MODELLING OF NIGER RIVER BASIN DEVELOPMENT UNDER UNCERTAIN CLIMATOLOGICAL CONDITIONS

Gunter MEON

Professor of Hydrology and Water Resources Management

Dept. of Environmental Engineering. University of Applied Sciences Lippe and Hoexter Wilhelmshoehe 44. D-37671 Hoexter meon@fh-hoexter.de

1 INTRODUCTION

West Africa has experienced striking fluctuations of precipitation on both recent and historical time scales. In particular, since the early 1970s, several long-term droughts with shorter periods of extreme dryness occurred in the West African Sahel. In interaction with factors caused or influenced by human activities, the significant decrease in rainfall lead to a drastic reduction of the average annual water availability of West African rivers. For the last 30 years, the mean annual water yield of the middle and lower Niger river was reduced by more than 30% if compared with the long term average flow occurring before 1970. In a number of years the Niger river run nearly dry for several weeks along the river stretch of the Republic of Niger, and adversely affected the water use conditions in terms of quantity and quality of the "lifeline" of this country.

In the late 1970s a consortium of consulting engineers under French guidance investigated the Niger river basin development in the Republic of Niger. At that time priority was given to hydropower development rather than water supply. They recommended to build a dam located some 30 km downstream of the border between Mali and Niger, and 190 km upstream of the capital of Niamey. The corresponding reservoir had an enormous useful storage of about 9 billion m^3. Based on economic and other reasons, the project was stopped.

Being aware of the fatal consequences of water shortage, in 1999 the African Development Bank (ADB) financed a feasibility study on river development of the Niger river reach flowing through the Republic of Niger. Aim was to investigate, if the reduced availability of surface water can be substantially improved with the help of a multipurpose dam to be constructed at the same location as planned previously. The new project variant should be designed as small as possible to minimise the investment costs and the environmental impact. For this, extensive environmental and socio-economic analyses were required.

The feasibility study was performed by a German-Lebanese-Niger consortium (Lahmeyer International e.a., 2000), and was supervised by authorities of the Republic of Niger and the ADB. The tasks related to water resources were challenging because of the following requests which had to be performed within a tight project schedule:

The uncertain climatological - and consequently, hydrological – conditions of the entire river basin required extensive scientific-oriented work on the available hydrometeorological data to arrive at representative data series to be used for the river management model.

- The complex water resources conditions required the programming of a new modelling system to simulate the river management of the middle Niger river and optimise the structural and operational components of the project basin.

2 TASKS IN WATER RESOURCES ENGINEERING

The planned reservoir-river system should be operated to fulfil the following demands for a planning horizon up to the year 2025:

- First priority: low flow augmentation during the dry season along the river flowing through the Republic of Niger, especially at the capital Niamey; to guarantee the water supply for domestic, agricultural (animals), public, commercial and industrial use. At the same time the low flow augmentation was considered essential to improve the water quality of the Niger river during the "critical" low flow period lasting from about April/Mai to June/July.

- Second priority: meeting the demand of new irrigation schemes to be developed along the river reach.

- Third priority: generation of hydroelectric energy.

In the feasibility study, the work related to water resources comprised the following main tasks:

- Hydrometeorological inventory of the Niger river basin needed for the project targets: collection, plausibility analysis, processing including extension of series of meteorological and hydrometrical data; establishment of a project data bank .

- Analysis of water demands along the entire project section of the Niger River for all water use sectors and given planning horizons up to the year 2025.

- One-dimensional hydraulic modelling of the project river section: main reason was to obtain reliable flow propagation times for water releases from the planned reservoir to the relevant downstream diversions and locations.

- Programming of a new river management modelling system which is adapted to the specific conditions of the 500 km long project section; the model works with a time step of one day.

- Simulation of the Niger project section with the new model: for this historical series of daily data were used which were considered to be representative for the life time of the investigated measures.

- Optimisation of the hydrologic design of the dam and operation of the reservoir considering economic and ecological constraints.

In this paper, emphasis is given on the data inventory and the river management modelling which has been performed by the author in cooperation with Lahmeyer International (2000).

