify and quantify possible environmental changes** induced by the Merowe Dam,
- to **provide a constructive critique** of the Merowe EIAR including recommendations for further study and for developing mitigation measures.

The expertise of the authors covers the fields of aquatic physics, chemistry and sedimentology. Additionally, we obtained input from other specialists. The review was deliberately focused on natural science issues, where the authors follow an active

research agenda (Friedl and Wüest, 2002; Friedl et al., 2004; Teodoru and Wehrli, 2005; Bratrich et al., 2004). Health aspects were covered only marginally and socioeconomic topics such as the resettlements and economic valuation were not addressed as they are outside our field of competence. Our report was written for the experts in Sudan, for the project parties and the interested stakeholders. With this case study we hope to intensify the scientific exchange and debate concerning environmental impact assessments for large dam projects.

1.1 General results

The following conclusions can be drawn for EIAR of large dam projects in general.

- The scientific analysis of environmental effects of river impoundments is vast and growing fast. The ISI database lists more than 200 publications under key words "Nile" and "dam". Relevant scientific results should be used explicitly in preparing an EIAR. The past experience with existing dams in the same river system proved particularly valuable for predicting the impact of a new dam.
- The practice of "peer review" as it is used for improving scientific publications could well add credibility to an EIAR, particularly if the original report is prepared by a company with close ties to the project.

1.2 Specific results

Our analysis has identified the following topics of major concern regarding the Merowe Dam project

- The Merowe dam will act as a major **sediment sink** for the suspended load of the Nile River. Because the reservoir is much smaller in volume compared to the Aswan High Dam Reservoir, it is likely to lose more than 30% of its capacity over the next 50 years. A concept of management for the 130 Mio. tons of sediment

accumulating every year in the Merowe Reservoir is lacking at present and deserves a high priority for a sustainable hydropower generation.

- Since about 90 % of the suspended load of the Nile water will be retained in the Merowe Reservoir, the outflow will have a large carrying capacity for particles and produce **erosion of the river bed and the side banks**. The Lahmeyer EIAR recommends monitoring of river cross sections to plan countermeasures for the cities and settlements downstream. Because bed and bank erosion is well documented after closure of the Aswan High Dam, geomorphological studies should be started immediately to identify key areas of concern.
- The Merowe Reservoir will become stratified during the hot season and settling algae can produce **anoxic conditions** in the bottom waters close to the dam. This will reduce the available habitat for fish species and increase the emission rates for the greenhouses gas methane and carbon dioxide.
- The total mass of organic matter contributing to **greenhouse gas emissions** will be an order of magnitude larger than estimated by the EIAR. In addition to the primary production within the reservoir, the suspended load of the Nile River will also carry organic material, which can be degraded to carbon dioxide and methane in the reservoir sediments at rates on the order of 200’000 - 300’000 tons of carbon per year.
- The effects of disrupting the river continuum on **aquatic biodiversity** have not been addressed adequately. The available species lists in the EIAR are inadequate and incomplete. Several species have migratory life cycles and spend time in both the tributaries and the main river. Such life cycles of important fish species should be analyzed in detail before a general assessment of the impacts of a large dam project on biodiversity can be made. Together with the Aswan High Dam, the Merowe Dam will genetically isolate an important reach of the Nile River.
- The dam and the hydropower station are designed for peak operation during a few hours per day. The resulting **hydropeaking** downstream is expected to produce water level fluctuations of about 4 m per day. Such intense fluctuations will have detrimental effects on aquatic ecosystems because the riparian zone of a river provides crucial habitat for aquatic life. The EIAR considers mainly economic

effects such as upgrading of necessary pumping stations and ferry landing sites, but neglects the effects on daily life of the riparian population. A retention dam at the outlet of the power station could mitigate such negative side effects.

- The design of the dam allows for water abstraction for **irrigation**. No planning details are available in the EIAR as the decision for or against irrigation was postponed. An overview by the World Commission on Dams (WCD, 2000) revealed a high failure rate for irrigation schemes in arid areas. Open planning and communication of the goals and the implementation of irrigation schemes at Merowe is a key factor for their success, and should be included in the EIAR.

1.3 Critical issues

In summary, the EIAR for the Merowe Dam Project provided a detailed overview of the technical, hydraulic and hydrologic framework, and discussed issues of resettlement and ecological and economical side effects. The EIAR failed

- to base its assessment on the available scientific literature,
- to develop a plausible sediment management concept,
- to critically assess the ecological functioning of the reservoir ecosystem including its greenhouse gas production and the effects on fish biodiversity,
- to offer strategies for mitigating the downstream effects of hydropeaking.

We hope that the following review can partially close these gaps and provide some concepts for improving future EIA reports.

2. General project description

2.1 Nile catchment and climate

Formed by the confluence of the three main tributaries, White Nile, Blue Nile and Atbara River, the Nile River flows over 6’700 km from the south glaciated highlands through alluvial plains and desert sands into the eastern Mediterranean (Figure 1). Stretching over 35 degrees latitude of the north-eastern African quadrant, the Nile River basin represents one-third of the entire African continent. With an area of almost $3x10^6$ km^2 extending over different geographical, topographical and climatological regions, the basin spans over nine African countries: Tanzania, Uganda, Rwanda, Burundi, Zaire, Kenya, Ethiopia, Sudan and Egypt (Figure 1).

The hydrographical and hydrological characteristics vary greatly over the basin with abundant rainfall in the headwaters and arid conditions in Sudan and Egypt. Therefore, although the watershed is large, the portion contributing to stream flow is almost half of the entire basin (only $1.6x10^6$ km^2) due to the fact that north of 18 °N latitude, rainfall is almost zero. Precipitation increases towards the headwaters to about 1’200 to 1’600 mm yr^{-1} on the Ethiopian Plateau and in the region of the Equatorial lakes: Victoria, Albert, Kayoga, and Edward (Mohamed et al., 2005). The seasonal pattern of rainfall follows the Inter-Tropical Convergence Zone (ITCZ), where the dry northeast winds meet the wet southwest winds and are forced upward causing water vapor to condense. The ITCZ follows the area of most intense solar heating and warmest surface temperature and reaches the northerly position of Ethiopian Plateau by late July. The southward shift of the ITCZ results in the retreat of the rainy season towards the central part of the basin after October. Therefore, the monthly distribution of precipitation over the basin shows one single but long wet season over the Ethiopian Plateau and two rainy seasons over the Equatorial Lakes Plateau (Mohamed et al., 2005).

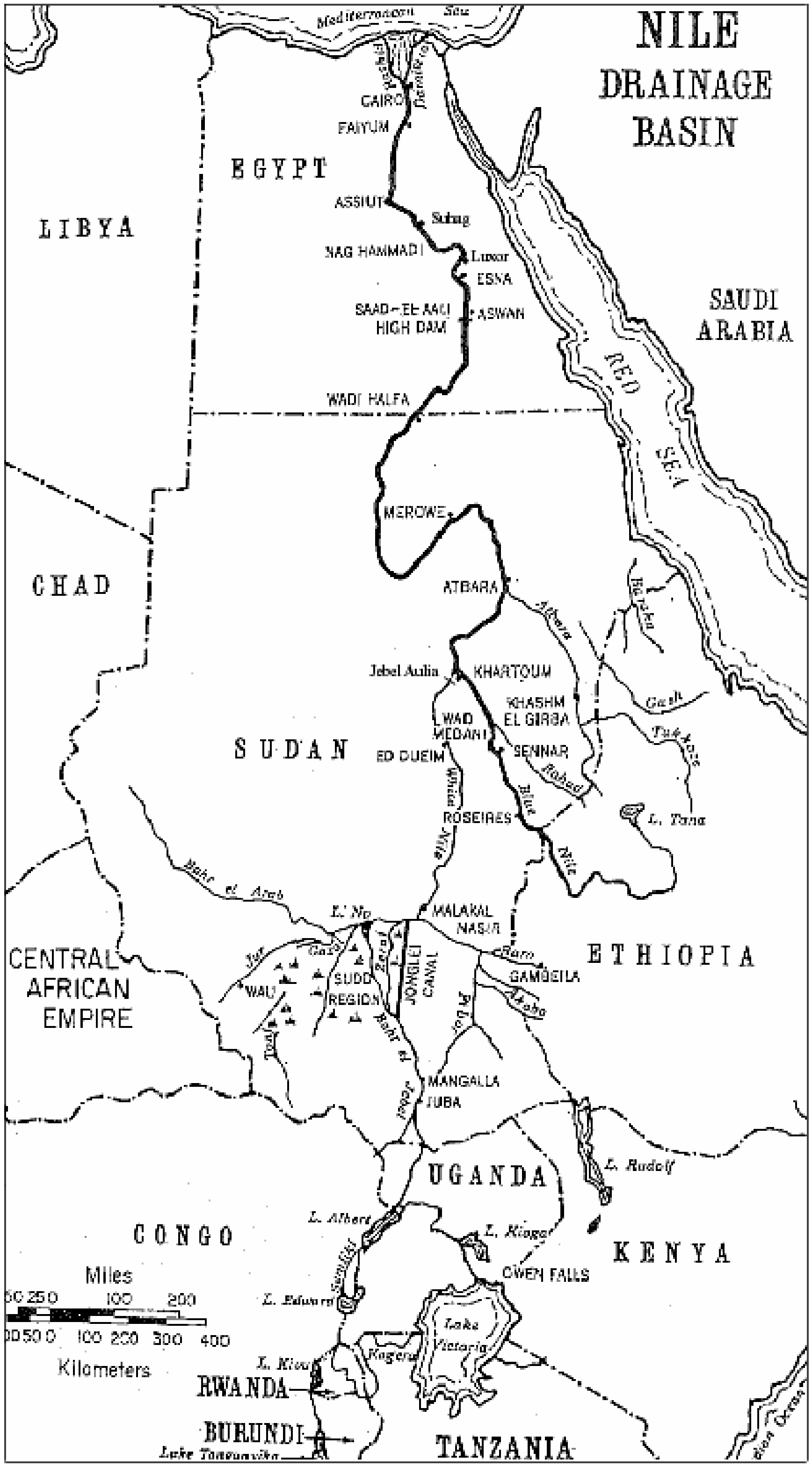

Figure 1. Map of the Nile River Basin

2.2 Nile hydrology

The Nile River system has two main sources of water: (i) the White Nile with its source on the Equatorial Lake Plateau region around Lake Victoria and (ii) the Blue Nile and the Atbara River having their headwaters on the Ethiopian Plateau. The White Nile starts with its small tributary Kagera River, entering Lake Victoria near the border between Uganda and Tanzania. The river travels north crossing the equatorial region, receiving water from numerous streams and lakes. After leaving the lake area, the White Nile enters southern Sudan through rocky gorges and then flows through a large swamp area (the Sudd region) where it is joined by the Sobat from the east and the Bahr el-Ghazal, from the west. In the Sudd region a huge quantity of water evaporates or is transpired by aquatic vegetation. Only a small part of the Bahr el-Ghazal flow ever reaches the White Nile, as most of its water disappears in the swamps. Further down, the White Nile travels a mild slope north to the confluence with the Blue Nile at Khartoum.

The Blue Nile originates from Lake Tana on the Ethiopian Plateau, a region of high summer rainfall at about 1’800 m above sea level (a.s.l.). Originating also from the Ethiopian Plateau, the Atbara River joins the main course of the Nile about 300 km north of Khartoum. From here, no significant tributary contributes to the hydrologic regime of Nile River. The altitude profile of the Nile from Lake Victoria (1’135 m a.s.l.) to the Mediterranean Sea is shown in Figure 2.

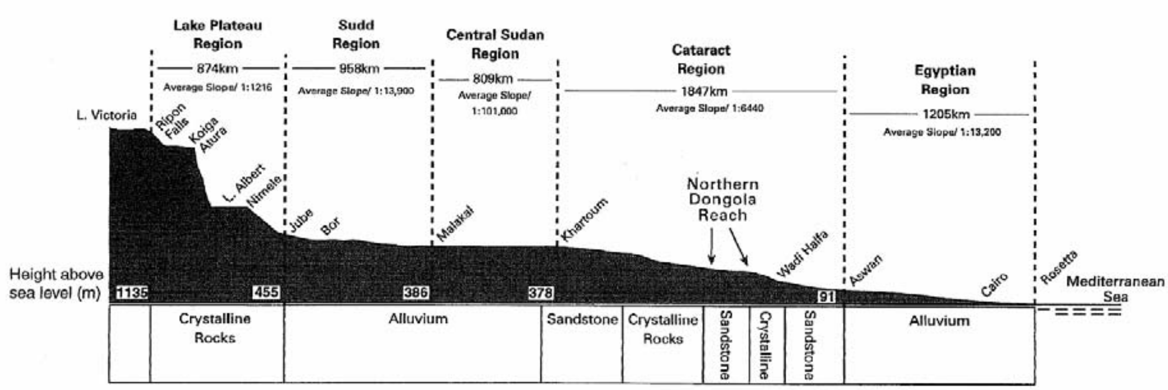

Figure 2. Altitude profile of the Nile River (after Said, 1993).

The present average contributions from each of the three main tributaries to the entire Nile River flow are schematically represented in Figure 3. Runoff from the Ethiopian Plateau via the Blue Nile and Atbara accounts for roughly 70 % of the annual water discharge, whereas the White Nile contributes about 30 % (Roskar, 2000). Although the contribution of the White Nile to the total annual flow is rather small, the White Nile is most important because of its continuous flow during the dry season when its discharge is large compared to that of the Blue Nile.

Subject to seasonal variations, about 80 % of the total annual discharge of the River Nile occurs during the summer rainy season (July to October) mainly with the Blue Nile and the Atbara River (Woodward et al., 2001). Atbara River runs dry at times of the year while the White Nile maintains the flow in the Nile over the entire year. Without the discharge of the upper White Nile the Nile River would probably run dry in May. The annual flow distribution and suspended sediment budget is shown in Figure 3.

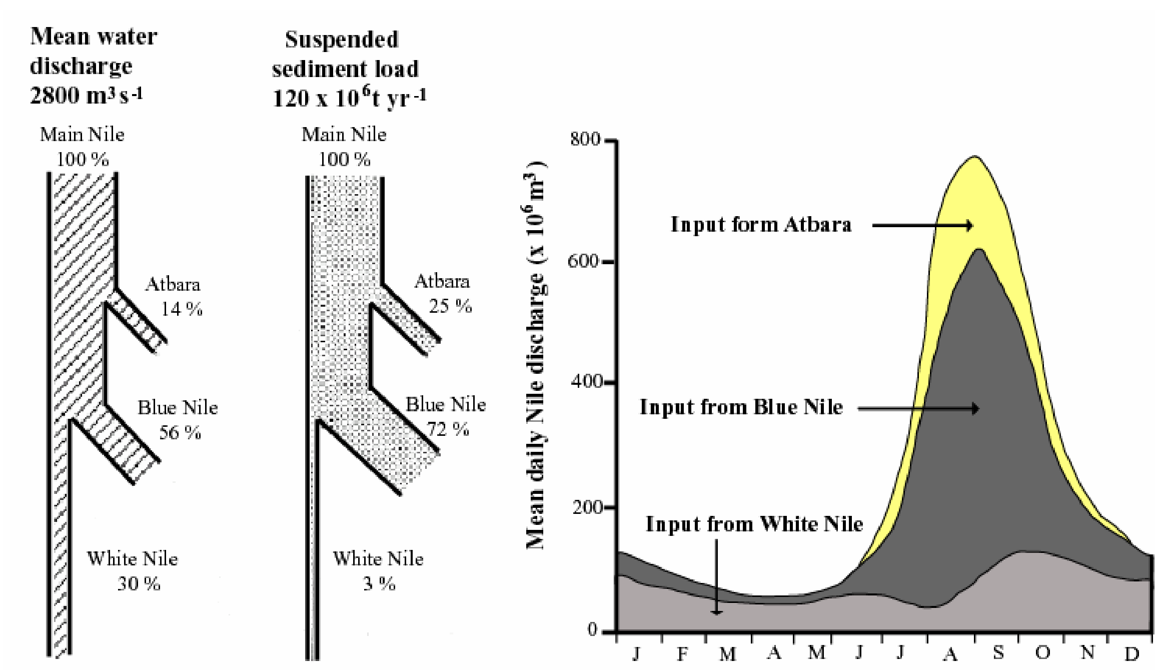

Figure 3. The water and suspended sediment budget of the present Nile basin (after Woodward et al., 2001)

River	Gauging stations	Catchment area $[10^9\ m^2]$	Mean annual flow $[km^3\ yr^{-1}]$
Nile	Aswan	3060	84.1
Atbara	Atbara	180	11.1
Blue Nile	Khartoum	330	48.3
White Nile	Khartoum	1730	26.0

Table 1. Catchment area and the mean annual flows over the period 1901 to 1995 for the Nile River (after Mohamed et al., 2005).

More than 95 % of the mean annual suspended sediment load of the Nile River upstream of the Aswan High Dam (120×10^6 t yr^{-1}, Woodward et al. 2001) comes with the Blue Nile (72 %) and the Atbara River (25 %) whereas the White Nile contributes only 3 % of the total load.

Apart from seasonal variations, the total annual discharge of the Nile River is subject to intense annual variations with the highest annual flows of 154 $km^3\ yr^{-1}$ recorded in 1878 (Abu Zeid, 1987) and 120 $km^3\ yr^{-1}$ measured in 1984 (Woodward et al., 2001). The lowest annual flow on record was observed in 1913 with only 42 $km^3\ yr^{-1}$ (Abu Zeid, 1987). The mean annual flow of the Nile River and the three tributaries calculated over the period 1901 - 1995 (Mohamed et al., 2005) is shown in Table 1. A number of hydrological changes affected the Nile regime over the last century as a result of river control measures.

2.3 Nile control measures

Summarized by El-Hinnawi (1980), the Nile River control measures started in the early 19^{th} century when a series of barrages were built to transform the old recession irrigation system to perennial irrigation so that instead of growing one crop per year, two or three corps could be grown on the same land. The Delta Barrage was built just below Cairo to control the Rosetta and Damietta branches of the Nile together with the Zift a Barrage on the Damietta branch. Constructed in 1902 and enlarged in 1938, a dam at Assiut was built

to provide perennial irrigation in central Egypt. In 1908, the Esna Barrage followed by Nag-Hammady in 1930 was constructed on the Nile River to improve the water supply for irrigation schemes in Upper Egypt.

The first Aswan Dam was completed in 1902 to store Nile water when the river was at its annual high level. Heightened several times latter on, at full storage the reservoir extended up to Wadi Halfa. At the end of each storage period the sluices were opened to drain most of the lake and remobilize the accumulated sediment. The new Aswan High Dam, designed to be never drained, caused a revolution in the Egyptian irrigation system. Practically, all the fertile sediment from the Ethiopian Plateau was deposited in the reservoir. Although the missing suspended particles created certain disadvantages, the extra stored water and the reduction of silting in the irrigation channels allowed the perennial irrigation as well as a significant increase in irrigated area.

