ASSESSING THE WATER RESOURCES POTENTIAL OF THE NILE RIVER BASED ON DATA, AVAILABLE AT THE NILE FORECASTING CENTER IN CAIRO

OCENA VODNEGA POTENCIALA REKE NIL NA OSNOVI RASPOLOŽLJIVIH PODATKOV, ZBRANIH V PROGNOSTIČNEM CENTRU ZA NIL V KAIRU

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View over Lake Nasser (photography Saša Roškar).
Pogled na Naserjevo jezero (fotografija Saša Roškar).

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Assessing the Water Resources Potential of the Nile River Based on Data, Available at the Nile Forecasting Center in Cairo

KEY WORDS: Nile Forecast Center, Egypt, watershed, Mean Areal Precipitation, flow

This paper estimates the monthly values of mean areal precipitation (MAP) and discharge data (Q) over significant sub-catchments of the Nile River watershed on the basis of daily and monthly gridded data (resolution of about 25 km^2) available at the Nile Forecast Center (NFC) in Cairo. On this basis, the author proceeds with an analysis of the MAP, Q, and annual runoff ratio for each sub-catchment, an analysis of the covariance of the basic temporal modes of the inter-annual variation of the MAP and Q between the Blue Nile and the White Nile, and an analysis of the resilience of a well-managed Aswan High Dam facility to historical climate variability. The main conclusions are: a) similar behaviour of the basic mode variability exists throughout the Nile sub-catchments, although the inter-annual basic mode variability over large areas is small; b) there is a dominant 44-month cycle for MAP, and 9 and 20 year cycles for total Nile Basin runoff at Aswan; c) the correlation coefficient between annual Q and MAP is low in the Equatorial Lakes and the marshlands of the White Nile and is much higher for areas in and downstream of the Blue Nile; d) in the past, the White Nile including the Sobat River has contributed an average of approximately 30% of the inflow to Lake Nasser (1912–1995 data) but with its contribution ranging from about 25% in the early years of the 20th century to 40% in the 1960's and a steady decreasing trend in recent years; e) assuming that irrigation demand in Egypt remains at present day levels, improved management of the High Aswan waters through the modern forecast-control system should be able to accommodate the historical climatic variability without significant detrimental effects for the Egyptian water supply (period of record 1872–1998); and f) for an increase of 8 km^3 in upstream water consumption and for the same climate variability of the inflows to the Aswan High Dam as in the past 128 years, the forecast-control scheme ensures the minimum of the current irrigation demand for Egypt. It is carefully pointed out throughout the analysis that data is not uniformly available throughout the Nile Basin and the analysis contains errors that are not homogeneous over the entire Nile watershed; furthermore, the historical climatic variability is likely not to be repeated in the area as evidenced by the behaviour in the 1960's (one event in this long record).

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Ocena vodnega potenciala reke Nil na osnovi razpoložljivih podatkov, zbranih v Prognostičnem centru za Nil v Kairu

KLJUČNE BESEDE: Prognostični center za Nil, Egipt, prispevno področje, povprečne ploskovne padavine, pretok