3 HYDROMETEOROLOGIC CONDITIONS OF NIGER RIVER BASIN, DATA ACQUISITION AND PROCESSING

The Niger River basin, located in western Africa, drains an active catchment of about 1.5 million km^2 and encompasses nine countries. The river has a length of about 4,200 km. The

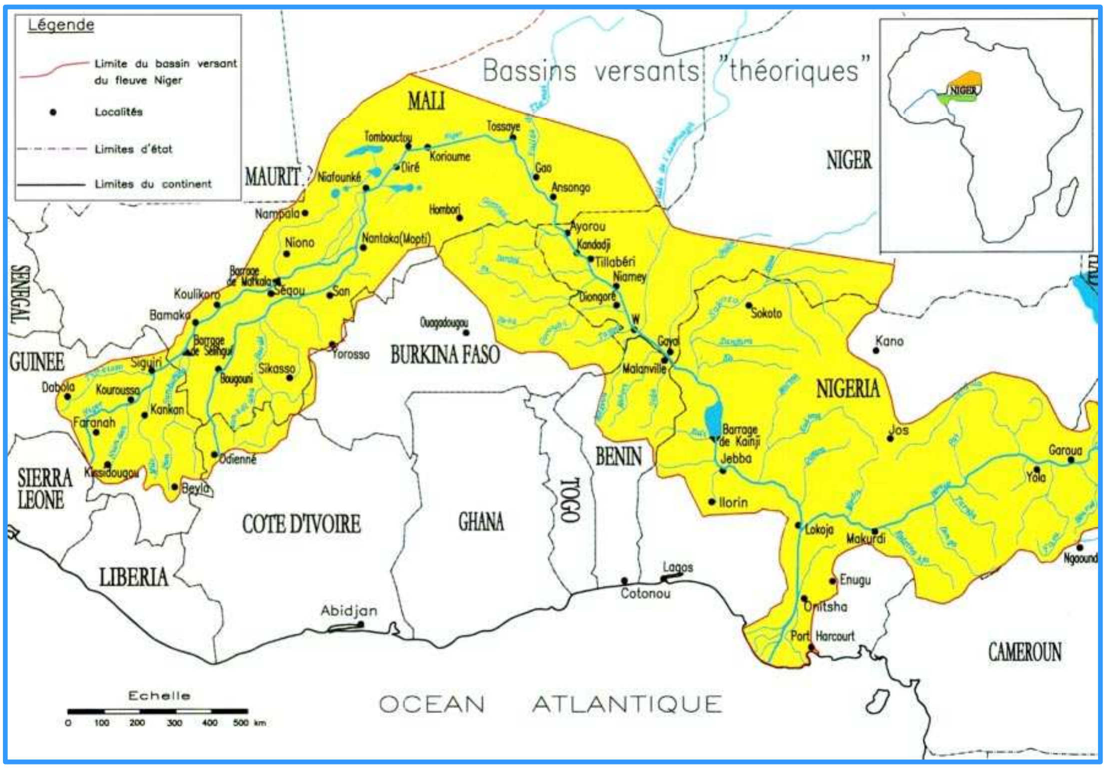

Fig. 1: Niger River basin; the project section comprises the river flowing through the Republic of Niger (source: Lahmeyer International e.a., 2000)

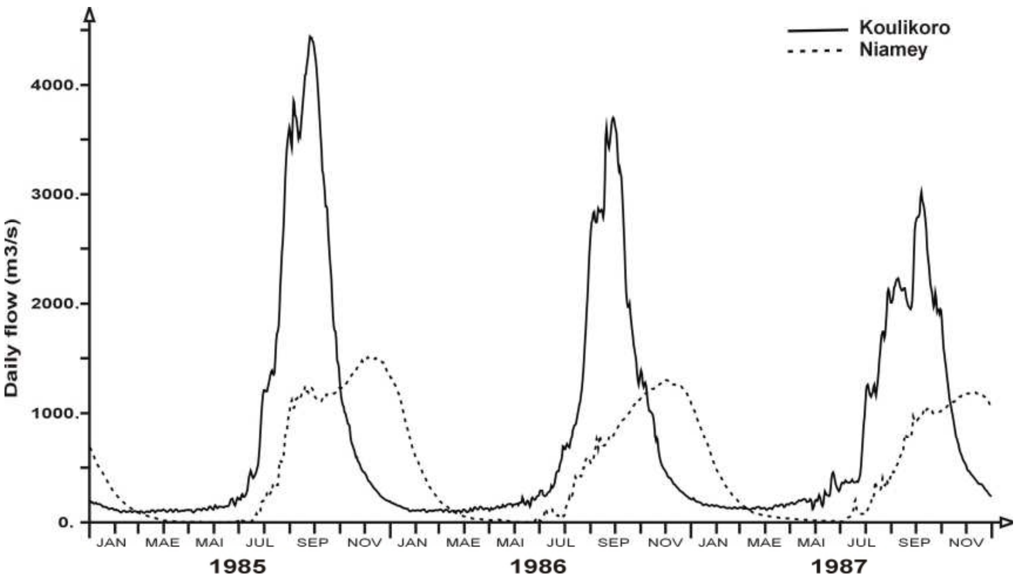

Fig. 2: Hydrograph recorded at Koulikoro (upstream of the Inner Niger Delta) and at Niamey during a dry period (source of raw data:NBA)

basin is displayed in Fig. 1. The project section comprised the river flowing through the Republic of Niger and included the damsite under study located near the village of Kandadji close to the border to Mali.