About 45 km south of Kharthoum, the Jebel Aulia reservoir was constructed in 1937 to hold back part of the White Nile flow during rich discharge of the Blue Nile. Since the Nile valley upstream of Jebel Aulia is very flat and open, a large quantity of water is being lost due to evaporation and seepage.

The Owen Falls Dam (Figure 1) completed in 1954 was the first control work on the upper White Nile. With a primary goal of producing hydroelectric power, the dam controls the outflow of Lake Victoria and therefore created the largest reservoir in the world.

In 1999, after a year-long debate, the Ugandan Parliament approved the construction of the Bujagali hydropower dam as a private hydroelectric power plant project in Uganda. The project is one of several hydropower plants planned to be scattered along the upper reaches of the White Nile including Owen Falls, Busowoko, Ralangala, Raruma, Ayago North, Ayago South and Murchison Falls. Situated 1’100 m a.s.l. at Bujagali Falls, about 8 km north of Lake Victoria, construction of the Bujagali plant was due to begin in January 2003, but was initially delayed after vocal protests by environmentalists and

residents of the area. In February 2005, the Ugandan Government announced that the project will go ahead. With a volume of up to 750'000 m^3 and a vertical drop of 30 m, the reservoir water will feed four turbines with a total installed capacity of 250 MW.

On the Blue Nile, the Sennar Dam (Figure 1) completed in 1925 serves the needs of Sudan by providing the basis for the Sudan's agriculture economy. Its main function is to store water for the Gezira irrigation scheme during the flood season of the Blue Nile.

Further upstream, near the Sudan-Ethiopian border, the Roseires Dam (Figure 1) was completed in 1966 with the two primary purposes of increasing the storage capacity of the Blue Nile water and producing hydropower. Far above Roseires, below the Blue Nile Gorge, Lake Tanna (Ethiopia) was considered for many years as a good place for a storage reservoir to hold back a large proportion of the Blue Nile flood. Ethiopian interests around the lake, including historical and religious sites, prevented the realization of the project until today.

A large hydropower and irrigation project is currently under construction on the Tezeke River (a tributary of the Blue Nile) in the Tigray Region of northern Ethiopia. Scheduled for completion by the end of 2006, the Tezeke Dam with a height of 185 m will be 10 meters higher than the highly controversial Three Gorges Dam in China.

In summer 2005, Ethiopia signed an agreement with an Italian construction company to build a 460 MW hydroelectricity dam across the Beless River, a tributary of the Blue Nile in the north-western part of the country. With costs of over 690 million dollars, this project would represent the largest hydropower dam in the country. Including irrigation and drinking water projects for the autonomous Benishangul-Gumuz Region bordering Sudan, the dam is expected to be completed in about three years.

Currently under construction, the Merowe Dam on the Nile River, about 800 km north of the capital Khartoum (Sudan) is the largest contemporary hydropower project in Africa.

Expected to be completed by 2008, the main purpose of the dam will be hydropower production.

2.4 Merowe Dam – technical details

Located on the Nile River in Sudan, about 800 km downstream of Khartoum and about 500 km upstream of Lake Nubia, the Merowe (or Hamadab) Project has originally been conceived as a multi-purpose reservoir dam for irrigation and hydropower production. In April 2002, the irrigation component (two irrigation intakes on the right and left bank of 150 m^3 s^{-1} each) was still studied at pre-feasibility level although the two irrigation intakes have been incorporated in the dam structure design.

The dam is designed to have a length of about 9 km and a crest height of up to 67 m. It will consist of concrete-faced rockfill dams on each river bank, an earth-rock dam with a clay core in the left river channel and a live water section in the right river channel (sluices, spillway and power intake dam with turbine housings). The powerhouse will be equipped with ten 125 MW Francis turbines. Once finished, the dam will create a reservoir with a volume of 12.4 km^3, representing about 20 % of the Nile's annual flow and a surface area of 800 km^2 stretched over 200 km river length. At the maximum storage level at 300 m a.s.l. and a maximum water depth of 57 m, the reservoir will submerge about 66 km^2 of irrigated and flood recession land. The reported average residence time is 0.2 years for an annual inflow of 84 km^3 yr^{-1} (Table 2).

The planners expect an annual electricity generation of 5.5 TWh, corresponding to an average load of 625 MW, or 50 % of the rated load. To utilize the extra generation capacity, the Sudanese power grid will be upgraded and extended as part of the project. It is planned to build about 500 km of new aerial transmission lines across the Bayudah desert to Atbara, continuing to Omdurman/Khartoum, as well as about 1’000 km lines eastwards to Port Sudan and westwards along the Nile, connecting to Merowe, Dabba and Dongola.

Special features of the project described by EIAR (2002) are listed below:

- The hydropower plant will be operated with a minimum water release flow of 600 m^3 s^{-1} for 20 h per day and a maximum flow of 3'000 m^3 s^{-1} for 4 h per day. This operation mode results in daily water level fluctuations in the river downstream with a maximum amplitude of 4.9 m from January to March.
- The dam design incorporates special sluices and particular operation rules to reduce reservoir sedimentation and related capacity losses over a 50 yr period to 17 % of the original active capacity (83 % will still remain active).
- The dam structure will be equipped with a grout curtain preventing water losses to the downstream groundwater.

	Value	**Unit**
Reservoir area	800	[km^2]
Length (river)	200	[km]
Max. water level	57	[m]
Annual inflow	84	[km^3yr^{-1}]
Storage volume	12.4	[km^3]
Evaporation	2.4	[km^3 yr^{-1}]
Retention time	0.2	[yr]
Max. daily water release flow	3000	[m^3 s^{-1}]
Min. daily water release flow	600	[m^3 s^{-1}]
Average suspended solids	1.7	[g l^{-1}]

Table 2. Merowe Dam: reservoir characteristics described by EIAR (2002)

3. Environmental issues - lessons from Aswan High Dam

It is important to recall that environmental effects of a river development program are usually complex and always cause changes with positive and negative implications for the environment. River impoundments generally cause a series of multifaceted ecological alterations. Elimination of the annual natural flooding, water storage, increased surface area, increased evaporation and infiltration to adjacent aquifers, reservoir sedimentation and downstream erosion, increased residence time and thermal stratification, high *in-situ* primary production, changing nutrient transport, greenhouse gas emissions and water-born diseases are a few typical consequences (Rosenberg et al., 1995; Rosenberg et al., 1997; Friedl and Wüest, 2002).

A reliable assessment of environmental effects of river damming requires adequate basic information. Unfortunately, such information was only partly available in the EIAR (2002) for the Merowe Dam Project as prepared by Lahmeyer International. In such a case of a limited database at the river reach of interest it is a useful strategy to review the existing literature on existing dams within the same river system. In the following we therefore review the available literature on the large impoundment 500 km downstream, the Aswan High Dam Reservoir. The review of the environmental impacts of the Aswan High Dam serves as a reference system for identifying and evaluating the magnitude of the potential impacts of the Merowe Dam on water quality and Nile River ecology.

The Aswan High Dam (AHD), the world second largest artificial lake by volume after Bratsk in Russia has been the subject of controversial discussions during the design, construction and after completion in 1965. With a design capacity of 162 km^3 at a maximum water level of 182 m a.s.l., its main purposes are electricity production and water storage. With an area of 6’000 km^2, the lake behind the AHD extends about 500 km south from Aswan with about 300 km in Egypt (Lake Nasser) and 200 km in Sudan (Lake Nubia). The total capacity of the reservoir consists of the dead storage of 31.6 km^3 (85 to 147 m a.s.l. of lake water level), the active storage of 90.7 km^3 (147 to 174 m) and

the emergency storage for flood protection of 41 km^3 between 175 and 182 m a.s.l. (Shalash, 1982).

3.1 Reservoir-induced seismicity

On 14 November 1981, six years after the AHD Reservoir reached its maximum level of 72 m (1975), a first earthquake occurred near the edge of the lake, about 65 km to the south-west of the dam on the Kalabsha fault at a depth of about 20 km (Kebeasy et al., 1991; Abu-Zeid et al., 1995). With 5.5 degree on the Richter scale, the local magnitude was felt as far as 900 km south at Khartoum and causing some damage at Aswan. As the event occurred at a significant distance from the reservoir and at considerable time after impounding (16 years), it was not clear whether it was a reservoir-induced earthquake.

Subject of many studies, the reservoir behind the AHD was considered not to contribute to seismic activity as the depth of seismicity was larger than 15 km and the penetration of water to affect water pressure at this depth was hypothetical (Meade, 1991). However, the theory of induced earthquake mechanisms of Simpson (1976) suggests that the first event should appear at some distance from the deepest part of the reservoir and may occur some time after impounding when the effects of increased pore-pressure overcome the effect of loading. Also, the existence of long-continuity aftershock sequence as in the case of Aswan with a frequency of 0 to 10 events per month between 1982 and 1998 was considered a feature of reservoir-induced seismicity (Selim et al., 2002).

The statistical investigation of reservoir-induced seismicity in AHD has shown a strong correlation with the water level fluctuations. The seismicity was observed active during periods of decreasing water levels (Selim et al., 2002). These correlations supported the conclusion of reservoir-induced seismicity at AHD.

3.2 Water losses

As an effect of increased water surface area exposed to arid climate conditions, the evaporation from the lake behind the AHD, based on isotope analyses, was estimated to vary between 18 and 21 % (19 % in average) of the total river input (Aly et al., 1993). A later review of previous literature data established a large range for evaporation from Lake Nasser between 1.7 m yr^{-1} and 2.9 m yr^{-1} (Sadek et al., 1997). Based on water balance, energy budget and modelling techniques, narrower range of 2.1 m yr^{-1} to 2.6 m yr^{-1}, with an average of 2.35 m yr^{-1}, was calculated by Sadek et al., (1997). In a 2002 technical report, based on the available data at the Nile Forecasting Center in Cairo, it was estimated that the annual evaporation from the AHD Reservoir varied between 12 and 12.6 km^3 yr^{-1} which correspond to an evaporation rate of 2.0 to 2.1 m yr^{-1} (Roskar, 2000). Compared to the reservoir volume of 162 km^3, the evaporation represents about 8 % per year but more than 15 % of the river inflow of 84 km^3 yr^{-1}.

In addition to the water loss via evaporation, the seepage of the AHD to the lateral groundwater aquifers was calculated to reach 1 km^3 yr^{-1} representing 1.2 % of the river inflow (Aly et al., 1993).

3.3 Water quality

Measurements between 1980 and 1990 in the AHD revealed annual water level fluctuations between 2 and 18 m with an average of 6 m (Rashid, 1995). Besides direct effect on vegetation abundance and distribution (Ali et al., 1995) and fish ecology, large seasonal fluctuations of the lake level affects the settling of the population around the lake shore.

A general effect of water storage due to river impoundment in arid and semi-arid areas is the onset of thermal stratification of the water column. Surface temperatures of 27 to 30 °C were measured in Lake Nasser from May to August 1976 and 1977 whereas

temperatures of 20 to 22 °C were recorded at 16 m depth (Rashid, 1995). During November to February 1976 and 1977, no differences in temperature were observed between the surface and deep water (Rashid, 1995).

The AHD Reservoir exhibits a distinct stratification pattern which varies from the main channel to the side bays, locally known as *khores*. Measurements in the AHD Reservoir showed that the thermal stratification of the water column starts usually in May extending from north to south to almost the entire water body. At the beginning of the flood period in late July, the thermal stratification is usually vanished in the southern reaches of the reservoir whereas the northern sectors remain stratified until late October when the seasonal cooling leads to deep convective mixing (Abu-Zeid, 1987).

Dissolved oxygen concentration in the water column reflects closely the main phases of thermal stratification. The oxygen profile decreased with depth. For example, from March to June 1976/1977, dissolved oxygen concentrations above 8.5 mg l^{-1} (with high values up to 14 mg l^{-1} near the surface) characterized the uppermost 10 m of the northern sector of AHD but were as low as 2 mg l^{-1} near the bottom (Abu-Zaid, 1987; Rashid, 1995). In July/August, the dissolved oxygen concentration ranged between 9.8 to 0.0 mg l^{-1} in the upper 15 m. A stable stratification of the lake water column was therefore, evident with an oxygen minimum between 10 and 25 m. During 1978 an oxygenated layer was limited to the top 10 m in July and August for the northern AHD whereas in October-November, stratification started disappearing with the oxic layer extending to 40-50 m below surface (Abu-Zaid, 1987). In December, the lake water becomes usually saturated or near-saturated with oxygen from the surface down to the bottom (Rashid 1995). Also, in the northern part of Lake Nubia, dissolved oxygen was absent near the bottom during August 1976 in the side bay whereas in the riverine section of the lake, the concentration was about 8 mg l^{-1} all the time (Rashid, 1995). In Lake Nasser (Egypt) oxygen-free conditions at the reservoir bottom were extending progressively towards the dam over a general stratification period of between 5 and 8 months (Entz, 1980a). The flood affected the stratification only in the southern part of the lake and therefore, the mixing process was often incomplete (Rashid, 1995).

Measurements of dissolved oxygen in the water column along the main body of AHD during 1982 and 1984 revealed a wide spatial and seasonal variation in concentrations (Ahmed et al., 1989; Mohammed at al., 1989). At 10 km south of the dam the values ranged from a minimum of 4.3 mg l^{-1} in autumn 1982 to a maximum of 9.0 mg l^{-1} in winter 1982. At 245 km south of the dam, the highest values of 8.1 were recorded in the summer 1982 and 1983 respectively (Figure 4). The saturation of water with oxygen in the AHD was associated with the high level of algal photosynthetic activity (Mohammed et al., 1989). The vertical distribution at 10 km south of the AHD showed oxygen supersaturation only in April and June 1982 and May 1983 at times of intensive phytoplankton development (Ahmed et al., 1989). The oxygen saturation in the reservoir remained below saturation in 1982 and 1984 with a lowest level of 28 % during summer when the thermal stratification was well established (Mohammed et al., 1989).

Salinity, defined as the total content of all dissolved ions per volume of water, is controlled by the net accumulation of salt from all sources minus the losses through outflow and mineral precipitation. Several indications of an increased salt content of the Nile water between Aswan and Cairo (Egypt) were observed during 1963-1971, after closing the AHD (Hilal and Rasheed, 1976). The longitudinal series and an earlier comparison of seasonal changes at Aswan and Cairo showed that the observed increase in salt content was mainly attributed to increases in the ions Na^+ and Cl^-. Conductivity values in Lake Nasser were higher than expected form the simple seasonal mixture of Blue and White Nile water (Talling, 1980). Monitoring of Lake Nubia has shown a gradual annual increase in average total dissolved solids concentration from: 153 mg l^{-1} in 1978 to 156 mg l^{-1} in 1979, 158 mg l^{-1} in 1980, 162 mg l^{-1} in 1981 and 163 mg l^{-1} in 1982 (ILEC, 2005). Constantly, about 30 % higher values were measured during the dry season months compared to the flooding and after-flooding season. This was explained by the increased contribution of the White Nile water with relative higher total dissolved solids compared to the Blue Nile and the dilution effect during the flood periods. However, the linear increase in total dissolved concentration between 1978 and 1982 was attributed to the water losses by evaporation.

Water quality measurements at the AHD indicate that the salinity varies from 5 to 20 %, depending on the reservoir surface and the seasons (Abu-Zeid, 1987). A salt balance model based on measurements since 1913 showed that the evaporation in the Aswan Reservoir resulted in a 10-15 % increase in total dissolved solids of the water released from the dam (Abu-Zeid, 1987). This increase in salt content per se is currently not a serious concern – critical is the loss of water.

3.4 Sedimentation

It has been shown that, prior the AHD construction and operation in 1964, more than 90 % of the Nile sediment load was carried to the Mediterranean Sea (Shalash, 1982). Since the operation of the AHD in 1968, the sediment balance has been drastically modified. Based on 100 years long records at various locations upstream and downstream of AHD, the total suspended solids (TSS) inflow concentration was determined as 1.7 g l^{-1} (kg m^{-3}) corresponding to an average load of $142x10^6$ t TSS yr^{-1} (Shalash, 1982). Outflow measurements and long-term predictions were used to calculate an average deposition in the AHD of up to $136x10^6$ t TSS yr^{-1}, representing a total retention of 96 % of the incoming load (Shalash, 1982).

Using an average sediment density of 1.56 g cm^{-3} (Shalash, 1982) and corrected for compaction (dry weight density of 2.6 g cm^{-3} and a porosity of 40 %), the amount of annually retained sediment of $136x10^6$ t TSS yr^{-1} corresponds to an accumulated volume of $87x10^6$ m^3 yr^{-1} (Shalash, 1982). A comparable sediment volume of $119x10^6$ m^3 yr^{-1} was measured to be annually deposited in the AHD Reservoir based on sedimentation data over a 5 years study interval between 1987 and 1992 (Eldardir, 1994). At this accumulation rate the reservoir dead storage capacity of 31.6 km^3 will be lost in ~ 360 years, close to the preliminary calculated design life time of 450 years (Shalash, 1982). This new results imply that after the 41 years since the AHD closure in 1964, the reservoir has lost ~ 11 % of its dead storage capacity (~ 0.3 % annually).

Several studies on the AHD Reservoir have shown that the major part of the sediment load is deposited close to the inflow of the reservoir in Lake Nubia where a new delta is forming.

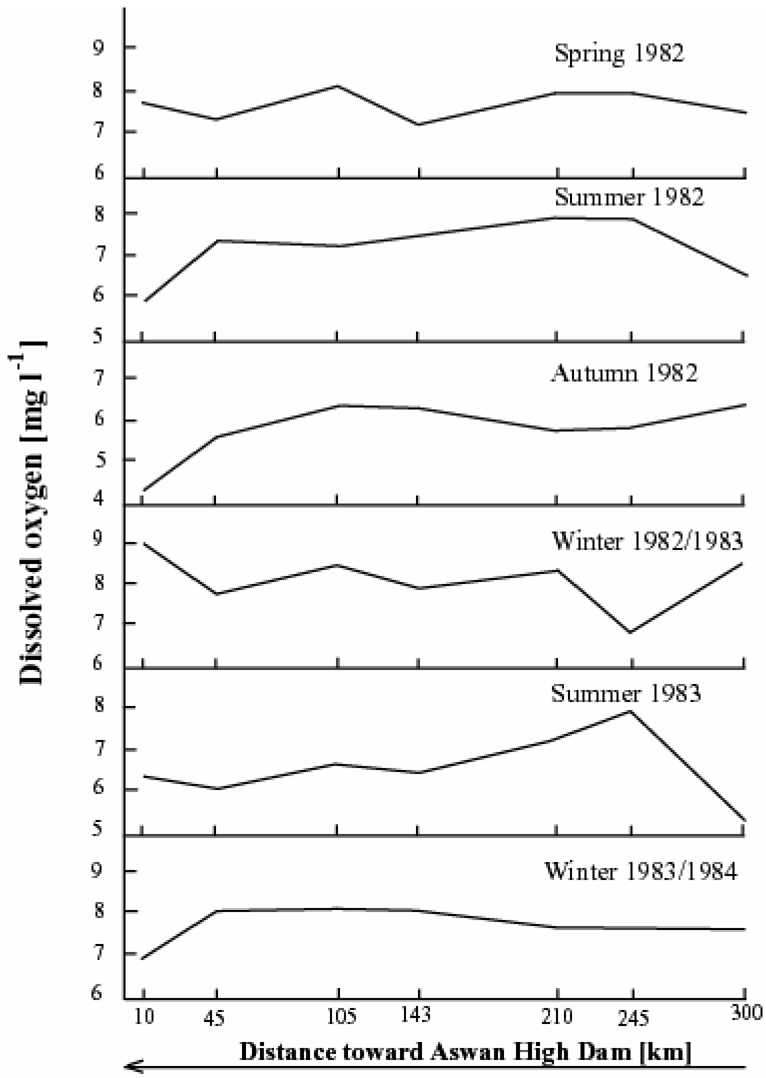

Figure 4. Seasonal local variations in dissolved oxygen concentration in Lake Nasser (Egypt) from spring 1982 to winter 1983/1984 (after Ahmed et al., 1989)

After less than 30 years, this new delta accumulated a 40 m thick fan about 200 km long and 12 km wide (Eldardir, 1994). The prediction based on sedimentary aspects and hydraulic factors anticipate that the new delta will appear on the lake surface with almost complete closure of the reservoir within the next 50 years (Eldardir, 1994). Therefore, dredging of this sediment may be soon required.