Na osnovi dnevnih in mesečnih padavinskih ploskovnih podatkov (ločljivost okrog 25 km^2) zbranih v Prognostičnem centru za Nil v Kairu prispevek ocenjuje mesečne vrednosti ploskovnih padavin (MAP) in pretokov (Q) za najpomembnejša vplivna področja Nila. Na tej osnovi avtor analizira MAP, Q, letni koeficient pretoka za posamezna vplivna področja, medsebojno spremenljivost osnovnih časovnih karakteristik medletne spremenljivosti MAP in Q za vplivni območji Modrega in Belega Nila in sposobnost dobrega prilagajanja izpustov iz jezera Naser (jezero »Birkat Nasser« za Visokim Asuanskim jezom) glede na klimatsko spremenljivost. Glavni zaključki so: a) na vseh vplivnih področjih Nila kaže osnovna spremenljivost podobne lastnosti ne glede na relativno majhno medletno spremenljivost; b) obstaja prevladujoča 44 mesečna perioda za MAP in 9 ter 22 letni periodi za pretok v Asuanu; c) korelacijski koeficient med letnima Q in MAP je nizek na vplivnem področju Ekvatorijalnih jezer in močvirij Belega Nila in precej višji na vplivnem področju Modrega Nila; d) Beli Nil vključujoč reko Sobat, je prispeval v povprečju okrog 30 % pritoka v Naserjevo jezero (podatki za leta 1912–1995), toda prispevek se je spreminjal od 25 % v začetku dvajsetega stoletja do 40 % v začetku šestdesetih in vztrajno pada v zadnjih letih; e) upoštevajoč domnevo, da bo potreba po vodi v Egiptu ostala v sedanjih mejah tudi v bodoče, lahko s pomočjo modernih metod rokovanja izpustov iz Naserjevega jezera amortizirajo vpliv klimatskih nihanj brez večjih težav za egiptovsko vodno gospodarstvo; in f) celo povečanje porabe vode gorvodno od Egipta za 8 km^3 na leto ne more ogroziti porabe vode v Egiptu v sedanjem obsegu, v kolikor bi uporabili za rokovanje izpustov moderen optimizacijski pristop. Skozi celotno analizo je večkrat poudarjeno, da ne obstajajo homogeni podatkovni nizi za celotno vplivno področje in da je to vzrok napak, ter da je zelo malo verjetno, da bi se klimatsko nihanje iz začetka šestdesetih let ponovilo (en sam dogodek v nizu).

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1. Introduction

It is not length alone that distinguishes the Nile most conspicuously from all its great rivals. At 6,671 km from source to outfall, it is the longest river in the world, but this statistic should be related to several much more remarkable facts. In the first place, no other river traverses such a variety of landscapes, such a medley of cultures, such a spectrum of peoples as the Nile. And none has historically had such a profound material effect upon those who dwell along its banks, representing the difference between plenty and famine, between life and death, for multitudes since the beginning of time.

The Nile River takes its source from Lake Victoria in east central Africa. It flows generally north through Uganda, Sudan, and Egypt to the Mediterranean Sea for a distance of 5,584 km. From its remotest headstream, the Luvironza River in Burundi, the river is 6,671 km long, and its basin has an area of more than 2,590,000 km^2.

The source of the Nile is one of the upper branches of the Kagera River in Tanzania. The Kagera follows the boundary of Rwanda northward, turns along the boundary of Uganda, and drains into Lake Victoria. On leaving Lake Victoria at the site of the now-submerged Ripon Falls, the Nile rushes for 483 km between high rocky walls and over rapids and cataracts, first northwest and then west, until it enters Lake Albert. The section between these two lakes is called the Victoria Nile. The river leaves the northern end of Lake Albert as the Albert Nile, flows through northern Uganda, and at the Sudan border becomes the Bahr el Jebel. At its junction with the Bahr al-Ghazal, the river becomes the Bahr al-Abyad, or the White Nile. Various tributaries flow through the Bahr al-Ghazal district. At Khartoum the White Nile is joined by the Blue Nile or Bahr al-Azraq. These are so named because of the colour of the water. The Blue Nile, 1,529 km long, has its source in Lake Tana in the Ethiopian Highlands; it is known here as the Abbai. From here the Nile flows northeast; 322 km below Khartoum it is joined by the Atbara ('Atbarah) River. The black sediment brought down by this river settled in the Nile delta before the construction of the Aswan High Dam and made it very fertile. During its course from the confluence of the Atbara through the Nubian Desert, the river makes two deep bends. Below Khartoum navigation is rendered dangerous by cataracts,

Figure 1: When the desert approaches the river (photography Saša Roškar).
Slika 1: Ko se puščava približa reki (fotografija Saša Roškar).

Figure 2: Traditional Irrigation (photography Saša Roškar).
Slika 2: Tradicionalno namakanje (fotografija Saša Roškar).

the first occurring north of Khartoum and the sixth near Aswan. The Nile enters the Mediterranean Sea through a delta that separates into the Rosetta and Damietta distributaries.