The course of the Niger river can be divided into 4 sections (Niger Basin Authority, 1999): The Upper Niger and the Bani river (from the source to the Inland Delta), the Inland Delta (from Segou to Tossaye), the Middle Niger (from Tossaye to Malanville) and the Lower Niger on the Nigeria/Cameroon side. The main river and its tributaries flow through different climatological zones. The flow regime of the Middle Niger which includes the project section is characterised by the retention effect of the Inland Delta. It stores a volume of water estimated at about 70 billion m^3 in a "normal" year as it frequently occurred within the 40 years before 1970. The flood arriving at Koulikoro in September is slowed and delayed in the delta. The greater part of it – reduced by about 45% through infiltration and evaporation - reaches the exit of the delta 2 to 3 months later and passes Niamey in December and January. Fig. 2 shows an hydrograph recorded at Koulikoro upstream of the Inner Delta and the corresponding hydrograph at Niamey. The enormous retention effect and its impact on the flow regime at Niamey is evident.

From Tossaye to Malanville rainfall increases from about 200 mm/a to 900 mm/a, and the potential evaporation varies from 1800 mm/a to 2200 mm/a. From Tossaye to the entry into the Republic of Niger, the river does not receive any tributary, and the flow keeps on decreasing through various losses up to the confluence with several small tributaries coming from Burkina Faso. These tributaries provide inflows of short duration which slightly change the flow regime of the main river at Niamey, most especially during the rainfall season lasting from about July to September.

To ensure the harmonious use and management of the common resources in the basin, the riparian countries jointly created the Niger Basin Authority (NBA) in 1980. NBA is charged with the collection of hydrometeorological data, control of water resources projects and hydraulic structures on the river system, and the real time hydrological forecasting (NBA, 1999; Oyebande and Balogun, 1992).

The hydrographs of Fig. 2 show the expiring years of an extreme dry period which occurred in the early 1980s. It becomes obvious that the reduced water yield of the Middle Niger was not only influenced by the drought of the Sahel zone but also strongly caused by rainfall anomalies of the humid and sub-humid sub-basins of the Upper Niger.

Available series of daily and monthly raw data (rainfall, evaporation, water levels, discharges, rating curves etc.) had been taken over from the NBA and other authorities of the project region. The recorded periods varied strongly and included gaps covering a few days up to several years. Regarding the uncertainties involved in many raw data the data work was focussed on the verification and filling-up of key data series by means of multi-regression analysis. Daily flow at Niamey has been recorded since about 1929 and provided a sound basis for the extension of flow series of stations located along the main river. At the planned damsite, flow data have been collected since 1975. Finally all processed data series covered the complete period of 1944 to 1998.

Statistical analyses of the series 1944 to 1998 confirmed to distinguish between the period prior to and after 1970. In the second period, the mean annual surface water yield was drastically reduced by about one third from 33 (1944 to 1969) to 22 billion m^3 (1970 to 1998). Table 1 shows the mean annual flow of at Niamey for different periods of analysis. The corresponding hydrographs are shown in Fig. 3, and Fig. 4 presents a linear trend analysis for the discharge at Niamey based on the period of 1944 to 1998.