Studies from the eighteenth century, and confirmed by more recent ones, have shown that during the natural hydrologic regime of the Nile River the annual deposition rate on the river bed and the often cultivated side banks was around 1 mm yr^{-1} accounting for 7 % of the annual average TSS load (Shalash, 1982). About $24x10^{6}$ t yr^{-1} nutrient-rich sediments were deposited mainly on the Egyptian flood plains before the AHD construction. At present only $2.1x10^{6}$ t yr^{-1} are left in the Nile water to be deposited on Egyptian soils (Balba, 1979). The low sediment content (25 and 40 mg l^{-1}) in the water downstream of the dam combined with more bank exposure due to low water levels, accelerated the Nile channel degradation. Field measurements over a period of 15 years after the AHD construction showed rates of river bed degradation between 2 and 5 cm yr^{-1} depending on the rate of decrease in water levels (Abu Zeid, 1987). Similar results were found by Kotob and Mottoleb (1981) after the first 12 years of the AHD operation, when annual bed degradation rates as high as 3 cm yr^{-1} were measured (Table 3).

In addition to the bed degradation, bank erosion was also observed along the river channel which was partially caused by local efforts for river regulation before closing the AHD (Abu-Zeid, 1897).

Observations since 1898 at the Nile delta and the littoral zone indicate active coastal erosion processes along the Mediterranean shore. Explained by recent hydrological changes in the Nile River regime, and the missing supply of suspended solids, the costal erosion was recently associated with a general subsidence (Frihy, 1998; Elraey et al., 1995; Stanley, 1996; Stanley and Wingerath, 1996; Stanley, 2000).

Location downstream from AHD	Distance from AHD	Max. drop in river bed	Max. drop in water level
	[km]	[cm]	[cm]
Aswan Dam	6.5	12	58
Esna Barrage	165	25	76
Naga Hammadi Barrage	359	25	75
Assuit Barrage	539	2	55

Table 3. Maximum drop in river bed and water level downstream AHD between 1964 and 1978 (after Abu-Zeid, 1987).

Studies by Stanley and Wingerath (1996) have shown that clay-sized material (< 2 μm) is the major fraction transported from the lake behind AHD to the river below. Based on kaolinite tracer analyses, this material was found to be of eolian origin due to erosion of lake-margins and river banks.

3.5 Biogeochemical cycles

3.5.1 Nitrogen

Available data on carbon and nutrient cycles in the AHD Reservoir are quite inconsistent and cover only short temporal and spatial scales, which hamper balancing these biogeochemical cycles with reasonable accuracy.

The nutrient concentrations in AHD were reported to be higher in the southern part of the reservoir. Ahmed et al., (1989) found a general decrease of NO_3 – N concentration towards the dam (Figure 5) when studying the Lake Nasser (Egypt) between 1982 and 1994. Exceptions form this trend were recorded during the summer 1982/1983 when high values up to 400 μg NO_3 l^{-1} were measured 100 km south of the dam (Figure 5). On the S-N transect, the average concentrations were 61, 136, 284 and 289 μg NO_3 l^{-1} for spring, summer, autumn and winter 1982, respectively whereas 261 and 286 μg NO_3 l^{-1}, respectively, were measured during the summer and winter 1983.

The vertical distribution at a sampling site 10 km in front of the dam showed low nitrogen concentrations for early spring and late summer. The lowest value of 2 µg N l^{-1} and 8 µg N l^{-1} was observed in September 1982 in the surface layers (Ahmed et al. 1989). The reduction of N concentrations in the trophogenic zone down to 8 m in August and September 1982 was attributed to high rates of phytoplankton growth (Ahmed et al., 1989; Mohammed et al., 1989, Figure 6).

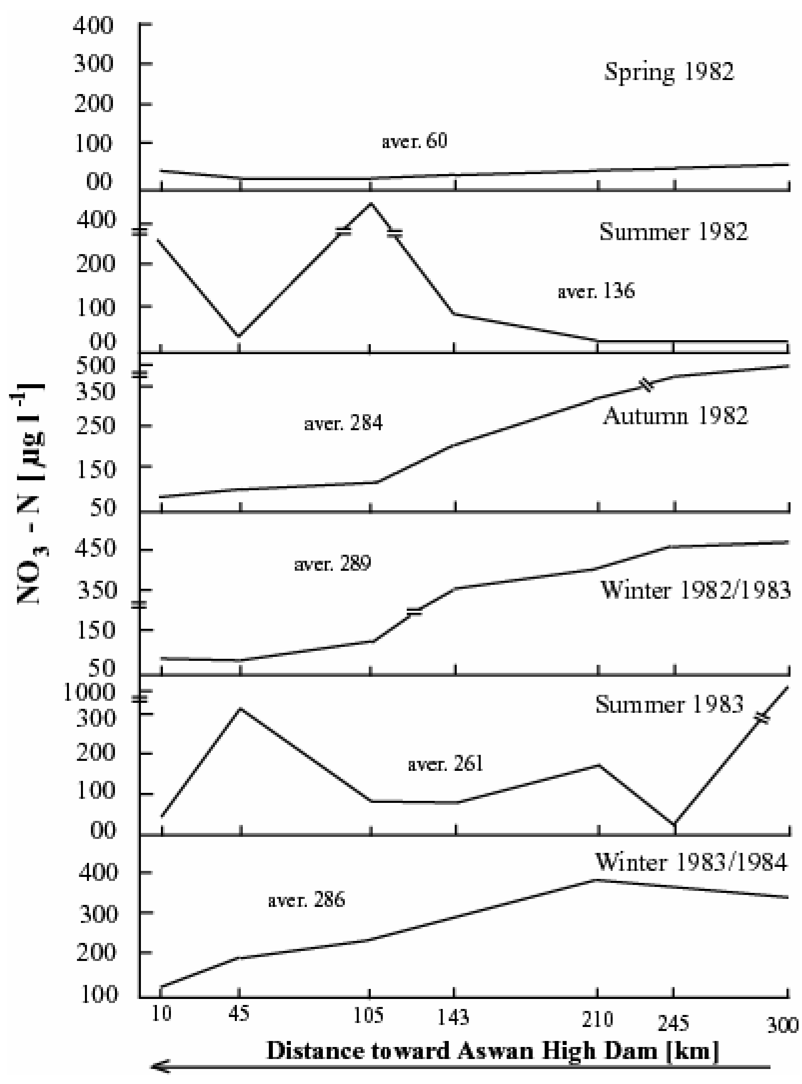

Figure 5. Seasonal local variations in nitrate - nitrogen concentration in Lake Nasser (Egypt) from spring 1982 to winter 1983/1984 (after Ahmed et al., 1989)

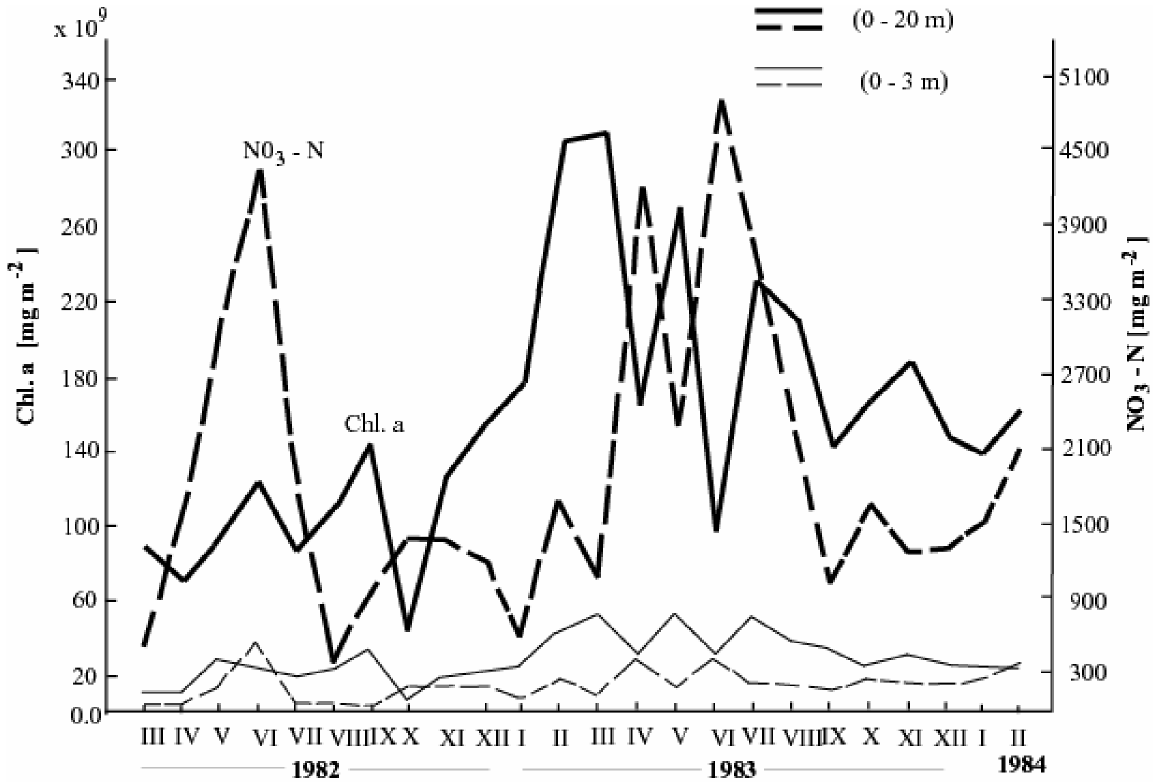

Figure 6. Depth-time distribution of NO_3-N and chlorophyll a concentration integrated over the water column down to a depth of 3 and 20 m in AHD at a station 10 km south of the dam (after Mohammed et al., 1989).

A close correlation between nitrate concentration and chlorophyll was found by Mohammed et al. (1989) (Figure 6). Low N-concentrations were postulated to limit the primary production for at least some algal genera or species (Mohammed et al., 1989).

A similar drop of nitrate-nitrogen down to 20 µg N l^{-1} limiting the growth of algae species was also reported for the Blue Nile during the maximum growth of the diatom Melosira (Rzoska and Talling, 1966).

Measurements carried out in during February 1970 in Lake Nasser close to the AHD showed irregular variations of nitrate concentrations from the surface to the bottom, ranging from a minimum of 280 µg N l^{-1} at 20 m depth to a maximum of 950 µg N l^{-1} at 10 m (Saad, 1980; Figure 7). Small amounts of nitrite were detected in Lake Nasser with

the vertical distribution fluctuating between a minimum of 20 µg Nl^{-1} at 50 m depth and a maximum of 42 µg NO_2 l^{-1} at 30 m (Saad, 1980; Figure 7). Average concentrations over the entire water column were 670 µg N l^{-1} for nitrate and 30 µg N l^{-1} for nitrite, respectively.

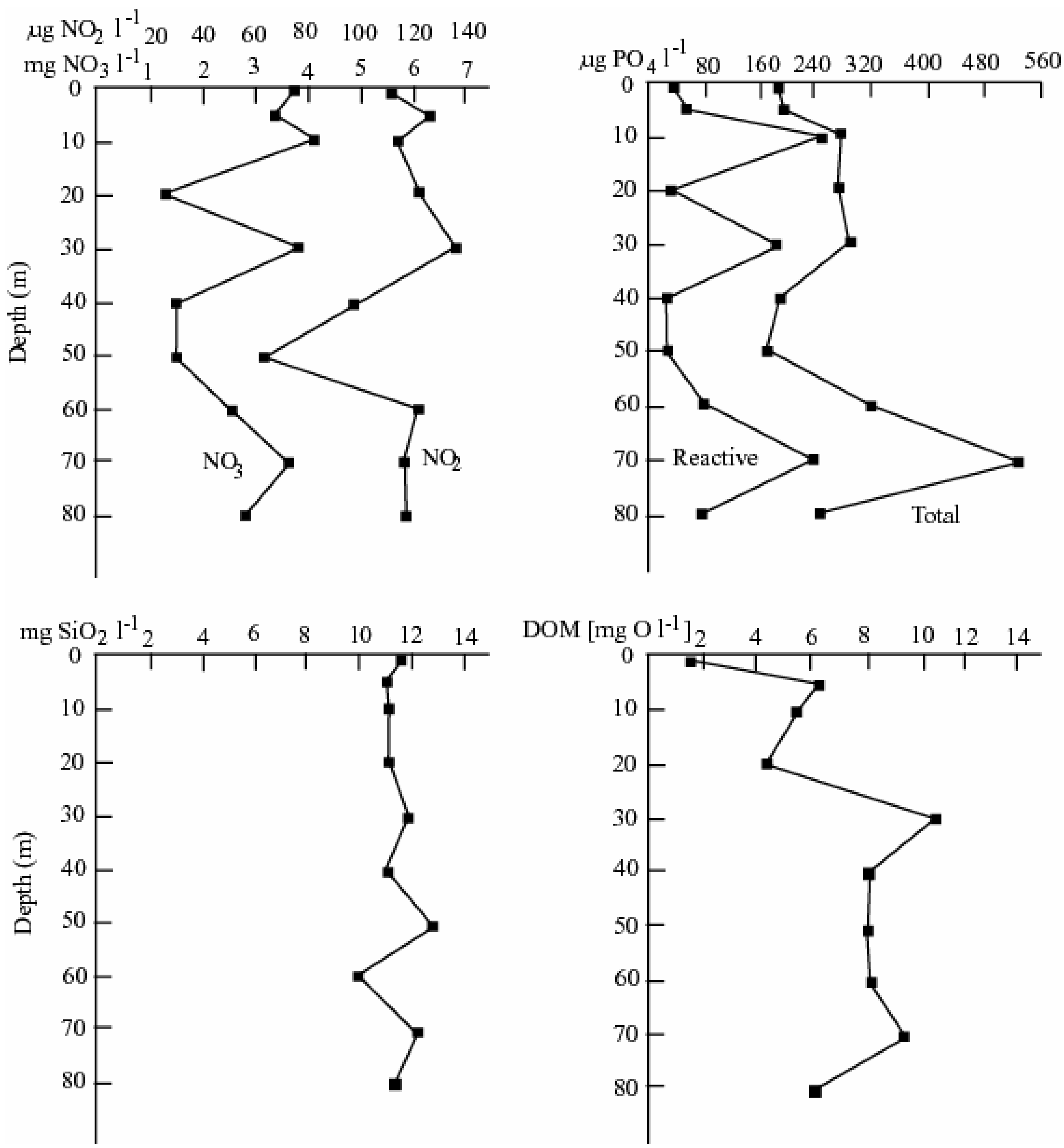

Figure 7. Vertical distribution of nitrate, nitrite, phosphate (reactive and total), silicate and dissolved organic matter (DOM) in Lake Nasser measured during February 1979 (after Saad, 1980)

Measurements of nitrite along the Nile River below the AHD form Aswan City to the Nile Delta (Figure 8) showed rather constant concentrations of 30 µg N l^{-1} between Aswan and Luxor followed by to a total depletion at the next stations and a slight increase up to 6 µg N l^{-1} at Rosetta. The dynamics of nitrate and nitrite indicate active processes of nitrification of ammonia from sewage input and denitrification of nitrate in suboxic zones in the stratified reservoir. Quite low nitrogen concentrations in the surface waters are a strong indication for primary production, while increasing nitrate concentrations in bottom waters are caused by mineralization processes (Saad, 1980).

The quality of available data allows only to calculate tentative scenarios of nitrogen uptake and release: If we assume that the decrease from 500 to about 60 µg N l^{-1} observed during the winters 1982/1983 and 1983/1984 (Figure 5) in the S-N transect in Lake Nasser (km 245 - km 10) was due to nitrogen uptake by mainly by phytoplankton and macrophytes, the annual biological nitrogen consumption in Lake Nasser would correspond to about 71’000 t N yr^{-1}. With a molar ratio of 106 C:16 N, the equivalent primary production rate required to fix annually 71’000 t N yr^{-1} is 67 g C m^{-2} yr^{-1}. This rate is found to be much lower than a minimum of 270 g C m^{-2} yr^{-1} characterizing the eutrophic systems. Also, if the concentration increase along the flow path by about 440 µg N l^{-1} in summer 1982 by 220 µg N l^{-1} one year later (Figure 5) was due to the mineralization of the organic matter, an average mineralization flux of 50’000 t N yr^{-1} or 70 % of the total nitrogen consumption could be estimated. In summary, the observed nitrogen dynamics points to a rather low primary production.

3.5.2 Phosphorus

Little is known about the phosphorus budget in the AHD. In general the PO_4 concentration was described to have a spatial and temporal variability with higher concentrations of between 120 and 160 µg P l^{-1} reported for the southern part of the reservoir (Lake Nubia – Sudan) compared to 30 and 160 µg P l^{-1} for the northern part of in Lake Nasser (Rashid, 1995). The values were highest in August and November and lowest in February and increased with depth (Rashid, 1995). In February 1970,

measurements in the Lake Nasser at a site close to the AHD showed PO_4 values fluctuating between a minimum of 10 µg Pl^{-1} at 50 m depth, and a maximum of 90 µg P l^{-1} at 10 m (Saad, 1980; Figure 7). Total phosphorus profiles also showed considerable irregular variations between 60 µg P l^{-1} and 175 µg P l^{-1} (Saad, 1980). In general, the values of reactive phosphate found in most samples of Lake Nasser were much lower than those of non-reactive phosphate illustrating mineral origin of total phosphorus. Therefore, high concentration of reactive phosphate was attributed to the decomposition of organic matter and the release of absorbed phosphate. The average concentration of the reactive phosphate of 35 µg P l^{-1} was about 2.5 times lower than total phosphorus (Kanawy, 1974).