The Nile Basin extends from 4° south to 31° north and includes ten different countries: Burundi, Egypt, Eritrea, Ethiopia, Kenya, Rwanda, Sudan, Tanzania, Uganda, and the Democratic Republic of Congo. Not only does the Nile provide fresh water to millions, but within its basin there are five major lakes with a surface area totaling more than 1,000 km^2 (Victoria, Edward, Albert, Kyoga, and Tana), vast areas of permanent wetlands and seasonal flooding (the Sudd, Bahr al-Ghazal, and Machar marshes), five major reservoir dams (Aswan High Dam, Roseires, Khashm El Girba, Sennar, and Jebel Aulia), and three hydroelectric power dams (Tis Isat, Finchaa, and Owen Falls). The course of the Nile flows from highland regions with abundant moisture to lowland plains with semi-arid to arid conditions. The entire Nile Basin consists of eight major sub-basins with very different physical, hydrologic, and climatic characteristics.

Egypt is the most downstream country and basically depends on the Nile River for its water. The climate is arid and annual rainfall does not exceed a maximum of 200 mm on the northern coast. Egypt's agriculture is possible only with irrigation. On its course through Egypt, the Nile River is entirely regulated by the Aswan High Dam (HAD), completed in 1970, which confines the HAD reservoir with a water level of almost 180 meters and a capacity of 170 billion m^3. The average Nile flow entering Egypt at Aswan during the period from 1900 to 1990 is estimated to be 84 km^3 per year. This figure is based on the 1959 Nile Waters Agreement between Egypt and Sudan, which allocates 55.5 km^3 to Egypt, 18.5 km^3 to Sudan and 10 km^3 to losses (mainly evaporation) annually. Although there were many doubts about the dam's benefits expressed publicly at the start of construction, building the HAD has brought immense socioeconomic benefits to Egypt. Since the completion of the HAD, Egypt has advanced enormously in efficient water use and crop intensity has increased by more than 200%.

Egypt and Sudan, however, are the only signatories to the Nile Waters Agreement while the other riparian countries remain outside the treaty and do not necessarily feel obliged to either recognize or abide by its provisions.

In the past, water resources have been adequate to meet existing and emerging demands from the various economic sectors of the Nile Basin countries. This is no longer the case since each Nile country is planning and expecting different benefits from the control and management of the Nile water resources. Water is a main strategic factor in many facets of the complex economic and social situation in the Nile Basin.

The potential water shortage situation predicted for Egypt is bound to be mirrored in Sudan since countries traditionally dependent on rain-fed agriculture for their food supply such as Ethiopia, Kenya, and Tanzania will need a substantial amount of water in order to meet the food requirements of their growing populations. In the extreme hypothetical scenario in which each country of the Nile Basin – regardless of downstream rights and other considerations – were to use all the existing water in its territory for the irrigation of arable soil in its territory, no water at all would reach the HAD reservoir. A large potential for conflicts over water use is therefore evident, which is why achieving an integrated regional development of water resources on a sustainable basis is a critical condition for the socioeconomic development of the Nile countries. To date, efforts to promote a water agreement between all Nile Basin countries have failed to materialize due to several factors. One of the most pronounced is the lack of a clear basin-wide water resources development strategy due to the absence of a reliable tool for accurately evaluating different Nile water development options and projects. Such a tool is of crucial importance since it would enable the countries of the Nile region to evaluate different water development scenarios with a high degree of confidence and thus help find generally acceptable solutions.

A technology with such potential began to be developed in Egypt in April 1991 at the Planning Sector of the Ministry of Public Works and Water Resources within the implementation of the *Monitoring, Forecasting, and Simulation of the Nile River-Egypt* project (MFS). The MFS project is expected to strive against the odds to strengthen technical and scientific relations with upstream Nile countries as well as links with relevant regional and/or national projects in this field. It is also attempting to reinforce, or prepare for reinforcing, regional cooperation in the fields of hydrometeorology, agriculture, remote sensing, hydrological analysis and forecasting, and water resources development.

The main goal of this study is to assess the water potentials in the Nile Basin using all the historical and recent data that is collected and organized in the Nile Basin Hydrometeorological Information System (NBHIS) of the Nile Forecast Center, the main achievement of the MFS project. The basic tools for data management developed during the MFS project's implementation are also used. The author has attempted to clarify some other issues and tried to find the answers for common questions using the available data and tools: what is the behaviour of the rainfall and runoff time series and what relationship or interdependence can be found between runoff and rainfall on the main sub-catchments; how the river responded to the climatic variation of the rainfall regime in the past and what can be expected in the near future; can the Aswan High Dam protect Egypt from any eventualities caused by climate variations.