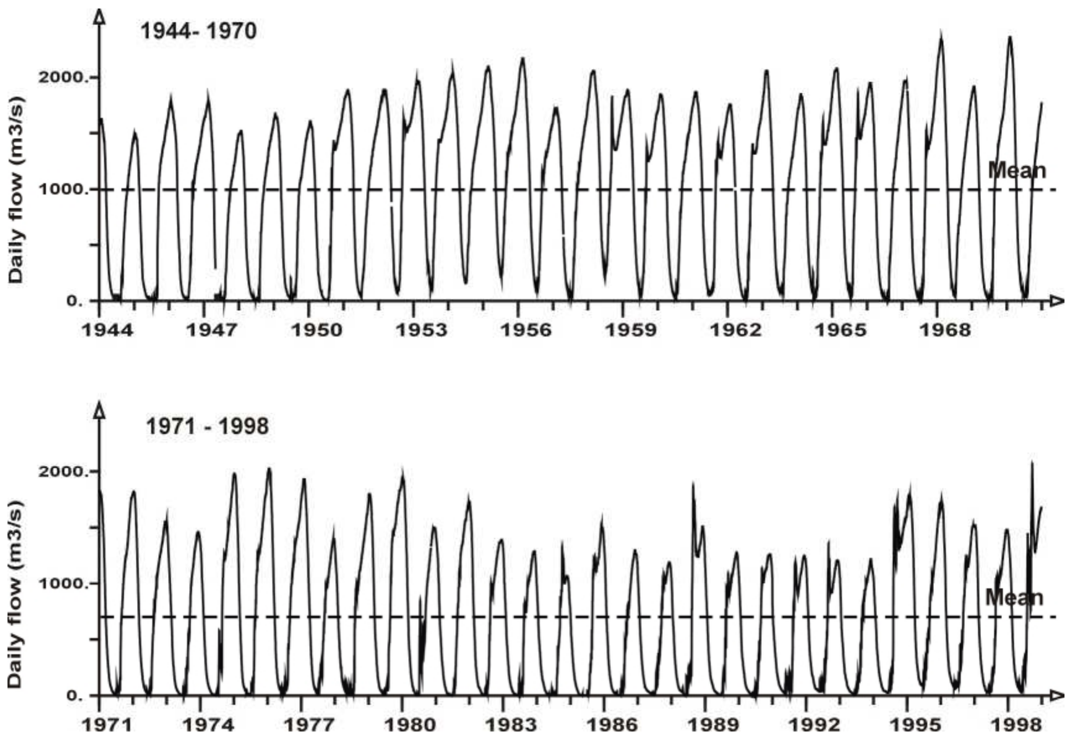

Fig. 3: Recorded natural flow of river Niger at Niamey for periods 1994-69 and 1971-98 (processed from raw data obtained from NBA)

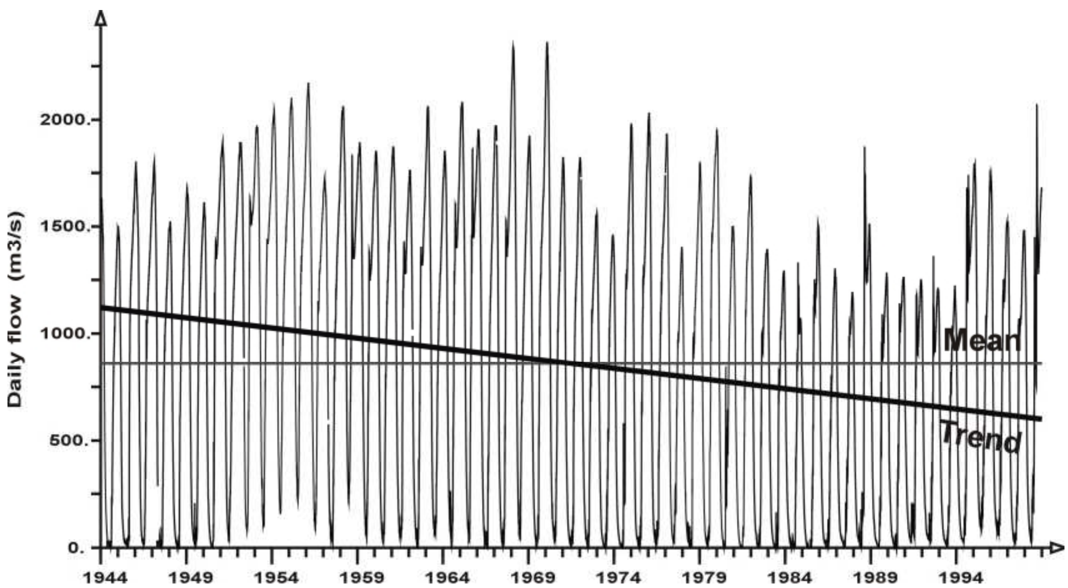

Fig. 4: Recorded natural flow of river Niger at Niamey, trend analysis for period 1944-98 (processed from raw data obtained from NBA)

Period	Mean annual flow of river Niger at Niamey	
	(m^3/s)	billion m^3
1944 – 1998	860	27
1944 – 1969	1.040	33
1970 – 1998	700	22

Tab. 1: Mean annual flow of river Niger at Niamey, based on recorded series of natural daily flow (source of raw data: NBA).