Some phosphate measurements along the Nile River below the AHD from Aswan City to the Nile Delta are shown in Figure 8. The values of reactive phosphate in the Nile water below the AHD ranged between a minimum of 4 µg Pl^{-1} at Suhag to a maximum of 40 µg P l^{-1} at Assyut. Reactive phosphate was depleted at the intermediate station of Luxor where the non-reactive phosphate contributed 100 % to the total phosphorus. During October 1988 and March 1990, a limnological study was conducted in Lake Nasser, Aswan Reservoir (a small water body between the old Aswan Dam and the AHD, 7 km to the south) and the Nile River north of the old Aswan Dam (Ali et al., 1995). The chemical parameters of the water bodies and hydro-soil samples are summarized in Table 4 and Table 5.

	Lake Nasser			Aswan Reservoir			Nile River		
	Max.	Min.	Mean	Max.	Min.	Mean	Max.	Min.	Mean
Temp. (°C)	30.0	16.0	25.8	24.5	15.0	20.8	27.0	17.0	22.5
D.O. [mg l^{-1}]	17.0	4.3	8.55	12.3	4.0	9.06	13.4	4.0	7.89
S.R.P. [µg P l^{-1}]	391	0.0	52	260	0.0	39	114	0.0	42
NO_3 [µg P l^{-1}]	409	0.0	115	890	0.0	280	615	0.02	221
NO_2 [µg P l^{-1}]	9	0.0	3	64	0.0	15	18	0.0	6

Table 4. Maximum, minimum and mean values of temperature, dissolved oxygen (D.O.), soluble reactive phosphate (S.R.P.), nitrate and nitrite of Lake Nasser, Aswan Reservoir and River Nile (after Ali et al., 1995).

3.5.3 Organic matter and silicate

A vertical distribution of the silicate and organic matter content in Lake Nasser is shown in Figure 7 and concentrations in the Nile River below the AHD are shown in Figure 8. The upper 40 m depth are characterized by a general concentration of 11.5 mg SiO_2 l^{-1} with an increase up to 13 mg SiO_2 l^{-1} at 50 m depth and a decrease to a minimum 10.2 mg SiO_2 l^{-1} at 60 m depth. The values at 70 and 80 m amounted 12.3 and 11.5 mg SiO_2 l^{-1}, respectively. Similar to the Lake Mariut (Aleem and Samaan, 1969), vertical distribution of silicate was postulated to be influenced by the physicochemical conditions of the lake rather than by diatom consumption (Saad, 1980). Dissolved organic matter (DOM) content in Lake Nasser was found to increase from a minimum of 1.56 mg l^{-1} at the surface to a maximum of 10.6 mg l^{-1} at 30 m depth attributed mainly to the decomposition of the phytoplankton in the water column (Saad, 1980; Figure7). In general, a constant concentration of about 8 mg l^{-1} was measured below 40 m (Saad, 1980). It should be noticed, however, that the irregular trend in vertical distribution of nutrients in February was due to the absence of a clear thermal stratification as a result of cooling-induced mixing of the lake water during winter (Saad, 1980).

Dissolved organic matter and silicate, along the Nile River behind the AHD measured at Aswan, Luxor, Suhag, Assyut, Cairo, Rosetta and Damietta, (see Figure 1) are shown in Figure 8. The gradual increase from 2.8 mg l^{-1} at Aswan to 4.2 mg l^{-1} measured at Rosetta (Figure 8) was attributed to regional conditions such as phytoplankton abundance and surface runoff as well as sewage and industrial pollution (Saad, 1980). Low values were ascribed to coincide with the decrease in the autochthonous and allochthonous supply of organic matter as well as the increase in decomposition rate. The silicate content showed a gradual decrease along the Nile River from Aswan towards the outlets, from a maximum of 11.2 mg SiO_2 l^{-1} at Aswan to a minimum of 3.2 mg SiO_2 l^{-1} at Damietta (Saad, 1980). Inverse correlated to the chlorosity content, the decrease in the dissolved silicate towards the delta was attributed mainly to the uptake by diatoms and therefore, assumed that the diatom population gradually increases along the Nile below the AHD (Saad, 1980).

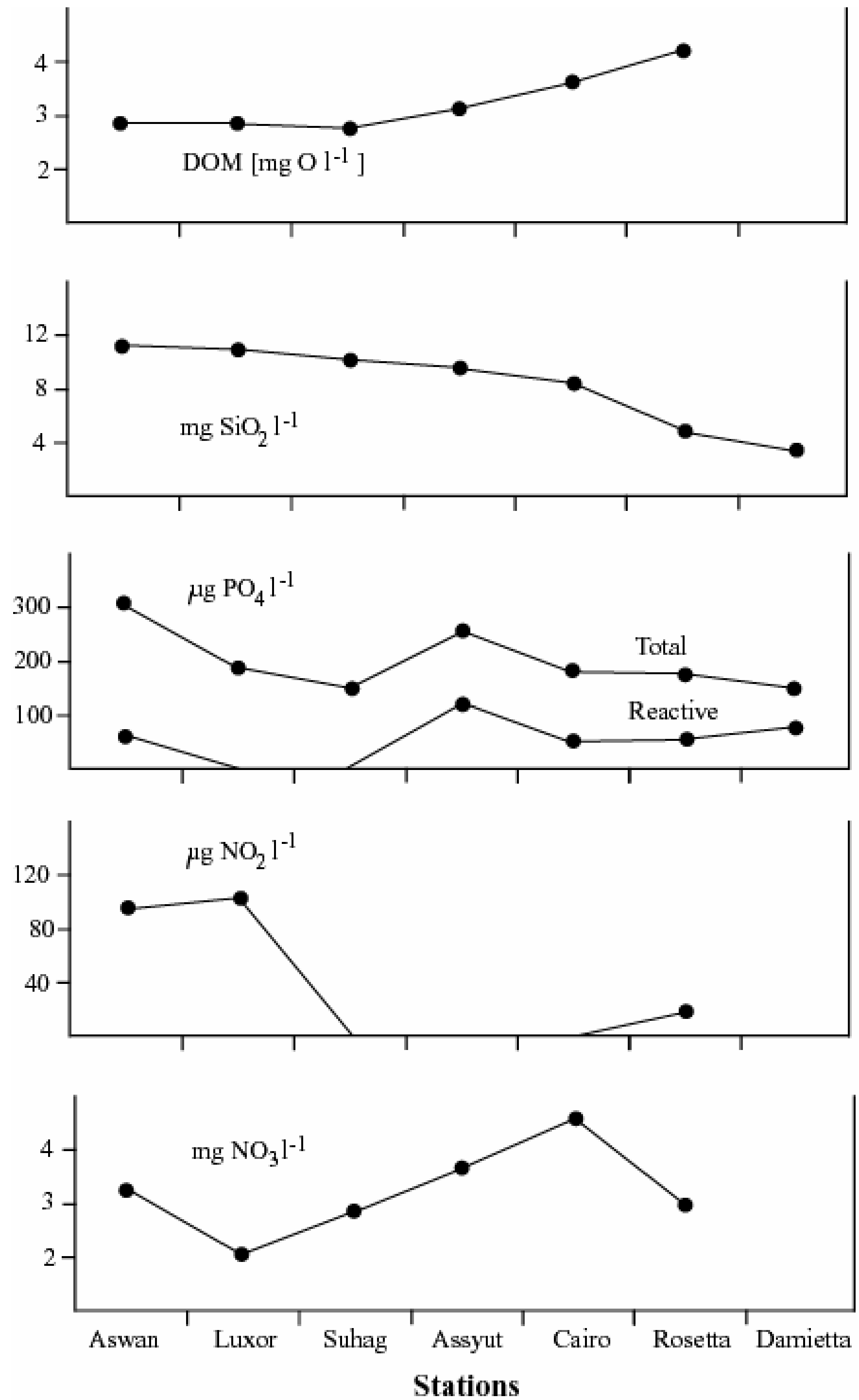

Figure 8. Distribution of DOM, silicate, phosphate, nitrite and nitrate along the Nile River below the AHD to the Nile Delta (after Saad, 1980)

	Organic Matter	PO_4
	[mg g^{-1}]	[µg P g^{-1}]
Lake Nasser	**19.3**	**0.58**
Berba East	18.8	0.50
Kalabsha a	39.1	1.03
Kalabsha b	19.4	0.57
Turgumi	7.5	0.23
Amada	11.7	0.55
Aswan Reservoir	**106**	**4.50**
Awad Island	124.5	2.48
Nag Tongar	87.5	6.53
River Nile	**51.9**	**0.28**
West Bank	51.9	0.28

Table 5. Chemical composition of hydrosoils from River Nile, Aswan Reservoir and Lake Naser (after Ali et al., 1995).

3.5.4 Primary production

Large geomorphological and hydrodynamic differences in the extent of thermal stratification and the depth of photic zone were considered the main reasons for different ecosystem characteristics of the main channel of the AHD Reservoir compared to side bays (Abu-Zeid, 1987). In general, rates of biological production in the AHD Reservoir were estimated as high as 8-15 g O_2 m^{-2} day^{-1} from diurnal changes in open water measurements in some side bays (Abu-Zeid, 1987). Similar, high rates of gross primary production between 5.23 and 13.2 g C m^{-2} day^{-1} were measured in March 1970 whereas, higher rates of between 10.7 and 16.4 g C m^{-2} day^{-1} were recorded in 1979 when the biologically activity zone of the lake extended down to about 4 m (Latif, 1984). However, an average of 10 g C m^{-2} day^{-1} or 3'650 g C m^{-2} yr^{-1} calculated from the above values represents an extremely high rate beyond the highest values measured in the lakes.

In order to estimate a realistic rate of primary production for the entire reservoir, some assumptions were made. The primary production corresponding to an average phosphorus concentration of 50 µg P l^{-1} (Table 4), typically varies between 150 and 250 g C m^{-2} yr^{-1}. It can be considered that the reservoir consists of 5 % side bays (300 km^2)

where the production reaches high rates up to 3'600 g C m^{-2} yr^{-1}, and the rest of 95 % main channel (5'700 km^2) with an average production of 200 g C m^{-2} yr^{-1}. According to this scenario, a weighted average primary production of 370 g C m^{-2} yr^{-1} can be calculated. Even suffering with large degree of uncertainty, above calculated primary production for the AHD varying between 200 and about 400 g m^{-2} yr^{-1} may represent a better estimate.

3.5.5 Greenhouse gas

Since the beginning of the 19th century, the anthropogenic emission of greenhouse gases to the atmosphere is considered to be responsible for a significant increase in radiative forcing leading to a global warming process. The current scientific concern is that under present rates of economic and population growth, the global mean temperature will rise by 3 °C by the end of this century accompanied by an increase of the global precipitation levels by 15 % (Harrison et al., 1989). Higher temperatures will lead to increased evaporation rates, and increased global precipitation will alter the river runoff depending on the regional climate and hydrology. Harrison and Whittington (2001) estimated the impact of potential climate change on hydropower production. They concluded that a temperature increase by 4.7 °C for the Nile catchment could result in a 22 % increase in precipitation whereas the hydropower production may decrease by 20 % due to more extreme hydrological events.

Carbon dioxide (CO_2) as the major anthropogenic greenhouse gas increases by approximately 0.4 % in the atmosphere (Siegenthaler and Sarmiento, 1993). Its anthropogenic sources are primarily fossil fuel combustion and biomass burning processes. Methane (CH_4) is the second most important greenhouse gas with sources in natural wetlands, irrigated rice paddies, cattle and artificial reservoirs. On a global scale, the CO_2 and CH_4 fluxes from man-made reservoirs contribute an estimated 4 and 20 %, respectively, to the total anthropogenic emissions (St. Louis et al., 2000). No references regarding the greenhouse gas emissions from the AHD reservoir were found in the literature.

The greenhouse gas emission from reservoirs is a complex process involving at least four emission pathways: ebullition, diffusive flux, storage and flux through aquatic vegetation (Bastviken at al., 2004). Measurements of CH_4 and CO_2 emissions from hydroelectric reservoirs in northern Quebec with ages between 1 and 13 years indicated that processes in the water column such as oxidation and vertical advection of gases had a large effect on the C gas emission rates to the atmosphere. The emissions are not related to the type of the flooded ecosystem (Duchemin et al., 1995).

It was estimated that 70 % and 90 %, respectively, of the global CO_2 and CH_4 emissions from reservoirs of 3'500 mg m^{-2} d^{-1} CO_2 and 300 mg m^{-2} d^{-1} CH_4 originate from tropical reservoirs (St. Louis et al., 2000) although they account for only 40 % of the total reservoir area of 500'000 km^2 (Galy-Lacaux et al., 1999). Even as upper boundaries, these fluxes may help to estimate the magnitude of the greenhouse gas emissions from the AHD. Therefore, with a surface area of 6'000 km^2, the reservoir could release on the order of 7'660x10^3 t CO_2 and 650x10^3 t CH_4 per year.

A more realistic prediction on the greenhouse gas emission from the AHD can be obtained using the average primary production. With a rate of 370 g C m^{-2} yr^{-1} and a total surface area of 6'000 km^2, the total *in-situ* carbon fixation within the reservoir would correspond annually to 2'200x10^3 t C yr^{-1}. If we consider that 20 % of the organic carbon production is accumulated in the sediment of the reservoir (up to 440x10^3 t C yr^{-1}) whereas the rest is degraded within the water column up to 20 % and 60 % is washed out of the system. Additionally, due to high sedimentation rate, half of the accumulated load may be buried in the sediment, therefore partially lost from the system, and the other half is available for anaerobic decomposition or oxidation. Following this scenario, out of a total 2'200x10^3 t C yr^{-1} produced *in-situ* within the reservoir, up to 220x10^3 t C yr^{-1} is annually available to be converted in the sediment into greenhouse gas. Decomposition of organic matter in the water column may contribute with up to 440x10^3 t C yr^{-1}.

3.5.6 Dissolved phosphorus balance

No literature data could be found on the nutrient inflow in the AHD. As they are important for predicting the range of the primary production in the new Merowe Reservoir, the phosphorus concentration can be roughly estimated from mass balance calculation. Considering that for an annual estimation the reservoir is a conservative system, the input must be balanced by the net sedimentation and the output.

For a primary production rate of 370 g C m^{-2} yr^{-1} or an equivalent P flux of almost 9 g P m^{-2} yr^{-1}, the phosphorus uptake would represent $54x10^9$ g P yr^{-1}. Following the same scenario as for the greenhouse gas estimation, 20 % of the P uptake as $10.8x10^9$ g P yr^{-1} can be considered to accumulate at the lake sediment, where half is retained by sedimentation and the other half is released back into the water column. Therefore, the net sedimentary P retention will be $5.4x10^9$ g P yr^{-1}.

It has been ascribed that prior the AHD construction, the Nile flood delivered annually to the Mediterranean coastal about 7.2 to $11.2x10^3$ t ($3.2x10^3$ t in dissolved form and 4-$8x10^3$ t on sediment) of biologically-available phosphorus and $6.7x10^3$ t inorganic nitrogen (Nixon, 2003). Low post-AHD discharges due to high nutrient retention in extremely productive lake behind the dam were estimated to be $0.03x10^3$ t P yr^{-1} and $0.2x10^3$ t N yr^{-1} (Nixon, 2003). Therefore, up to $3.2x10^3$ t yr^{-1} P can be considered to represent the net P retention in the sediment of the AHD. This value is comparable with above estimated retention of $5.4x10^9$ g P yr^{-1}.

The outflow P concentration can be calculated from the average value reported for the small lake behind the AHD of 39 µg P l^{-1} (Table 4 – “Aswan Reservoir”). If the annual discharge at the AHD is 84 km^3 yr^{-1}, the output load would represent $3.3x10^9$ g P yr^{-1}. However, the output load can be actually much higher.

The mass balance can be approximated by the following equation:

$$P_{input} - P_{net\_retention} - P_{output} = 0$$

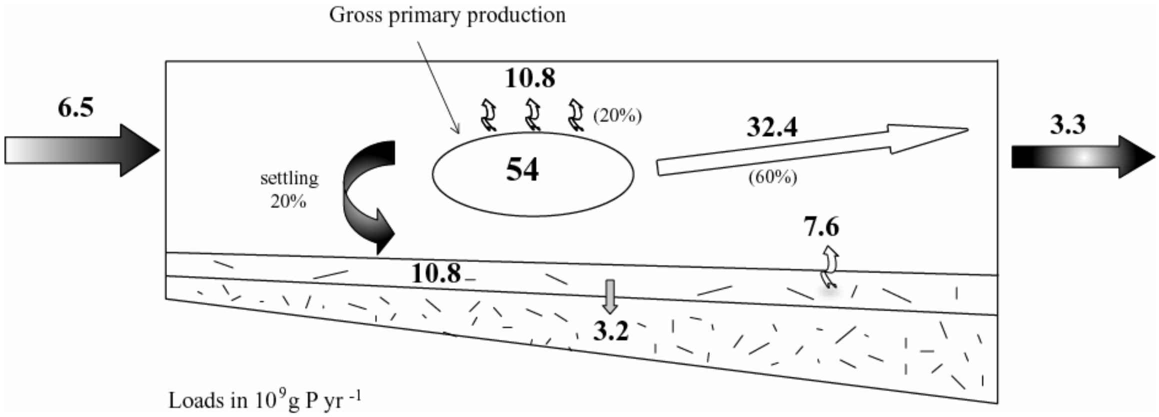

Figure 9. Phosphorus mass balance for the AHD expressed in 10^9 g P yr^{-1}.

Where: P_{input} represent the inflow P load; P_{net_acc} is the net P retention in the sediment; and P_{output} is the P output load (Figure 9).

If all parameters are considered in the equation, the balance indicates an input load of $6.5x10^9$ g P yr^{-1}. For an inflow of 84 km^3 yr^{-1}, the incoming P concentration would correspond to ~ 77 µg P l^{-1}.

3.6 Aquatic ecology

According to Latif (1984), the phytoplankton in the AHD Reservoir consists largely of:

(i) blue-green algae constituting 95 % in August 1976 and 81 % in October 1979 of the total phytoplankton;

(ii) (ii) diatoms with up to 66 % in November 1988 but only 2 %, respectively in August 1988;

(iii) (iii) green algae with up to 8 % in November 1988 and 3 % respectively in August 1988.

In the AHD the diatoms were dominant in cold winter months whereas the heat tolerant blue-green algae were found to be dominant in summer (Ahmed et al., 1989; Mohammed

et al., 1989). The general conclusion was that the diatom population is replaced by the green-algae as the temperature gradually rises, which in turn are succeeded by blue-green algae. Diatoms and blue-greens were the most dominant groups although their distribution and abundance were affected by thermal stratification and floods (Mohammed et al., 1989).

The undesirable blue-green algae species Cyanophyta, typical an impoundment organism, was found predominant in the northern sector of the AHD (Abu-Zeid, 1987). Capable of nitrogen fixation and representing a dead end in the food chain, they cause taste and odor problems (Abu-Zeid, 1987).

The zooplankton in Lake Nasser is described to belong to the common group of Copepoda, Cladocera and Rotifera (Rashid, 1995). In the main channel and side bays, Copepoda is the dominant zooplankton with 72 and 75 %, respectively, followed by Rotifera with 17% in main channel and 10 % in side bays and Cladocera with 11 % in the main channel and 15 % in side bays (Rashid, 1995).

The chironomid (benthos) fauna is rich in the shallow lacustrine areas of the lake. In the semi-riverine section their abundance decreases, and in the riverine section, the chironomids are replaced by ephemeropteran (mayflies) larvae whereas the bottom oligochaetas are replaced by bivalves (Rashid, 1995). The abundance of all mussels in Lake Nasser was massively reduced during the fist year of the reservoir formation as a result of oxygen-free bottom conditions. Even under low oxygen conditions, an increase in the biomass of oligochaetes was observed after 1973. This was possible due to their ability to withstand oxygen deficiency for several weeks or months, being able to utilize the high organic matter content of the sediment (Entz, 1980a).

The fish population of the AHD Reservoir is dominated by 9 families. A list of the families and the main species is given in Table 6. The fish abundance and distribution in AHD is described to vary among the different sectors of the reservoir and side-bays. Many factors play an important role in the fish population and density as the migration of

certain type of fish is dependent on the arrival of the turbid flood water, the preference of riverine or semi-riverine conditions, reproduction habitats and spawning or food and feeding habits. The fish food items in the AHD Reservoir are periphyton, phytoplankton and zooplankton, insects larvae (chironomids), gastropods, bivalves, juvenile fishes and fresh water shrimps (Rashid, 1995).

	Family	***Species***
1	Cichlidae	*Tilapia nilotica*
		Tilapia galilaea
		Tilapia zilli
		Oreochromis aureus
		Astatotilapia sp.
		Hemichromis letournexi
2	Centropomidae	*Lates niloticus*
3	Characinidae	*Alestes nurse*
		Alestes baremose
		Alestes dentex
		Citorrhinus spp.
		Distichodus spp.
		Hydrocynus forskahlii
		Hydrocynus lineatus
		Hydrocynus brevis
4	Cyprinidae	*Barbus spp.*
		Barbus bynni
		Labeo niloticus
		Labeo coubie
		Labeo horie
5	Bagridae	*Bagrus bayad*
		Bagrus docmac
6	Clariidae	*Heterobranchus bidorsalis*
		Clarias lazera
7	Schilbeidae	*Eutrophius niloticus*
		Schilbe mystus
		Schilbe uranoscopus
8	Synodontidae	*Synodontis schall*
		Synodontis serratus
9	Mormyridae	*Mormyrus kannume*
		Mormyrus caschive
		Mormyrus anguilloides
		Petrocephalus bane

Table 6. The list of main fish families and species in the AHD Reservoir

According to their feeding habits, the fish species in the AHD can be classified into six categories (Lowe-McConnell, 1987; Rashid, 1995):

(a) Periphyton feeders: *Labeo* spp, *Oreochromis niloticus, Oreochromis aureus* and *Sarotherodon galilaeus*.

(b) Omnivores: *Barbus* spp. and schilbeides.

(c) Molluscivores: *Synodontis* spp and mormyrids

(d) Piscivores: *Lates* spp., *Hydrocynus* spp., *Bagrus* spp., *Clarias* spp. and *Heterobranchus* spp.

(e) Plankton feeders: *Alestes* spp.

(f) Macrophyte feeders: *Tilapia zilii*

Although fish may sometime change their feeding habits according to food availability, changes in the food web will certainly trigger major changes in the fish population, densities and distribution and species composition.

Different characteristics of reproduction and spawning behavior of each fish species and their ability to adapt to new created conditions is an important aspect controlling the fish dynamics and species composition. For example, species as *Oreochromis niloticus, Sarotherodon galilaeus,, Hydrocynus forskahlii* and *Alestes nurse* are spawning fractionally in most of the years whereas the other species spawn once or twice per year (Rashid, 1995). Even characterized by low fecundity and low mortality rate because of the parental care of up to 3 mm in diameter eggs (Latif and Rashid, 1972 and 1983), the fractional spawner *Oreochromis niloticus* is the most predominant species in fish landings in AHD contributing up to 70 % of the catch (Rashid, 1995). Its excellent growth of up to 55 cm, its preference for shallow near-shore waters and mouth-breeding habits has used to explain its perfect adaptation. Reaching a large size, *Lates niloticus* is another important contributor to the fish landing in the AHD ensuring his linger by producing several millions pelagic eggs of about 600 µm in diameter (Rashid, 1995).

Spawning of some cyprinids and characins species which live mainly in Lake Nubia (Sudan) is induced by the flood. The fishes move upstream beyond the Second Cataract

where the area of the reservoir is much narrower and the early flashes of the flood probably trigger their spawning process (Rashid, 1995).

Since 1965, the fishery in the eastern Mediterranean is suffering a great decline. The impoundment of the nutrient-rich floodwater at the AHD has been postulated as a main cause of this decline. The lack of nutrient-rich Nile sediment, deposited in the AHD Reservoir, has been ascribed to affect the sardine fishery and crustacean population in the eastern Mediterranean by 60 % (George, 1972). In contrast, an increase in fish population by a factor of 5 to 6 has been reported in Lake Nasser few years after the AHD construction (El-Hinnawi, 1980; George, 1972). The total fish landing in AHD of 34’000 t in 1981 was followed by a decrease to about 15’700 t in 1989. In 1990 the fish landing increase to 22’000 t, reaching in 1991 a total of 30’800 t. However, after the initial “bloom”, the fishing yield was predicted to stabilize as the environmental conditions of the lake are expected to reach a steady-state. Further, an increase in population of predator species and other factors (increase in fishery activities) were used to predict a remarkable decline in fishing yields in the next years (George, 1972).

The most important species in the fish landings in AHD are cichlidae with *Oreochromis niloticus* and *Sarotherodon galilaeus* forming about 90 % of the total fish landings (George, 1972; Rashid, 1995). Cyprinids *Labeo nilotica* and *L. horie* rank second and together with *Barbus bunni* formed 6 % (Rashid, 1995). The catfish *Bagrus* spp. and the large species *Clarius lazera* is the next rank contributor. The characins *Alestes baremose, Alestes dentex* and the tiger fish *Hydrocynus* spp., centropomids *Lates niloticus*, synodontids and schilbeids, close the list of predominant species (George, 1972; Rashid, 1995). It has been shown that seasonality plays an important role in fish landing with the period of March to April, which coincides with the peak spawning of Tilapia in Lake Nasser, being characterized by the highest fish landings.

Water stratification in the reservoir created by the Roseires Dam on the Blue Nile caused heavy fish mortality in 1967, when oxygen depletion affected temporally the entire

reservoir water body (El-Hinnawi, 1980). Also, the Nile oyster (*Etheria eliptica*) has been smothered by enormous quantities of silt deposited in the upper reaches of the lake.

3.7 Water-born diseases

The creation of AHD combined with changes in the downstream irrigation to a perennial system has caused an increased in the incidence of schistosomiasis (El-Hinnawi, 1980). Intermediate host of bilharziasis snails (*Bulinus* sp.) were reported to appear in the shallow littoral zones of AHD Reservoir in great number at the end of 1974 (Entz, 1980a). In 1942, *Anopheles gambiae* introduced malaria from Sudan in the area of the actual AHD resulting in about 100'000 deaths of which 10'000 occurred in Upper Egypt (George, 1972). Progressive inundation of the cultivated river valley with rich soils triggered a massive development of chironomid swarms (lake flies) in Lake Nasser within the first 10 years of its existence (Entz, 1980b). While the relatively calm water of the reservoir favors the spread of some diseases, the rapid water flow through dam sluices encouraged the breeding of a black fly (*Simulium*) carrying a human disease known as river blindness – onchocerciasis (George, 1972). *Culex pipiens*, the vector for filariasis was reported to be present along with the latter reported *Phlebotomus* spp., vector of the disease kalazar – leishmaniasis (George, 1972).

4. Assessment of the Merowe Dam

In the following section, the experience from the AHD is extrapolated to the Merowe Dam by taking into account the similarities as well as the differences of the two reservoirs on the same river system. The environmental alterations deriving from the future dam construction are identified and the extent of the ecological impacts quantified and discussed in detail below.

4.1 Seismicity

Summarized by Adams (1983), the effects of man-made reservoirs to local seismicity have been scientifically recognized since middle of 1940 (Lake Mead in Colorado) with a wide public attention of induced seismicity by reservoir construction following the filling of the Lake Kremasta in Greece. Large earthquakes as in China (at Xinfengjiang 1962), Central Africa (at Kariba in 1963) and India at Konya in 1967 were reservoir-induced. The Konya earthquake had a magnitude of 6.5 on the Richter scale and caused more than 200 deaths. Analyses of more than 100 reservoirs, which presumably induced earthquakes, suggested that a minimum depth and volume were necessary for induction. A depth over 100 m was by far the most important factor for a seismic effect.

Based on the moderate size of the reservoir (maximum water depth 57 m), no reservoir-induced seismicity has been anticipated by the EIAR (2002) for the Merowe project although the project design adopted a Maximum Credible Earthquake of 6 on the Richter scale. However, the study of some reservoirs located in northern New Mexico and Brazil revealed that seismic activity was triggered even around small reservoirs with water depths of less than 50 m (Coelho, 1987; El-Hussain and Carpenter, 1990). Seismic activities extending up to some 20 km from the reservoir site suggest that geological conditions such as the existence of active faults and pre-reservoir groundwater elevation are very important for reservoir-induced seismicity (Coelho, 1987; El-Hussain and Carpenter, 1990).

Even there are still many discussions concerning the processes that triggers seismic activities in man-made reservoirs, there are two basic mechanisms, to which most of the scientists agree: (i) the additional stress on the underlying formations caused by filling of the reservoir which is more related to the volume of the water in the reservoir rather than water levels; and (ii) the increase in pore water pressure along faults which depend upon the water levels in the reservoir above pre-reservoir groundwater levels rather than the volume of water (Abu Zeid, 1995). It is generally accepted that water weight or pressure cannot cause earthquakes in areas not subjected to previous seismic activity. In all reported cases of reservoir-induced seismicity, there were existing historic active faults in the area of the reservoir but only three documented chases have recorded seismicity greater than a 6 on the Richter scale (Abu Zeid, 1995).

The EIAR (2002) describes the Merowe area lying in an inter-plate region relatively stable with the tectonic situation "…quite complex but without significant implications for the project". Their conclusion is based on the fact that the generally north-west to south-east faults of Tectonic Rift System do not extend to the area of the project. From the experience of AHD and some other cases, reservoir-induced seismicity may occur at the Merowe Reservoir within the first few years after the reservoir filling even though the maximum depth of the reservoir will not exceed 57 m. However, it is unlikely that the magnitude of a possible earthquake at Merowe will go beyond the Maximum Credible Earthquake design of 6 on the Richter scale. Therefore, reservoir-induced seismicity may not represent a major hazard for the Merowe Dam project. However, an updated seismic hazard assessment should be carried out before the dam construction to determine if all required measurements for the safety of the structure have been taken into account.

4.2 Hydrology

As in the other cases of control measures along the entire Nile, damming the river at Merowe will alter the hydrological regime eliminating the downstream annual flooding which flushed and cleansed the river once a year. The natural hydrological regime of the

Nile River is characterized by wide annual and seasonal variation. A factor of almost four was found between the lowest flow of 42 $km^3\ yr^{-1}$ recorded during the year 1913 and the highest runoff of 154 $km^3\ yr^{-1}$ measured during 1978 (Abu Zeid, 1987; Aly et al., 1993). Seasonal variation in the flow regime as presented by EIAR (2002) show also large differences between the dry periods when the flow does not exceed 900 $m^3\ s^{-1}$ and the flood periods between July and October with an average runoff of 7'400 $m^3\ s^{-1}$ (annual peaks up to 10'000 $m^3\ s^{-1}$, EIAR, 2002).

For the Merowe Reservoir, EIAR (2002) predicted an annual inflow of 84 $km^3\ yr^{-1}$ corresponding to an average flow rate of 2'660 $m^3\ s^{-1}$. The same flow of 84.7 $km^3\ yr^{-1}$ was calculated by Roskar (2000) for the period 1900 to 1990 for the Aswan Reservoir. In 2004 at the 7th German-Arab Business Forum in Berlin, Egon Failer, director of the Hydropower and Water Resources Division from Lahmeyer International GmbH presented an annual flow of 65 $km^3\ yr^{-1}$ (Failer, 2004). According to this author, the river inflow would vary between 700 $m^3\ s^{-1}$ to a maximum of 5'600 $m^3\ s^{-1}$ during flood periods. An average value of 2'055 $m^3\ s^{-1}$ was predicted by Failer (2004) based on "long-term measurements over 50 years".

Some hydrological parameters according to EIAR (2002) are presented in Table 6. Some parameters as the residence time, evaporation and reservoir filling rate were re-evaluated and the results are discussed below.

The reservoir volume represents 12.4 km^3 with the seasonal storage capacity described as 8.3 km^3. The daily dam operating rules are:

(i) on-peak production for 4 h at 3'000 $m^3\ s^{-1}$ representing $43.2x10^6\ m^3\ day^{-1}$ and;

(ii) off-peak production for 20 h at 600 $m^3\ s^{-1}$ corresponding to $43.2x10^6\ m^3\ day^{-1}$.

This represents an annual turbinated volume of 31.5 $km^3\ yr^{-1}$. With this operation rules, the storage volume of the reservoir can be safely filled within 4 weeks during the wet season (average flood discharge of 6'400 $m^3\ s^{-1}$) even if the power plant is running at the maximum capacity of 3'000 $m^3\ s^{-1}$.

Merowe Reservoir			
Maximum reservoir area	[km^2]	800	
Reservoir area at low stand	[km^2]	350	
Agricultural area	[km^2]	66	
Storage volume	[km^3]	12.4	
Permanent volume	[km^3]	4.1	
Volume change	[km^3]	8.3	
Reservoir length	[km]	200	
Maximum depth	[m]	57	
Hydraulic head	[m]	51	
Average depth	[m]	15.5	
Water level change	[m]	15	
Residence time	[yr]	0.15	
Power generators	[MW]	1250	

Water balance			[km^3 yr^{-1}]
Average annual inflow	[m^3 s^{-1}]	2664	84.0
Average runoff flood (4 months)	[m^3 s^{-1}]	6400	67.2
Average runoff dry season (8 months)	[m^3 s^{-1}]	800	16.8
Max. runoff flood	[m^3 s^{-1}]	7400	77.8
Max. runoff dry season	[m^3 s^{-1}]	900	18.9
Average daily release	[m^3 s^{-1}]	1000	31.5
Max. release flow (4 h day^{-1})	[m^3 s^{-1}]	3000	15.8
Min. release flow (20 h day^{-1})	[m^3 s^{-1}]	600	15.8
Average irrigation	[m^3 s^{-1}]	233	7.3
Max. irrigation flow (8 months)	[m^3 s^{-1}]	300	6.3
Min. irrigation flow (4 months)	[m^3 s^{-1}]	100	1.0
Max. theoretical turbine flow	[m^3 s^{-1}]	2498	31.5
Average evaporation	[mm day^{-1}]	6	1.75

Regime at low flow		
Aver. runoff dry season (8 months)	[m^3 s^{-1}]	800
Minimum turbinate	[m^3 s^{-1}]	600
Reservoir filling rate	[m^3 s^{-1}]	200
Max. time to fill empty reservoir	[day]	480
Regime at high flow		
Aver. runoff flood (4 months)	[m^3 s^{-1}]	6400
Peak capacity	[m^3 s^{-1}]	3000
Reservoir filling rate	[m^3 s^{-1}]	3400
Min. time to fill empty reservoir	[day]	28

Table 6. Our calculated parameters concerning Merowe Reservoir and its hydrology

The stored volume can then feed an additional continuous runoff of 400 $m^3 s^{-1}$ during 8 months. If used only during four peak hours (1/6 of the day), the additional peak discharge is 2’400 $m^3 s^{-1}$. This means that the reservoir can operate as designed with 3’000 $m^3 s^{-1}$ during 4 peak hours and with 600 $m^3 s^{-1}$ during the rest of the day (20 hours). Critical questions regarding the hydrological regime and the dam operation rules target some subjects as:

(i) how often do very dry years occur and what are their discharge characteristics?

(ii) (ii) what is the probability that the reservoir cannot provide the 4 hours of peak power?

According to Roskar (2000), the trend of runoff has shown an average of 100.6 $km^3 yr^{-1}$ for the period 1871-1900 with 82.9, 84.4 and 87.1 $km^3 yr^{-1}$ being the averages for the subsequent 30-year time periods. The frequency analysis with the assumption that the natural flow will have the same periodic behavior in the future as during the past 128 years indicates a high probability that the flow will not be lower than 80 $km^3 yr^{-1}$ in the future and might slightly increase up to 95 $km^3 yr^{-1}$ around 2125 (Roskar, 2000).

4.3 Water losses

An experiment at the AHD employing increased upstream water consumption showed that it is possible to secure water supply for Egypt in the range of the current irrigation demand (55.6 $km^3 yr^{-1}$ based on the 1959 Nile Water Agreement) even if the upstream water consumption in Sudan would increase from the current 18.5 $km^3 yr^{-1}$ to 25 $km^3 yr^{-1}$ (Roskar, 2000).

The annual volume lost due to evaporation within the reservoir was considered by EIAR (2002) to be as high as 2.4 $km^3 yr^{-1}$ (Table at Page 2-1) or even smaller down to 1.9 $km^3 yr^{-1}$ (Page 4-5). An evaporation rate of 3 $m\ yr^{-1}$ (8.22 mm day^{-1}) as reported by EIAR (2002) may represent a slightly higher estimate compared with the most recent values of

2.08 m yr^{-1} to 2.3 m yr^{-1} calculated by Sadek et al. (1997) for Lake Nasser. Using these new data the evaporation may result in an annual water loss from the Merowe Reservoir of around 1.75 km^3 yr^{-1} (±20 % error). Comparable with 1.9 km^3 yr^{-1}as calculated by EIAR (2002), this annual evaporation from the reservoir at the maximum level represents 14 % yr^{-1} of the total storage volume. Therefore, with a surface area more than 85 % smaller compared to the AHD, impounding the Nile River at Merowe will result in a water loss by evaporation of up to 2 % of the annual river inflow of 84 km^3 yr^{-1}. The annual precipitation in the area characterized by an average of 50 mm yr^{-1} would represent an additional input of 0.04 km^3 yr^{-1}. Corresponding to about 2 % of the evaporation, precipitation can be neglected in the total water balance.

The possible water use for irrigation is described in the EIAR (2002) as following: 2x150 m^3 s^{-1} for 8 months and 2x50 m^3 s^{-1} during 4 months. This represents 6.3 km^3 yr^{-1} and 1.05 km^3 yr^{-1}, respectively, or a total of 7.4 km^3 yr^{-1}. Therefore, the water abstraction for agricultural use would reach a high value of up to 60 % yr^{-1} of the reservoir volume or 9 % of the annual river inflow. Except for the Multaga irrigation scheme for which the net irrigated area is described as 5’600 ha, no additional information is given by the EIAR (2002) concerning the total proposed irrigation scheme. At the end of January 2006, Yang Zhong, the Deputy Managing Director of the contractor firm, stated that “with the dam’s bulky reservoir, more than 60’000 hectares of farmland could be irrigated through the long sluices, benefiting more than 3 million Sudanese” (Xinhua, 2006).