The findings obtained from the flow data analysis are similar to other studies on water yield (Olivry e.a., 1998; Oyebande and Balogung, 1992) and to findings from rainfall statistics of West Africa (for example Nicholson, 1993 and 1998; Servat e.a., 1998). Apart from the significant reduction of annual and seasonal mean rainfall (June to August) since the early 1970s, further anomalies were identified or discussed like an increased interannual rainfall variability (Hulme, 1992; Adejuwon e.a., 1990), and large-scale atmospheric-oceanic causes (Lamb, 1983). Further analysis of available scientific publications on the anomalies and fluctuation of rainfall in West Africa did not provide any clear prediction if the observed trends will continue, decrease or even increase in the close future. Consequently, for the project it was decided to use the data period of 1966 to 1998 as an representative period for the simulation runs with the river management model. The selected representative series is dominated by phases of dry and very dry years since the early 1970s but also includes some normal and wet years. This series implies a rather pessimistic scenario of water yield for the lifetime of the plant. Furthermore, the series takes in account the increasing human impact on factors connected with the regional water availability, e.g. land cover changes.

In addition a sensitivity analysis using other simulation periods was performed and considered for the project design.

A scientifically based creation of synthetic data series on a daily basis would have been possible with considerable additional effort, but would have gone far beyond the scope of the feasibility study. As described in Chapter 5, the sensitivity analysis confirmed that the reliability of the reservoir to deliver the expected demands could be kept on a very high level even if the "most pessimistic" historical data series 1970-98 was applied.

4 DEVELOPMENT OF A NEW RIVER MANAGEMENT MODEL FOR THE PROJECT RIVER SECTION

In contrast to the usual practice in international engineering consultancy, the project was not "adapted" to an existing software, but a new software package was developed for the project. The structure of the new river management model is shown in Fig. 5. The model can be used for planning purposes. If the planned reservoir will be constructed the model can easily be extended to deal with online data and forecasted data, and be integrated into a comprehensive real-time water resources management system of the Niger river stretching through the Republic of Niger. The model works under Windows and includes various graphical and tabular tools for the evaluation and presentation of results. Basically it simulates the surface water balance of the system on a daily basis for given hydrometeorological time series, demands and operation strategies. Furthermore it includes hydraulic parameters taken over from the hydraulic modelling of the main river (travel times of water releases from the reservoir to relevant downstream locations) and optimisation procedures for the generation of hydroenergy