Neglected by the EIAR (2002), another possible water loss due to increasing water level in the lake may come from infiltration to adjacent aquifers. The lateral seepage in Lake Nasser (Egypt) was calculated to reach annually 1 km^3 accounting for 0.6 % yr^{-1} of the lake content (Aly et al., 1993). Extrapolating the estimated percentage to the Merowe Reservoir, the lateral seepage may contribute to the total water loss with 0.07 km^3 yr^{-1}. Even being as twice as high as the contribution from annual precipitation, the seepage is rather small for the total water balance. According to our calculations, the total water losses from the Merove Reservoir including evaporation, irrigation and seepage of 9.2 km^3 yr^{-1} represents 11 % of the annual Nile River inflow.

4.4 Reservoir water balance

Based on previous calculated parameters, a zero-order water balance is computed below and the results are schematically shown in Figure 10. The inputs into the reservoir are represented by:

Q_{IN} - average inflow of 84 $km^3\ yr^{-1}$;

P - annual precipitation which contribute insignificantly with only 0.04 $km^3\ yr^{-1}$ for the maximum reservoir area of 800 km^2.

The outputs are:

Q_T - the annual turbinated flow of 31.5 $km^3\ yr^{-1}$;

E - annual evaporation of 1.75 $km^3\ yr^{-1}$ at the maximum surface area of 800 km^2;

I - the water abstraction for irrigation of 7.4 $km^3\ yr^{-1}$;

S - lateral seepage of only 0.07 $km^3\ yr^{-1}$;

According to the Nile Water Agreement of 1959, Sudan has the right to use 18.5 $km^3\ yr^{-1}$ from an average flow of 84 $km^3\ yr^{-1}$ and must ensure annually a minimum release of 55.5 $km^3\ yr^{-1}$ downstream to Egypt, while 10 km^3 is assumed as annual loss via evaporation (Roskar, 2000). Therefore, during the dam operation, additionally to the turbinated flow of 31.5 $km^3\ yr^{-1}$, a supplementary flow (Q_S) of minimum 24 $km^3\ yr^{-1}$ must be released downstream.

During the impounding period, ensuring a minimum release downstream of 55.5 $km^3\ yr^{-1}$, and neglecting the evaporation and irrigation needs, the reservoir can gain annually 28.5 km^3, reaching its maximum storage capacity of 12.4 km^3 in 159 days (5 months).

$$84\ km^3\ yr^{-1} - 55.5\ km^3\ yr^{-1} = 28.5\ km^3\ yr^{-1}$$

The length of the impounding period depends mainly on the starting time. Generally, the dam operation policy is to diminish the impounding phase as much as possible in order to

produce electric power as soon as possible. Therefore, in order to establish the optimum period, a simulation of the reservoir impounding for different starting dates must be performed. The absence of sufficient hydrological data restrains us to run such simulation. It is known that about 80 % of the total annual discharge of the River Nile occurs during the summer rainy season from July to October. Therefore, during the 4 months period, if no significant water for irrigation is required, the reservoir can fill up to 95 % of its total storage capacity.

After impounding, if all the parameters are considered, the changes in the water volume (ΔV) over a period of time (ΔT) are dictated by the following equation:

$$\Delta V/\Delta T = Q_{IN} + P - Q_T - I - E - S - Q_S$$

According to our calculation, even at full energy production and securing a minimum downstream flow of 55.5 $km^3\ yr^{-1}$, the reservoir can store annually up to 19 km^3, representing more that 150 % of its capacity. This implies that the reservoir can operate at the maximum capacity even for a smaller water inflow as low as 65 $km^3\ yr^{-1}$. This allow, on a regular base, for additional upstream water storage, increased irrigation scheme or mitigate drought periods.

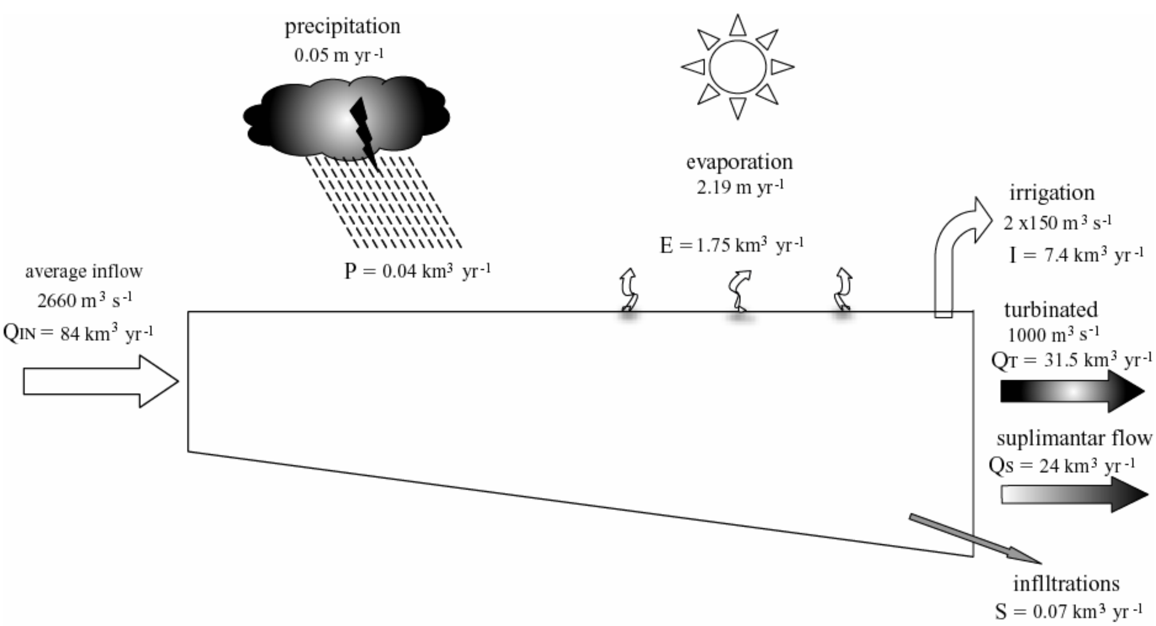

Figure 10. The water balance for the Merowe Reservoir

4.5 Water quality

The EIAR (2002) states that due to the seasonal water level variations, the area of the reservoir will fluctuate between a maximum of 800 km^2 at the highest level and 350 km^2 at low stand. Therefore, water level fluctuations may expose during the dry season up to 450 km^2 of reservoir slops to soil-forming conditions which oxidizes and rapidly degrades previous formed lacustrian organic matter (Beuning et al., 1997). Consequently, the operation schedule will have direct influences on the texture and sediment composition. It is known that both sediment composition and water conditions play an important role in controlling the production and distribution of aquatic plants. The submerged aquatic plants exploit nutrient sources from the surrounding water and sediment. Therefore, nutrient availability from these sources will influence directly the submerged plant community and abundance on the disturbed littoral zone. Overall, this may have a substantial environmental impact on the aquatic life

A common effect of water storage due to river impoundment in arid and semi-arid areas is the onset of thermal stratification of the reservoir water column. Thermal stratification in natural lakes depend on external driving forces as hydro-meteorological conditions, location, wind induced surface forces, etc and internal properties such as lake morphometry (surface, shape depth), light absorption and the theoretical water residence time, function of reservoir volume and flow. The variations in the water level are important for the mixing of the lake water column and the distribution throughout the reservoir of the water during the seasonal flood. The extent of the flood and the penetration-depth distribution will determine the general pattern of thermal stratification.

Stratification of the water column is also expected in the Merowe Reservoir. An empirical dependence of reservoir stratification on residence time (RT) expressing the temperature difference ($\Delta T_{0\text{-}30}$) between the surface and the deeper layers at 30 m was found by Straskraba and Mauersberg (1988) for several reservoirs in Czech Republic. This is approximated by the equation:

$$\Delta T_{0\text{-}30} = 20\ (1\text{-}\exp\ (-0.0126 * RT_{IV\text{-}IX}))$$

Applying this formula, a residence time of 54 days (own calculation, see the Sedimentation subchapter), provided temperature difference between surface and hypolimnion in Merowe Reservoir of about 10 °C. This is in good agreement with the temperature difference of 6 and 10 °C measured in the AHD between surface and 30 m depth (Latif, 1984).

Consequently, during the summer period starting in April or May, the water column in the Merowe Reservoir will become stratified. The stratification can extend over the entire reservoir length. During the flood period from August to October, the thermal stratification may be destroyed, especially on the upper stretch of the reservoir. The extent of the vertical convective mixing and the level of the remaining thermal stratification will depend upon the water level in the reservoir and the flood regime. With a total length of 200 km, it may be possible that a large part of the reservoir volume will be subject to totally mixing during the flood period although some stratification on the lower stretch will probably remain. Similar to the AHD, the overturn due to cooling during the winter periods will result in convective mixing between deep waters and the surface, allowing oxygenated waters to penetrate into the deeper waters of the reservoir.

4.6 Sediment balance

Located about 700 km upstream of Lake Nubia, where no additional water input contribute to the total flow of the Nile River, it can be assumed that the sediment load entering the Merowe Reservoir will be the same or slightly higher than at AHD: 1.7 g l^{-1} or 143 x 10^6 t yr^{-1} at a flow rate of 84 km^3 yr^{-1}.

Heavily loaded with sediments, the deposition of the particles in the reservoir depends upon several factors. The retention time and the depth are the most important ones. Retention time within the Merowe Reservoir was postulated by the EIAR (2002) to be as high as 0.2 yr, equivalent of 73 days. A reservoir volume of 12.4 km^3 and an annual flow of 84 km^3 yr^{-1} allowed as calculating a lower residence time of 0.15 yr (54 days). It seems

that EIAR (2002) use in their calculations the same average flow of 65 km^3 yr^{-1} of Failer (2004). For a maximum length of 200 km and a residence time of 0.15 yr, the average water velocity in the reservoir will correspond to 4.3 cm s^{-1}.

Water velocities of between 2.7 km h^{-1} (75 cm s^{-1}) to 3.3 km h^{-1} (92 cm s^{-1}) could be calculated for the present natural river flow condition using the EIAR (2002) travel time from Khartoum to the dam site of 10-20 days (Page 3-5) and a distance 800 km (Page 4-7). Therefore, a slowdown of the water velocity in the range of one order of magnitude is expected to occur after the river impoundment. Sediment deposition dominates typically at low velocities below 10 cm s^{-1} (Hakanson and Jansson, 1983).

A residence time of 4.5 days and a main stream velocity of 33 cm s^{-1} resulted in the case of Iron Gate I Reservoir (Danube River) in a TSS retention of 56 % of the incoming load (Teodoru and Wehrli, 2005). For a residence time of 2.7 yr which correspond to a water velocity of 0.016 cm s^{-1}, the TSS retention in Lake Brienz (Switzerland) was found to be as high as 97 % of incoming load (Finger et al., submitted). Water velocity between 0.06 to 0.89 cm s^{-1} during November and 0.01 to 0.55 cm s^{-1} in December were measured in AHD (Eldardir, 1994). With a residence time of 1.9 yr and a reservoir length of 500 km, an average flow velocity of 0.62 cm s^{-1} for the AHD corresponds to sediment retention of between 96 and 98 %. As the average velocity in the Merowe Reservoir seems to be higher compared to the AHD, one might expect that the sediment retention to be lower. A simplified linear correlation between the above mentioned cases of Iron Gate I, AHD and Brienz implies that the sediment retention capacity of the Merowe Reservoir will be up to 92 % of the incoming load (Figure 11). Therefore, with a retention capacity of more that 90 % of the incoming load, a suspended solids accumulation of about $130x10^6$ t yr^{-1} is expected in the Merowe Reservoir. For a surface area of 800 km^2, this corresponds to an average sediment flux of 164 kg m^{-2} yr^{-1}. Using the bulk same density of 1.56 g cm^{-3} calculated by Shalash (1982) for AHD Reservoir, the volume of the sediment expected to accumulate annually in the Merowe Reservoir is $84x10^6$ m^3 yr^{-1}, equivalent to an average sedimentation rate of 10.5 cm yr^{-1}.

Studies on the AHD Reservoir have shown that the major part of the sediment is deposited close to the reservoir inflow (southern part) where a New Delta of about 200 km in length, 12 km in width and 40 m thickness was formed in less than 30 years (Eldardir, 1994).

Therefore, as the main volume of the sediment will be deposited in the upper stretch of reservoir, the "special sluices" of the Merowe Dam will not play any important role in decreasing reservoir sedimentation. It is expected that this situation will extend at least over the half lifetime period of the reservoir when half of the dead storage capacity and part of its active capacity has been already lost.

However, our calculation implies that with a deposition rate of $84x10^6$ m^3 yr^{-1}, the Merowe Reservoir will lose its total volume of 12.4 km^3 in about 150 yr at an annual rate of 0.7 % yr^{-1}, whereas the dead storage capacity of 4.1 km^3 will be lost in less than 50 yr at an annual rate of 2 % yr^{-1}. Therefore, over a 50 years period, the total storage capacity could be diminished with 34 %.

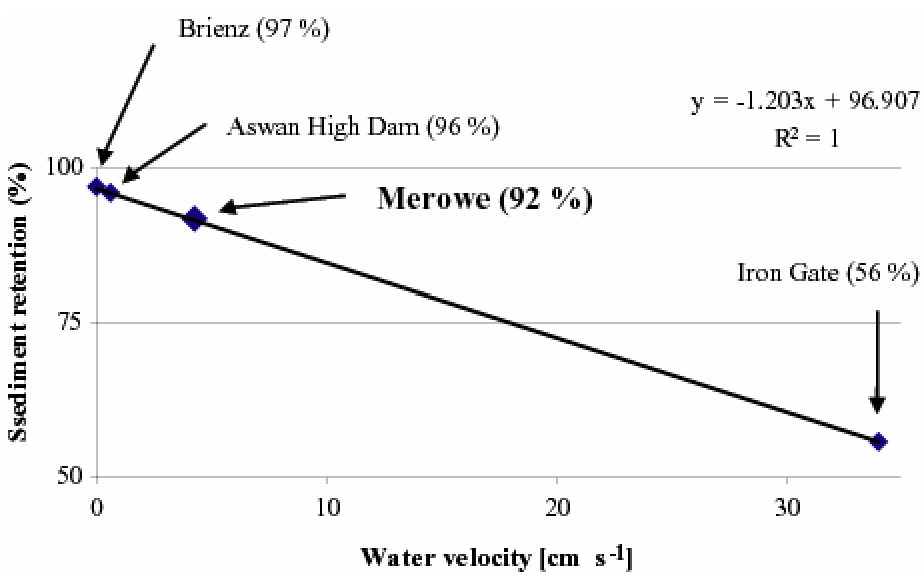

Figure 11. Estimated sediment retention (% of the incoming load) function of water velocity

Although it seems rather difficult at this stage to predict the extent of downstream erosion, it is clear that with less than 10 % of the total incoming sediment load passing through the Merowe Dam, downstream sedimentation will be proportionally diminished. Therefore, the erosion rates of the river bed and the banks are expected to increase dramatically. Scouring of the river channel downstream may result in lowering the river level with possible influences on the adjacent aquifers water table. Since no natural flooding will occur below the dam, traditional flood recession agriculture along the river course will not be possible any longer. These potentially severe consequences are not adequately discussed in the EIAR (2002). As a positive effect of high sediment accumulation in the Merowe Reservoir, the lifetime of the downstream AHD Reservoir will be prolonged. However, retaining almost the entire sediment load of the Nile River, both reservoirs will substantially accelerate the general erosion of the Nile Delta and the coastal Mediterranean Sea.

4.7 Biogeochemical cycles

4.7.1 Primary production

The thermal stratification with higher suspended particle sedimentation and higher temperature in the epilimnion is expected to increase reservoir production. Extremely high rates of a few 1'000 g C m^{-2} yr^{-1} were measured in some specific side bays of the AHD. As such extremely high rates can not be representative for the entire AHD Reservoir, we considered an weighted average of 370 g C m^{-2} yr^{-1} to represent a more realistic estimate based on the observed phosphorus content and calculated input.

Using the average primary production calculated for the AHD of 370 g C m^{-2} yr^{-1} and applying to the Merowe area of between 350 and 800 km^2 at the minimum and maximum capacity, respectively, the organic carbon *in-situ* produced within the reservoir may varies between 130'000 and 300'000 t C yr^{-1}. Note that this value represents a lower

estimate as the primary production reported for the AHD was one order of magnitude higher.

4.7.2 Greenhouse gas emissions

Generally, starting with the impounding phase which result in flooding of the landscapes, terrestrial plants die and not longer assimilate carbon dioxide (CO_2) by photosynthesis and therefore the sink for atmospheric CO_2 is highly reduced. In the same time, increased reservoir productivity is responsible for *in-situ* production of large amount of organic carbon. Therefore, additionally to the current existent biomass described by the EIAR (2002), a large fraction of organic carbon will be annually produced *in-situ*. Moreover, a larger fraction of particulate organic carbon may be transported from upstream areas and accumulated in the sediment of the reservoir, and therefore, contributing to the total greenhouse gas emission.

The organic carbon stored in plants, algae and soil is converted by bacterial decomposition within the water column or sediment to: (i) CO_2 under oxic conditions or (ii) methane and CO_2 in the absence of oxygen, and then released to the atmosphere. The methane can be exported by ebullition or by diffusion. Ebullition results in direct flux of methane bubbles from the sediment to the atmosphere with limited impact of CH_4 oxidation in the water column. The ebullition flux is related to the net CH_4 production rate in the sediment and the hydrostatic pressure changes, usually due to water level fluctuations. As the diffusive transport is much slower than ebullition, a large proportion of the diffusive CH_4 flux exported from anoxic sediment will be reoxidized by methane-oxidizing bacteria into CO_2 which has a lower global warming potential.

In the case of stratified water column as in the chase of Merowe, CH_4 will be stored in the anoxic layer. The storage will be emitted rapidly by diffusion during the winter deep mixing periods. The diffusive flux component will depend on the difference in methane concentration between the water and the atmosphere, and on the physical rate of exchange between the water and the air (turbulence, wind speed). The flux of CO_2 and

CH_4 released from the reservoirs surface are quite variable as they depend on a number of factors including the lake area, amount of organic carbon flooded, age of the reservoir, water temperature, primary production, water column stratification, the frequency and the extent of reservoir drawdown, lake sediment conditions, etc.

To calculate the potential greenhouse gas emission from the Merowe Reservoir, we follow the same scenario as for the AHD. Out of the total *in-situ* carbon production of 130’000 and 300’000 t C yr^{-1}, we assume that (i) 20 % (26’000 – 60’000 t C yr^{-1}) is accumulated at the lake sediment; (ii) 20 % (26’000 – 60’000 t C yr^{-1}) undergoes bacterial decomposed within the water column and release mainly as CO_2. Further, it can be assumed that half of the total carbon accumulation will be buried in the sediment of the reservoir whereas the other half (13’000 – 30’000 t C yr^{-1}) will be converted into greenhouse gas. As the percentage CO_2 to CH_4 produced during decomposition of organic matter depends upon many unknown parameters (the oxidation rates, the time and the extent of oxygen-free condition in the water column and below the sediment water interface or the diffusive fluxes from the sediment), we limit our evaluation to the total organic carbon available for CO_2 and CH_4 production. Therefore, according to this scenario, annually between 13’000 – 30’000 t C yr^{-1} will be potentially available for greenhouse gas production in the sediment of the reservoir, whereas decomposition of the organic matter in the water column can contribute with between 26’000 and 60’000 t C yr^{-1}. The available carbon is actually expected to be much higher considering that a large fraction may comes with the river inflow and will be accumulated in the sediment of the reservoir or decomposed within the water column.

Eldardir (1994) measured for AHD a sedimentary organic matter content of between 8 to 40 mg g^{-1}, with lower values characterizing the upper stretch of the reservoir where the New Nile delta is presently forming. Considering 8 mg OM g^{-1} measured in the upper stretch of the AHD to represent the organic matter content of the suspended load, the retention of $130 x 10^6$ t TSS yr^{-1} in the Merowe Reservoir will result in annual accumulation of more than 1’000’000 t OM yr^{-1}. As the OM consists of 40 % C, the accumulation of equivalent 400’000 t C yr^{-1} is therefore expected. Further, assuming that

50 % of the total amount will be buried in the sediment whereas the rest of 50 % will be a subject of microbial degradation, the incoming load is anticipated to contribute annually with up to 200'000 t C yr^{-1} to the total degradable carbon.

Therefore, using this balance approach we were able to predict that annually, between 240'000 and 290'000 t C yr^{-1} will be available for greenhouse gas production. Note that, this annual value is one order of magnitude higher than the total reservoir degradable biomass of 34'000 t reported by EIAR (2002).

4.7.3 Phosphorus balance

As phosphorus was ascribed to limit the primary production in the AHD, a simplistic mass balance approach was used to predict the changes in dissolved phosphorus concentration within the reservoir (Figure 12). The reservoir can be described with a box-model approach where the input is compensated by the net sedimentary retention and the output.

Considering an inflow concentration of around 77 µg P l^{-1} as estimated for the AHD, the input flux (F_{input}) into Merowe Reservoir would represent $6.5x10^9$ g P yr^{-1}. For a maximum reservoir area of 800 km^2, an average primary production rate of 370 g C m^{-2} yr^{-1} will be responsible for a phosphorus uptake up to $7.3x10^9$ g P yr^{-1}. We can consider that 20 % of this as $1.5x10^9$ g P yr^{-1} settles to the reservoir floor where half is buried in the sediment and the other half released back into the water column. Therefore, the net sedimentary P retention represents $0.75x10^9$ g P yr^{-1}. Using the net P retention of 6 % of the total phosphorus uptake as calculated for the AHD, the sedimentary retention in the case of Merowe would represent about $0.4x10^9$ g P yr^{-1}, a value comparable with the previous estimate.

Approximated by the equation below, with an inflow load of $6.5x10^9$ g P yr^{-1} and a net P retention of between 0.4 and 0.7 $x10^9$ g P yr^{-1}, the output flux would range between 5.7 and $6x10^9$ g P yr^{-1}.

$$P_{input} - P_{net\_retention} - P_{output} = 0$$

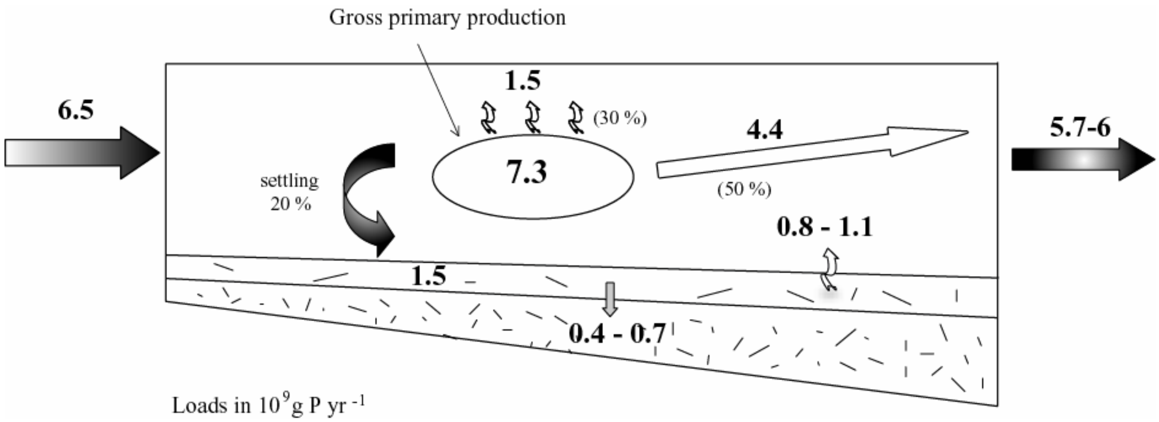

Figure 12. Dissolved phosphorus mass balance for the Merowe Reservoir

Compared to the input of $6.5x10^9$ g P yr^{-1}, the output will be between 4 and 8 % smaller. The average output concentration for an annual discharge of 84 km^3 yr^{-1} corresponds to about 70 mg P l^{-1}.

Therefore, the internal processes within the reservoir are expected to play a relative minor role in the overall nutrient budget. The nutrient concentration in the Merowe Reservoir will be highly dependent on the input and to a lesser extent on primary production or sedimentation.

4.7.4 Increased salt content

Even not addressed in the EIAR (2002), increased salt content within the reservoir is expected due to evaporation and irrigation. Following a simple assumption of linear dependency between the evaporation rate and the increased water salinity, an annual loss of almost 15 % (1.7 km^3 yr^{-1}) of the reservoir volume by evaporation is expected to increase the reservoir salt content by 15 %.

Moreover, during irrigation, the water become enriched in nutrient and dissolved solids. Up to 9 % (7.4 km^3 yr^{-1}) of the river inflow is expected to be annually used for

agriculture purpose. As part of this volume will eventually return to the reservoir or to the river downstream, an increased nutrient and salt content is therefore expected.

4.8 Aquatic ecology

In general, reservoirs are complex and dynamic ecosystems, characterized by reduced diversity (less species than natural ecosystems) but on a higher productivity level. Presently, the fish population of the Nile River at the Merowe section is mainly dominated by the riverine (*lotic*) species, well adapted to seasonal changes of flowing water and to a lesser extent by lake (*lentic*) species. Any alterations of their natural habitats resulting form hydrological changes of the river system is therefore expected to influence the biological productivity, affecting the entire food web on the long term. Consequently, the transformation of a relatively large area of the river stretch into a reservoir is anticipated to result in a gradual disappearance of specific riverine species, whereas the lacustrine or easily adaptable ones may benefit from the Merowe Reservoir construction.

Riverine fish species that usually inhabit shallow water and benthic ecosystems will seek similar depths and habitats in the new reservoir. Species that cannot find suitable habitat will not adapt to the new conditions and will disappear from the reservoir area. Accordingly, a number of river species are expected to disappear gradually as a result of inappropriate conditions for their life cycle.

The migratory species might be impacted by the dam which will hinder their movements (landlocked). The migration should be altered as early as the initial stages of construction. It is expected that a landlocked population will establish in the reservoir and migrate towards the upstream reaches or tributaries for spawning. More critical problems will appear for the migratory fish populations below the dam as they will be trapped in about 700 km of river stretch between AHD and Merowe. No ladder construction was recommended by the EIAR (2002) based on the "*evidence*" of no migratory fish and

technical details ("*the ladder would be far too high and too long for fish to be able to pass*").

Changes in water level will affect structural and functional aspects of the aquatic ecosystems in the reservoir. Important changes in water level can have both positive and negative consequences for fish populations. If the water level will be raised during the spawning season, fish spawning and recruitment may increase. Negative impacts may result primarily from the drawdown zone: fishes could be stranded during spawning, and habitats or spawning areas will be destroyed. Also, weed beds and food sources will be altered and deep waters will be depleted in oxygen.

Downstream changes in flow regime, temperature, water chemistry and turbidity will have an adverse effect on the majority of fish species. As bottom release, the temperature of the outflow water will be lower in summer than it would be for natural conditions. Therefore, coldwater pollution together with low dissolved oxygen concentration in the discharged water during the summer can have major impacts on the downstream fish population. However, if the oxygen content in the water downstream would tend towards natural values during re-oxygenation, the water temperature is expected to need a longer distance before reaching the equilibrium values. If the impacts generated by the reduction of oxygen will be limited to relatively short distance, the temperature changes can induce higher impacts, especially in the summer period.

The daily water release in normal operation will fluctuate depending on the power demand. However, a daily water level fluctuation in the downstream river up to 5 m is expected. Even this may not affect the lotic species that are generally better adapted to large variations both in temperature and in river flow, impact on the lentic fishes may be significant as they use to live in systems where the amplitude changes at much lower frequency.

Daily operation of the powerplant together with high sediment retention in the reservoir will result in increased downstream erosion. Fish species that spawn on sand bars will see

their spawning area reduced or dried up, especially on weekends when the flow provided at the powerhouse will be minimal. This can also lead to the elimination of backwaters that provide aquatic habitat for native species and the reduction of riparian or wetland vegetation. Therefore, conditioned by the daily and weekly flow variability, reduced downstream spawning areas will have negative impacts on both lotic and lentic fish population. Nutrient retention in the reservoir may also lead to a decrease of downstream aquatic productivity resulting with subsequent lower fishing yield.

Flood events act as biological triggers for reproduction in some fish species of cyprinids and characins. As the reservoir will alter the natural distribution and timing of downstream flow regimes, this will alter the spawning of those fish species.

During operation of the powerplant, some fish will transit through the turbines being wounded or killed. Depending on the number of fishes that will eventually move through the turbines, this phenomenon is generally expected to have little influence on the overall fish population of the reservoir.

It seems that new reservoirs construction always creates hope among local people in terms of commercial fishing, so productivity becomes an important issue.

In general, stratified water column with high nutrient availability and reduced turbidity favor an increase of the productivity of the reservoir, especially right after impounding. The production of plankton in the early stages of the reservoir impounding is the basis for the reservoir productivity. Even the changes from riverine to lake environment will result in decrease of river specific fish species in favor to lake species, high food availability may support an overall increase in total fish biomass. The initial period of increased biomass is generally expected to be followed by stabilization in fish productivity, as the environmental conditions of the lake are expected to reach a steady-state. This can be related to the carrying capacity of the reservoir. An increase in population of predator species or an increase in fishery activities are generally used to predict a decline in fish yields in the next years. Therefore, the new environmental conditions resulting form the

Merowe Dam construction can be favorable for commercial fishing in designated areas of the reservoir.

The similarity of the Merowe Reservoir with the AHD allow as to predict that after few years, the composition of fish species in the future reservoir will be probably be comparable to the actual composition of the AHD Reservoir. Therefore, the important species in the Merowe Reservoir for commercial fishing are expected to be represented by: (1) cichlidae dominated by *Tilapia nilotica* and *Tilapia galilaea*; (2) cyprinids with *Labeo nilotica*, *L. horie* and *Barbus bunni*; (3) catfish *Bagrus* spp. and the large species *Clarius lazera*; (4) characins with *Alestes baremose, Alestes dentex* and *Hydrocynus* spp*., (5)* centropomids with *Lates niloticus*; (6) synodontids and (7) schilbeids.

Traditional fishing methods practiced and observed on the Nile will be ineffective during the reservoir impounding and operation. Commercial fishing however may be initiated in the reservoir only after the fish populations have increased to a certain level. The period before the commercial fishing can be initiated may be a few years after impounding.

4.9 Health-related impacts

Although it is not necessary expected to trigger dramatically health problems, the arid conditions of the reservoir site and the characteristics of the reservoir area with large seasonal water level fluctuations seems to justify a cautious approach.

Serious consequences which accompany changes in the aquatic environment related to dam construction is the explosive spread of water-borne human disease. In several parts of Africa, the creation of vast areas of standing waters by dam construction favored the increase of the population of the vector snail host of schistosomiasis.

Stagnant waters will create perfect breeding condition for mosquitoes, vectors of malaria and yellow fever and the water flea host of the guinea-worm. As malaria was endemic in

Sudan in 1942 resulting in about 100'000 deaths (George 1972), precautionary measures for local transmitting malaria may be justified.

Thus, the reservoir could increase the existing risks especially at high water levels favoring water column stratification with deep-water oxygen depletion and CH_4 and H_2S accumulation in the hypolimnion and the release during the turnovers periods of late fall and winter. In the upstream area of the reservoir, the accumulation of large amounts of sediment may result over decades, as in the case of AHD, in development of submerged islands. Seasonally, during the low water level they may become wetlands or pounds, offering ideal conditions for insects and mainly mosquitoes to reproduce. This may also favor an increase in anopheles transmitting malaria.

The presence of stagnant water around the construction site due to excavation, ditches or other activities may induce good breeding conditions for *anopheles* in the immediate area and generate malaria among the construction personal or local population if not managed properly.

5. Summary of the environmental impacts

5.1 Hydrology and water balance

The Merowe Dam is the biggest hydropower project in Sudan and second major component of the water development scheme on the lower Nile River after Aswan High Dam. Scheduled to be completed in summer 2008, the goal of the project is to provide economic development through electricity generation and irrigated agriculture. With an installed capacity of 1’250 MW, the Merowe Dam will produce twice the current amount of electricity in Sudan. Little is known about the irrigation scheme

At the time of completion, Merowe Dam will create a reservoir “lake” with a surface area of 800 km^2, a maximum depth of 57 m, storing a volume of 12.4 km^3. The location of the reservoir in a geological inter-plate region with a complex tectonic situation, the existence of active historical faults, and the additional stress on the water volume or the increase in pore water pressure along faults can induce seismic activity at the Merowe within the first few years after the reservoir has reached its maximum level. However, it is believed that the magnitude of the possible reservoir-induced earthquake at Merowe will not exceed the Maximum Credible Earthquake design of 6 on the Richter scale. Even unlikely to become a seismic hazard, an assessment of the potential consequences of dam failure due to seismic activity or other kind of accidents on downstream population appears nevertheless advisable.

By storing the annual runoff of the Nile, the construction of the Merowe Dam will significantly affect the present natural hydrology of the about 900 km of the river stretch between AHD Reservoir and Merowe Dam, eliminating the annual flooding which flushed and cleanse the river once a year. However, the downstream hydrology of the Nile River below the Egyptian border to the Mediterranean coast was already affected by the earlier AHD construction of 1971.

Storing the high summer flood flow and releasing over the rest of the year, the operation of the Merowe Dam will create large seasonal and annual water level fluctuations in the reservoir between 6 to 10 m (EIAR 2002, page 3-6). Water level fluctuations may expose extensive areas of the reservoir slops to soil-forming conditions degrading previous formed lacustrian organic matter. Consequently, the operation schedule will have direct influences on the texture and composition of the reservoir sediment with direct influence on the submerged plant community and abundance on the disturbed littoral zone. Overall, this may have a substantial environmental impact on the aquatic life.

Large downstream daily water level fluctuations of between 4 to 5 m, will expose large spawning areas along the river stretch to impropriate habitat conditions with direct consequences on the downstream fishes and fishery. Wide-ranging daily fluctuations of the water level may have also socio-economic implications representing an issue for ferry the landing sites and pumps along the river. Additionally, a general lower downstream water level together with seasonal or daily fluctuations will produce high river banks erosion, induce scouring of the river bed lowering the river level and possibly lowering the water table of the adjacent aquifers.

The evaporation from the reservoir will result in a total water loss of 1.75 km^3 yr^{-1}. Slightly less than 1.9 km^3 yr^{-1} calculated by the EIAR (2002), the annual losses by evaporation will represent 2 % of the annual Nile River inflow of 84 km^3 yr^{-1}.

The water use for irrigation scheme proposed by the EIAR (2002) represents a total of 7.4 km^3 yr^{-1}. Therefore, the water abstraction for agricultural use would reach a value of 9 % of the annual river inflow.

The annual precipitation in the area characterized by an average of 50 mm yr^{-1} would represent an additional input of 0.04 km^3 yr^{-1}. Representing only 2 % of the total evaporation, the contribution of precipitation to the total water balance can be considered negligible. The lateral seepage from the reservoir may contribute annual with 0.07 km^3 yr^{-1}, a value twice as high as the annual precipitation but rather negligible.

According to our calculations, the total water losses from the Merove Reservoir including evaporation, irrigation and seepage corresponds to 9.2 km^3. This represents 11 % of the annual Nile River inflow.

The daily dam operating rules will correspond to an annual total turbinated volume of or 31.5 km^3 yr^{-1}. According to the Nile Water Agreement of 1959, Sudan has the right to use 18.5 km^3 yr^{-1} from an average flow of 84 km^3 yr^{-1}, and must annually ensure a minimum release of 55.5 km^3 yr^{-1} downstream to Egypt. Therefore, during the dam operation, additionally to the turbinated flow of 31.5 km^3 yr^{-1}, a supplementary minimum flow of 24 km^3 yr^{-1} must be provided.

During the impounding period when no electric power is generated and therefore, no water is released through turbines, ensuring a minimum release downstream of 55.5 km^3 yr^{-1}, and neglecting the evaporation and irrigation needs, the reservoir can gain annually 28.5 km^3. With an annual inflow of 84 km^3 yr^{-1}, the average time required to fill up the reservoir volume can be calculate as 159 days (5 months). This period can be shorter or longer, depending on the starting time. The extent of the impounding period can be predicted running a simulation model for different starting dates. In the absence of sufficient hydrological data we could not run such a simulation but knowing that 80 % of the total discharge occurs during the rainy season, the optimum period for reservoir impounding seems to be between July and October when the reservoir can fill up to 95 % of its total storage capacity.

According to our water balance calculation, even at full energy production and securing a minimum downstream flow of 55.5 km^3 yr^{-1}, the reservoir can store annually up to 19 km^3, representing more that 150 % of its capacity. This imply that the reservoir can operate at the maximum capacity even for a lower water inflow down to 65 km^3 yr^{-1}, supporting additional water storage upstream Merowe, increased irrigation scheme or drought periods.

5.2 Sedimentary aspects

One of the major issues of the Merowe Dam Project is related to a large volume of sediment expected to be annually trapped behind the future dam which will result in limited lifetime of the project to only 150 yr. Subsequent impacts are the increased lifetime of the AHD, downstream erosion along the Nile lower course and a general transgression of Nile Delta associated with local subduction favoring salt water intrusion and loss of large fertile agricultural areas.

An average suspended solids concentration of 1.7 g l^{-1} and an annual water flow of 84 km^3 yr^{-1} imply an incoming suspended solids load of $143x10^6$ t yr^{-1}. Based on one order of magnitude drop in water velocity due to river impounding at Merowe, we predict a sediment retention capacity in the reservoir as high as 92 % of the suspended solid incoming load. Therefore, up to $130x10^6$ t yr^{-1} will be annually deposited in the reservoir, corresponding to an average sediment flux of 164 kg m^{-2} yr^{-1}. Using a sediment density of ~ 1.56 g cm^{-3}, the annual volume of the sediment expected to be accumulated in the reservoir corresponds to $84x10^6$ m^3 yr^{-1}, equivalent to an average sedimentation rate of 10.5 cm yr^{-1}.