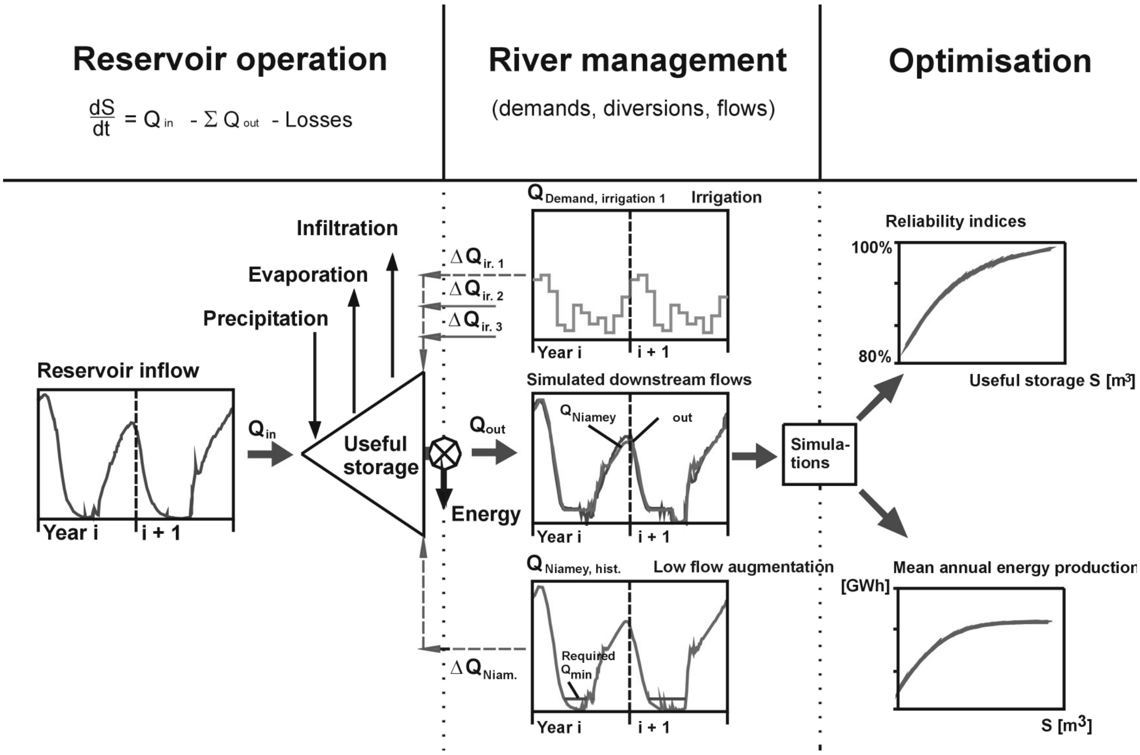

Fig. 5: Structure of new water management model for the river Niger flowing through the Republic of Niger, developed by Meon (Lahmeyer International e.a., 2000)

The simulation model consists of three main components or modules

1) Reservoir operation:

Using the reservoir storage equation the daily outflow is computed for given reservoir specifications, operation rules and downstream demands. According to the given priorities of demands, energy generation ranks third and is not needed to optimise the daily outflow. Such an energy based optimisation would require to integrate the plant into the power system of the country and would – to a large extent - counteract on the first two project targets. The released water, however, is used to maximise the daily energy output for given boundary conditions. For this, internal procedures optimise the flow combination through the power conduits in order to maximise the power output for a given total reservoir outflow and reservoir water level.

2) River management:

This component continuously interacts with the first component. All daily needs of water along the river section are identified, superimposed and transmitted to the plant. The contribution of flows of several tributaries from Burkina Faso as well as losses from evaporation, infiltration and unidentified sources are considered; for the latter, the actual daily flow recorded at Niamey is taken into account. The daily release from the reservoir is routed downstream and reduced by diverted water along the river. For each day it is checked if the demands can be fulfilled.

3) Performance indices for reservoir design and system operation:

The simulation model does not include automatic optimisation procedures to meet the main targets, like for example, stochastic dynamic programming tools. Regarding the requirements for the model – robust tool for the engineering practice, user-friendly handling, efficient algorithms without any overload, transparent and understandable results – and the short computation time of a simulation run (about one minute on a standard PC), the optimisation of the reservoir design and river management is obtained with the help of various simulations using different initial and boundary conditions. For each simulation run, the model calculates a number of performance indices of reliability, vulnerability and resilience, for example:

The reliability to meet the daily demands for the simulation period (number of deficit days for which the demand can be met, divided by the total number of deficit days)

The total water deficit which cannot not be delivered for each year and the simulation period.

4 RESULTS OF SIMULATION, HYDROLOGIC RESERVOIR DESIGN AND SYSTEM OPERATION

In this paper only a few results can be presented. Fig. 6 shows an extract from a simulation for the representative period of 1966-1998. For the extremely dry phase 1983-86 the stored volume of reservoir water at the damsite and the corresponding simulated hydrograph at Niamey are shown. For comparison, the natural hydrograph is included. It is evident that in this simulation run the target minimum flow, which was given as 120 m^3/s, can be guaranteed in 1983 and 1986, whereas in 1984 and 1985 the demand cannot be satisfied for a number of deficit days during the dry phase.