At this deposition rate, Merowe Reservoir will loss its dead storage capacity of 4.1 km^3 in less than 50 yr, whereas the total storage capacity of 12.4 km^3 will be lost in about 150 yr.

The main volume of the sediment is expected to accumulate in the upper stretch of reservoir, where, as in the case of AHD, a new delta is likely to form in relatively short time after impoundment. The sediment is expected to move gradually towards the dam. This situation is anticipated to extend at least over the half lifetime of the reservoir when the entire dead storage capacity and 50 % of its active capacity has been already lost. Therefore, the “special sluices” of the Merowe Dam and “particular operation rules” expected by the EIAR (2002) to “reduce the reservoir sedimentation” will not play any important role in the first decades. In conclusion, over the first 50 years period, the total

storage capacity of the Merowe Reservoir will be diminish with 34 % and not 17 % as predicted by the EIAR (2002).

High sedimentation deposition especially in the upper reach of the reservoir together with long anoxic periods of the deep waters is expected to smother the benthic organisms of the new forming lake.

With more that 90 % reduced sediment load below the dam the sediment accumulation along the river will be diminished and river bed and banks will be eroded. Induced scouring of the river channel downstream may result in lowering the river level with possible influences on the adjacent aquifers water tables. Moreover, no natural flooding below the dam will heavily impact the traditional recession farming along the river course. Together with the AHD, the Merowe Reservoir is expected to increase the general erosion of the Mediterranean shore and to accelerate the transgression of Nile Delta, favoring salt water intrusion over the large fertile agricultural areas.

5.3 Water quality and geochemistry

The onset of water column thermal stratification is expected in the Merowe Reservoir. Thermal stratification will depend on external driving forces as hydro-meteorological conditions, location, wind induced surface forces, etc and internal properties such as lake morphometry, light absorption and the theoretical water residence time. Using an empirical dependence of reservoir stratification and residence time, we predict a temperature difference between surface and 30 m below of about 10-12 °C. Therefore, starting in spring, the water column of the Merowe Reservoir may become stratified extending over the entire reservoir length. During the flood period, the thermal stratification may be destructed, especially on the upper stretch of the reservoir. With a length of 200 km, the lower stretch of the reservoir, especially the areas in front of the dam or the side bays are anticipated to be less affected by the flood. However, the

overturn due to the changes in climatic conditions during the winter period will allow convective mixing between the surface and the deep waters of the reservoir.

Thermal stratification, high light penetration, increased water temperature in the epilimnion and relatively high riverine nutrient supply will maintain high rates of primary production up in the eutrophic level.

With an approximated average rate of 370 g C m^{-2} yr^{-1}, *in-situ* primary production is expected to produce annually between 130’000 and 300’000 t C yr^{-1}. We consider that 20 % of the organic carbon produce *in-situ* within the reservoir will be accumulated at the lake floor. With high sedimentation rates, half of the total accumulated carbon is expected to be rapidly buried in the sediment of the reservoir. Therefore, the other half (between 13’000 and 30’000 t C yr^{-1}) represents the potential sedimentary organic carbon available for greenhouse gas production. Under expected anoxic conditions below the sediment/water interface, decomposition of organic matter will result mainly in CH_4 production which will be exported to the atmosphere. During transport towards the surface, a fraction of the CH_4 is expected to be oxidized and converted to CO_2. Stratified water column in the Merowe Reservoir will result in storage of both CO_2 and CH_4 in the hypolimnion. During turnover periods, especially in the winter, convective mixing will release rapidly the accumulated gas to the surface.

We also expect that another 20 % of the total organic carbon production (26’000 to 30’000 t C yr^{-1}) will undergo bacterial decomposed within the water column which will result in oxygen consumption and CO_2 production. As the supply of dissolved oxygen from atmosphere will be limited by stratification, constant oxygen consumption will lead to a gradual decreased in dissolved oxygen concentration and even total oxygen depletion in the deepwater.

Therefore, both CO_2 and CH_4 will be produced during decomposition of organic matter within the Merowe Reservoir. As the CO_2 and CH_4 fluxes reaching the surface depends upon a large number of factors, we limit out estimation to only the potential organic

carbon for greenhouse gas production. Therefore, the available organic carbon for greenhouse gas production in the sediment is expected to range annually between 13’000 and 30’000 t C yr^{-1}. This will be supplemented by between 30’000 to 60’000 t C yr^{-1} from the water column. The values are actually expected to be much higher if considering that annually, about 400’000 t C yr^{-1} with an upstream origin will be accumulated to the sediment of the reservoir and contributing with half to the total greenhouse gas potential.

Using a simplistic mass balance approach we estimated that the internal processes within the Merowe Reservoir will retain annually up to 8 % of the inflow load. Therefore, the nutrient concentration in the reservoir will be dependent on the input and to a lesser extent on primary production or sedimentation.

Pollution and eutrophication of the reservoir could create public health hazard for people drinking water or eating fish from the reservoir.

Together with water stratification, low oxygen concentration is expected to have high impact on life conditions of the organisms of the reservoir possible causing fish mortality when oxygen depletion will temporally affect the entire reservoir water body.

Additionally to the quality of water discharges which are likely to contain high levels of nutrient, organic matter and hydrogen sulfide, the impacts of bottom water release from the reservoir could be related to coldwater pollution and anoxic conditions. As bottom release, the temperature of the outflow water will be lower in summer than it would be under natural conditions. Therefore, coldwater pollution together with low dissolved oxygen concentration in the discharged water during the summer are expected to impact the downstream fish population. However, the oxygen content in the water downstream would tend towards natural values by re-oxygenation. On the other hand, the water temperature is expected to need a longer distance before reaching the normal values. Therefore, if the downstream impacts on the biological productivity generated by the low oxygen concentration will be limited to relatively short distance, large temperature changes are expected to induce higher impacts.

5.4 Ecology and health-related impacts

Based on present conditions and water quality of the Nile River, strong eutrophication of the reservoir is anticipated. The input of relatively large amounts of nutrients will induce an increase of biological productivity. Plankton, benthic organisms and fish will benefit and the biomass will increase rapidly. As a result, the reservoir is considered to have positive effect on the lake species as these fishes may find suitable habitats and food whereas the river species are expected to show a decline.

The migratory species which usually swim to the upstream reaches of the river or tributaries for spawning will be blocked by the dam. No fish ladder is fore seen.

Conditioned by the daily and weekly flow variability, reduced downstream spawning areas will have negative impacts on both lotic and lentic fish populations. Nutrient retention in the reservoir may also lead to a decrease of the downstream aquatic productivity resulting automatically in a decrease in fish yield downstream.

Flood events act as biological triggers for reproduction in some fish species. As the natural distribution and timing of downstream flow regimes will be destructed, the impact on the spawning of those fish species is expected.

Due to rapidly changes in the daily and seasonal flow downstream of the dam site, only aquatic organisms tolerant to flow fluctuations and to sudden changes in temperature and dissolved oxygen will prevail. Aquatic organisms will be more affected by the sudden temperature and oxygen changes than by rapid flow increases.

The initial period of increased biomass is generally expected to be followed by stabilization in fish productivity, as the environmental conditions of the lake are expected to reach a steady-state. Therefore, benefiting from newly formed reservoir, commercial fishing could be initiated after a period of few years after impoundment.

Stagnant water and exposure of large area of the river bed can create perfect breeding condition for mosquitoes, vectors of malaria and yellow fever and the water flea, host of the guinea-worm. As malaria was endemic in Sudan in 1942 resulting in about 100'000 deaths, precautionary measures should be considered.

The reservoir water quality may also be less adequate for human consumption under high annual drawdown of dry periods due to reduced dilution, eutrophication and pollution, as well as the presence of decaying vegetation.

The presence of stagnant water around the construction site due to excavation, ditches or other activities may induce good breeding conditions for *anopheles* in the immediate area and generate malaria among the construction personal or local population if not managed properly. It cannot be fully excluded that *anopheles* will find favorable conditions in the upper reaches of the reservoir, specially during the seasonal receding of the water level which will expose the annual drawdown zone and favor the creation of temporary shallow stagnant pools in some areas.

Although it is not necessary expected to trigger dramatically health problems, the arid conditions and the characteristics of the reservoir area with large seasonal water level fluctuations seems to justify a cautious approach.

6. The Lahmeyer report

6.1 International standards

The environmental impact assessment report should be seen as guidance, identifying at the beginning the environmental issues resulting from the project implementation, estimating their extent and providing a basis for deciding whether or not a project should be carried out. Among the goals of the EIAR, the report should contribute to the sustainability and viability of such projects by foreseeing conflicts and deficiencies as well as reparation and mitigation costs. Such a report should propose at the end a few tools to help the decision makers to minimize negative impacts. There are several published guidelines such as the report by the World Commission on Dams (WCD, 2000) or the Operational Policies of the World Bank (www.worldbank.org), which provide specific requirements for establishing an EIAR for a large dam project. No reference is made, however, to such international standards in the Merowe Dam report.

6.2 Important deficiencies

The EIAR (2002) was not made available for public review. Therefore a chance was missed for involving major stakeholders and the general public in a discussion of the quality of the information and the assessments of the report. In addition, it seems that no formal peer review of the report was carried out by qualified environmental assessment specialists, prior to the submission to the Sudanese Government.

It does not appear that Lahmeyer have carried out any specific technical studies for evaluating potential impacts. No reference is made in the report to such studies.

Key environmental issues such as reservoir sedimentation, irrigation, water quality, downstream ecological impacts resulting from hydropeaking were not addressed adequately, as specified below.

6.2.1 Sedimentation

We predict that an annual sediment volume of approximately 84×10^6 m^3 yr^{-1} will be accumulated in the Merowe Reservoir. As this value is extremely high compared to the total storage of 12.4×10^9 m^3, the reservoir is expected to lose its total capacity (dead and active) in less than 150 yr. For comparison, the dead storage capacity (20 % of the total reservoir volume) of the AHD will be lost in 360 yr whereas it will take another 1'000 yr until the reservoir will lose its active capacity (55 % of the total volume). Therefore, sedimentation represents a major issue for the Merowe Dam Project and more detailed information should be acquired.

On page 4-6, the EIAR (2002) made the following statement: "…*the future reservoir will trap 100 % of the river bed load and much of its suspended load*". On page 2-2, the EIAR specifies potential mitigation strategies: "*The dam design incorporates special sluices and particular operation rules to reduce the reservoir sedimentation and to reduce the capacity losses over 50 yr period to 17 % of the original active capacity (83 % will still remain active)*".

The proportion of bed load to suspended load varies from river to river. In general, large rivers at lower elevations are less steep and therefore the proportion attributable to bed load is small (Meade et al., 1990). This is the case for the Nile River for which the bed load transport does not represent an issue. The issue here is represented by the suspended load.

According to EIAR (2002), the volume of sediment annually retained in the reservoir will correspond to 28×10^6 m^3 yr^{-1}. Using the conversion factor of 1.56, this annual volume is equivalent to a sediment mass of 44×10^6 t yr^{-1}. Compared to the inflow load of 143×10^6 t

TSS yr^{-1} calculated from a water flow of 84 km^3 yr^{-1} and a TSS concentration of 1.7 kg l^{-1}, the sediment retention capacity of the reservoir would correspond to only 30 % of the incoming sediment load.

Compared to our estimated retention of 90 % of the incoming load for a residence time of approximately two months, the EAIR (2002) assumption is based on unknown or unshared data and represents a factor of 3 lower retention. This low retention contradicts existing experience with large dams such as the Iron Gates Reservoir (Teodoru and Wehrli, 2005) and the AHD. No technical information is given to sustain the claim that "*special sluices*" and "*particular operation rules*" can indeed ensure the transport of the suspended load for 200 km along the Merowe Reservoir.

6.2.2 Hydrology

Long hydrological time series and their interpretation is often a matter of controversy. The EIAR (2002) does not specify the source of the hydrological data on which the average annual runoff and its variability were based.

Peak operation of the hydropower scheme will create daily water level fluctuations between 2.6 and 4.9 m below the dam. This hydropeaking will have significant impacts on small-scale irrigation pumps and ferry landing sites expected to occur over a small distance of only 20 km downstream the dam. Further consequences for the local population and the riparian morphology and ecology are not discussed in any detail. Good practice in large dam design would require a serious evaluation of mitigation measures such as a small dam to limit the amplitude of these daily level fluctuations.

6.2.3 Irrigation

The Merowe Dam is described as a multi-purpose project for hydropower production and irrigation. At the completion of the EIAR in April 2002, the irrigation component was still studied at pre-feasibility level "although two irrigation intakes on the right and left

bank of the river (2x150 m^3 s^{-1}) have been incorporated in the dam structure design" (EIAR, 2002; page 2-1).

According to our calculations, the proposed irrigation scheme would lead to an annual abstraction of up to 7.4 km^3 yr^{-1}. As this diversion would represent 9 % of the river flow, the irrigation scheme should be assessed in the report together with the operation rules, a plan for limiting salinization of irrigated land, and total water allocation within Sudan. Such an important aspect should not be ignored simply due to the fact that the plans are still in limbo.

6.2.4 Water quality

No database on water quality parameters was presented by the EIAR (2002). The general prediction that "*no significant change of water quality is expected to occur, neither immediately after impounding nor in the long term*" disregards long-term observations on reservoirs in arid areas. The optimistic assessment was based on the following assumptions (EIAR, 2002; page 4-4)

(1) "*Remarkable very little biomass exists within the reservoir area – 25,000 t of readily degradable and 9,000 t of slowly degradable biomass*";
(2) "*Very short residence time of only two months*";
(3) "*Annual draw-down of the reservoir which will tremendously reduce reservoir depth, length and volume*";
(4) "*Operation of bottom outlet and low water intake level*".

Based on the water residence time and the local climate, we demonstrate that strong water column stratification, with temperature differences between the surface and the deep waters of several °C will occur during the summer period.

Moreover, it seems that the Lahmeyer report disregards *in-situ* reservoir production. Low primary production rates will produce between 320'000 and 750'000 t of organic matter

per year, which is one to two orders of magnitudes more than the existing biomass in the reservoir area before flooding. In addition, inflow organic matter will be degraded within the reservoir.

6.2.5 Greenhouse gas

The report assumes that greenhouse gas emissions were limited to the degradation of existing biomass in the reservoir area. A "*total emission of some 600,000 t of CO_2*" was predicted by the EIAR (2002) on page 4-4. "*Since anaerobic decomposition would not occur, due to the continual exchange of water within all parts of the reservoir, no methane would be produced*", so that "*…greenhouse gas emissions from the Merowe project are considered to be non-significant*".

These predictions contradict the current scientific knowledge. Even in the absence of anoxic bottom water, high sedimentation rates in the reservoir and therefore high burial efficiencies will result in prevalence of anoxic condition within the sediment. Therefore, during decomposition of organic matter, both CO_2 and CH_4 will be produced within the sediment of the Merowe Reservoir. As the CO_2 and CH_4 fluxes released from the reservoirs depend on a large number of factors, we limited the evaluation to the total carbon available for greenhouse gas production. Our calculations showed that annually, between 40'000 and 90'000 t C yr^{-1} will be available to be converted into CH_4 by organic matter decomposition within the water column and the sediment. Considering the large fraction of organic matter input via total suspended solids, the available carbon will be actually much higher, between 250'000 and 300'000 t C yr^{-1}. These simple estimates show that monitoring of the water column for oxygen and greenhouse gases is of high priority for a sound assessment of reservoir performance.

6.2.6 Fishes

Concerning the fish populations, the EIAR (2002) considered the Merowe Dam Project having no significant impacts on fish fauna, being "*…mainly limited to changes in the*

future reservoir" (page 4-7) due to the fact that "…*no endangered species have been reported and there is no evidence of fish migration other that local movements in the Main Nile river*" (page 4-7).

The report disregards the fact that the present fish population of Lake Nubia consists of several migratory fish. Several species like *Barbus bynni*, *Barbus perine, Labeo coubi*, *Labeo horie* and *Laboe niloticus* which belong to Cyprinidae family are migratory fish. The ecological assessment is based on incomplete species lists and disregards the life cycle of the different species involved. The isolation of a very large fish population on the 700 km river stretch between Aswan and Merowe represents a dramatic fragmentation of one of the largest river systems in the world and requires a much more careful and detailed monitoring and assessment.

6.3 Recommendations for mitigating negative impacts

6.3.1 Recommendation on reservoir level operation

In general, the operation policy of a dam is to "refill" the reservoir volume during the high flow, which in the case of Merowe is represented by the summer period between June and October and to have the reservoir full at the beginning of the following dry season. In the course of autumn, winter and spring, the water levels will usually decrease progressively due to the water release for energy production and/or irrigation demands and evaporation.

The seasonal fluctuation in the Merowe Reservoir of between 800 km^2 at maximum level and 350 km^2 at low stand imply that more than 450 km^2 of reservoir floor will be exposed to aeolian transport and soil-forming conditions. Therefore, it should be considered that, in order to minimize the environmental impacts, the operation policy should be done in such a manner to reduce the exposure of the reservoir sediment. This would represent a

substantial advantage in terms of environmental impacts of the aquatic life and landscape as well as the water losses.

Daily operation scheme of the dam will create downstream water level fluctuations ranging between 2.6 and 4.9 m with significant impacts on small-scale irrigation pumps and ferry landing site. A retention dam at the outlet of the power station could mitigate such negative side effects of hydropeaking. Therefore, the feasibility of a small second dam downstream Merowe, to equalize the daily fluctuations, should be included.

6.3.2 Recommendation on sedimentation

Our predicted annual sediment retention of up to 90 % of the river incoming load is expected to accumulate in the upper stretch of the reservoir, where a new delta will form in relatively short period. The simplest appropriate solution for reducing the sediment retention in the Merowe Reservoir is increasing the discharge during the summer period as 80 % of the annual sediment load occurs with the flooding between July and October.

For a precise estimation of the incoming sediment load, TSS measurements over a full annual cycle should be carried out. A detailed sediment management plan should address the problems of reservoir sedimentation and provide detailed measures and operation rules to mitigate the impact on the reservoir lifetime.

6.3.3 Recommendations on water quality

The water quality in the Merowe Reservoir will mainly depend on the inflow and on the pollution in the catchment area, and to a lesser extent on internal processes. Of particular importance are the summer temperature variations, the flood and the return of water from irrigated areas.

Mitigation measures for reservoir water quality generally focus on maintenance of water quality upstream by treating the sewage of large upstream cities and by preventing water

stratification and oxygen depletion. This can be done by limiting the water residence time and designing optimal water intakes for the power plant. The position of the intake influences the nutrient content, oxygen conditions and fish population in the reservoir and downstream. An intake located in the hypolimnion will help to minimize the stratification in the reservoir and assist the transport of oxygen to greater depth. Therefore, the intake should be made flexible to “mix” and maintain a minimum O_2 level. A flexible solution will also help in the future to mitigate unforeseen problems.

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