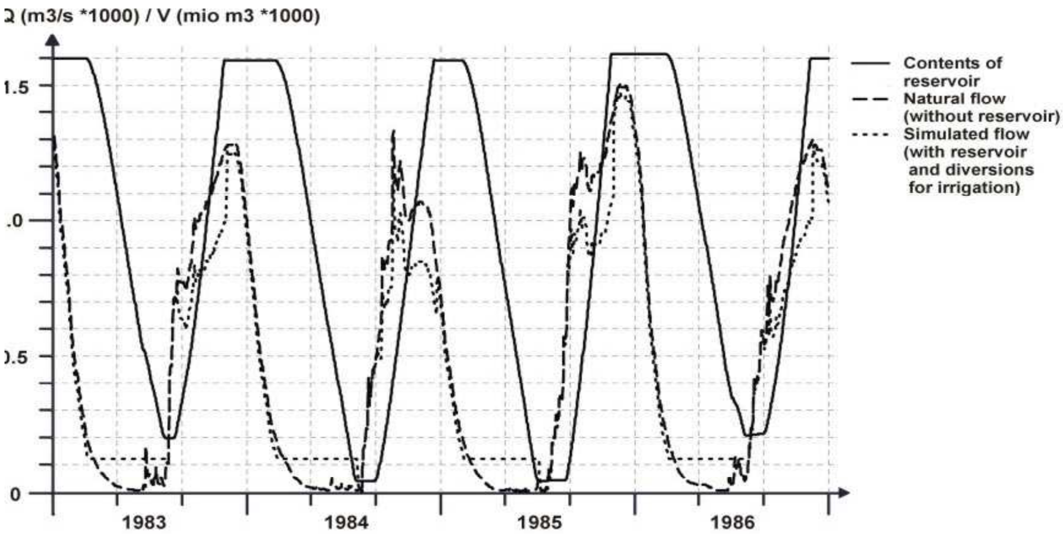

Fig. 6: Excerpt of simulation: contents of reservoir and corresponding flow of river Niger at Niamey for a required minimum target flow at Niamey of 120 m^3/s

Fig. 7 shows the duration curves of daily flow (natural and influenced by reservoir operation) at Niamey for the representative simulation period. Under natural conditions the given target minimum flow of 120 m^3/s cannot not be reached in about 30% of the simulation time; if the reservoir is operated the reliability increases from about 70% to more than 98%.

Fig. 8 present results obtained from numerous simulations. The reliability index is presented in dependence on the given target minimum flow and the useful storage expressed by the maximum and minimum operation water levels.

Fig. 9 refers to the sensitivity analysis of the simulation periods. Assuming the same reservoir characteristics and operation rules, the reliability index was computed using the representative data series 1966-98 (pessimistic scenario of future water yield), the series 1970-98 (very pessimistic) and the complete data series 1944-98 processed for the project (rather optimistic). For all simulation periods the reliability indices are high and rather stable for a target minimum flow up to about 130 m^3/s.

Based on all simulations, sensitivity analyses, economical and ecological evaluations it was decided to select a useful storage having a capacity of about 1.5 billion m^3 which is about 7% of the mean annual yield, and by far lower than the storage capacity of 9 billion m^3 recommended in the previous feasibility study. From the hydraulic and sanitary point of view the minimum target flow at Niamey should exceed about 100 m^3/s. According to the simulations, the reliability of meeting the demands of deficit days is close to 99%, if a minimum target flow of 120 m^3/s is aimed at. The total "losses" of water yield caused by reservoir evaporation and infiltration minus rainfall on the reservoir surface amount to about 2.5% of the natural reservoir inflow.

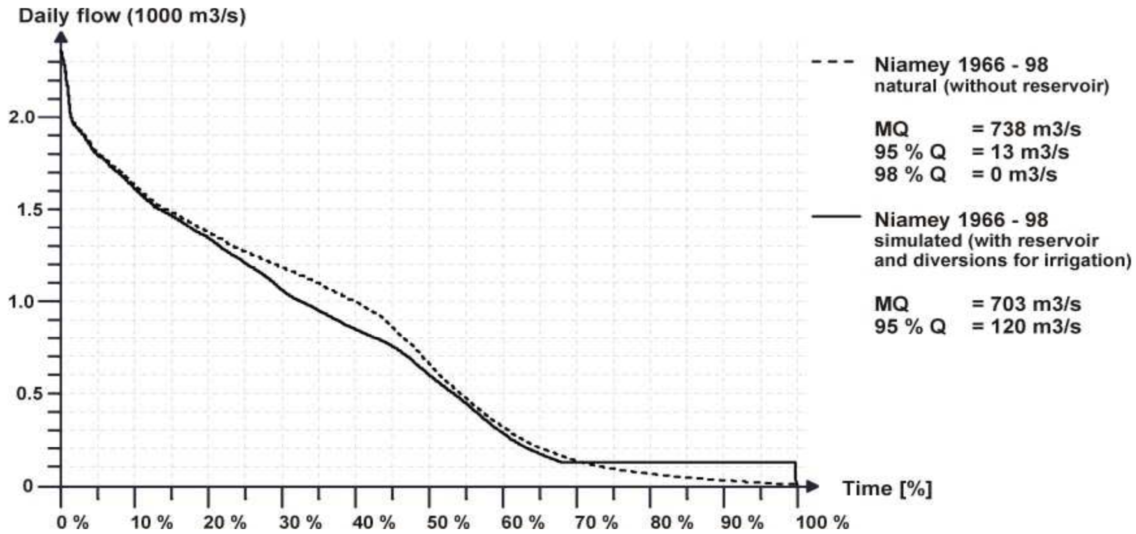

Fig. 7: Duration curves of daily flow of River Niger at Niamey (natural and simulated for a required minimum target flow of 120 m^3/s)

6 CONCLUSIONS

The results of the study show impressively that the water resources development of a large river basin "suffering" from uncertain climatological conditions can be well planned with the help of a thorough data analysis and modern modelling tools. The development of a new programming system tailored to the specific conditions of the project basin turned out to be an essential and efficient component of the feasibility study.

Various simulation runs on a daily time step led to an optimum design of the multipurpose plant and to useful operation rules of the reservoir-river system. It was shown that the given targets can be reached with a comparatively small dam under acceptable minor environmental impacts and with a high degree of supply reliability.

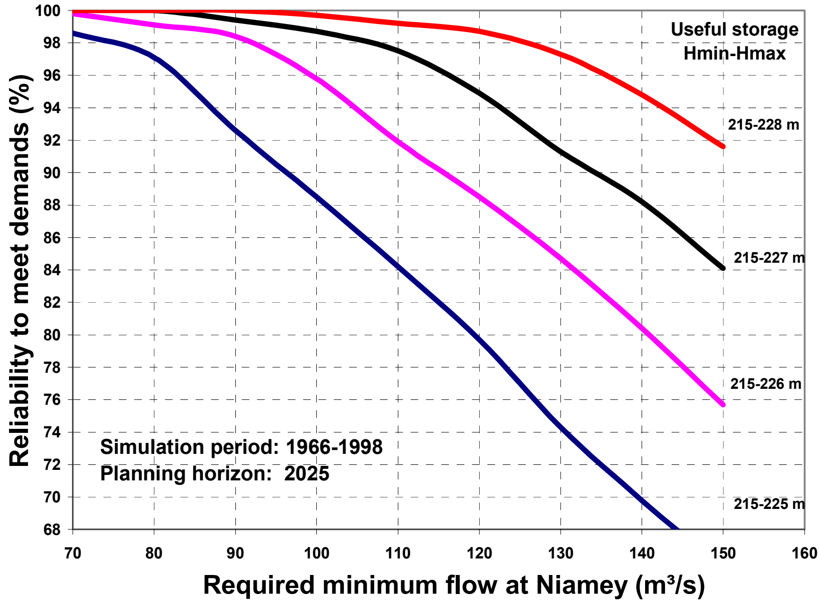

Fig. 8: System reliability in dependence on the size of the useful storage and the required minimum flow at Niamey; based on numerous simulations of the reservoir-river system

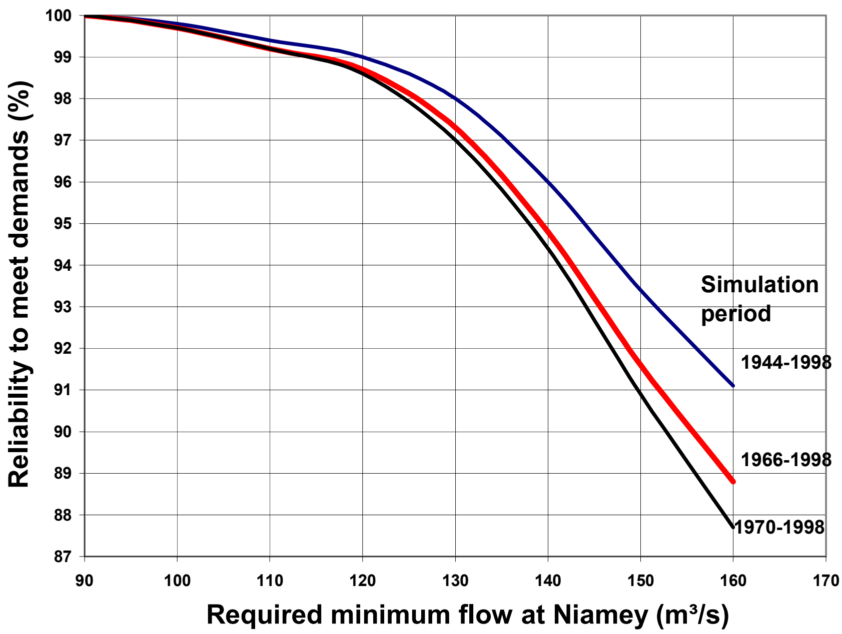

Fig. 9: System reliability in dependence on the simulation period

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