2. Data sources

All data used in this paper was obtained from the Nile Basin Hydrometeorological Information System established at the Nile Forecast Center during the implementation of the MFS project.

2.1. Rainfall data

A wide variety of historical rainfall observations was assembled in the NBHIS. So far, the database includes mostly monthly rainfall figures for the time period before the implementation of the MFS project along with daily measurements collected during the implementation of the MFS project since June 1992. The station file that contains stations' identification data includes 282 daily and 577 monthly rainfall stations (see Ref. 5.). There is monthly precipitation data available for the period from January 1940 to

December 1995 and daily precipitation data for the years 1970, 1971, 1972, 1973, and 1985 and for the period from June 1, 1992, until the present.

Precipitation data is stored in time series and gridded formats. An age-old hydrological problem is how to convert point values into aerial values. Gridded or areal precipitation data is created using climate statistics and observed precipitation time series data (see Ref. 2, 3, 4). To cover as long a time period as possible, monthly data was chosen as the main precipitation data source. Based on monthly gridded rainfall data, the monthly areal precipitation for the period from January 1940 until December 1995 was computed for the following profiles: Jinja (outflow from Lake Victoria), Mongalla (White Nile), Helit Dolieb (Sobat River), Malakal (White Nile), Diem (Blue Nile), Khartoum (Blue Nile), Atbara Kilo 3 (Atbara River), and Dongola (Aswan High Dam inflow).

2.2. Hydrological data

Observed river or lake stages were assembled for about forty stations over the whole Nile Basin area. Using the most accurate rating curves available, the stages were transformed to discharges or streamflow. All the data is stored in the NBHIS. There are daily data available covering time period from 1945 to the present with varying lengths of data records for particular stations (see Ref. 1). In addition to daily data, ten-daily and monthly data is available for much longer time periods than daily, since the main profiles data in the NBHIS is available starting from 1912 with the exception of Aswan where data is available from 1871. In order to analyze streamflow behavior for particular profiles for as long a record length as possible and due to the fact that only monthly rainfall data is available for a longer time period, monthly data was chosen as the basic data source in this paper. The following main profiles were considered:

- **Aswan**, the final outlet of the entire Nile Basin outside Egyptian borders;
- **Atbara Kilo 3**, the outlet of the Atbara river immediately upstream of its junction with the Main Nile;
- **Diem**, the hydrological measuring station on the Sudanese-Ethiopian border indicating the inflow of the Blue Nile from the Ethiopian Highlands to the Sudanese plains;
- **Khartoum on the Blue Nile**, the final outlet of the Blue Nile immediately upstream its junction with the White Nile;
- **Malakal**, the hydrological station on the White Nile indicating the contribution of White Nile, the Sobat River, and the Bahr al-Ghazel basin;
- **Helit Dolieb** on the Sobat River upstream of Malakal, indicating the contribution of the Sobat River;
- **Mongalla**, the station indicating the outflow of the White Nile from the Equatorial Lakes area before the White Nile enters into vast areas of swamps and marshes;
- **Jinja**, the outlet of the Victoria Lake basin.

It should be pointed out that the NBHIS at the NFC does not provide sufficient data for the time being to address and discuss issues such as:

- the role of the dynamic process of evapotranspiration versus multi-year storage in the Equatorial Lakes and White Nile marshlands (i. e., is the water lost or is it in storage?);
- the estimation of open channel losses to evaporation in the multitude of Nile River channels through semi-arid and arid areas;
- the groundwater recharge regions throughout the White and Blue Nile; and
- the influence of soil structure and land use on runoff production.

The analysis of these issues is essential to obtain a comprehensive hydrological picture and water balance along the Nile River. We therefore based our conclusions in this paper only on the surface runoff data, its spatial and time relationships, and the relationship between rainfall and runoff.

3. Survey of the eight major sub-basins

Eight major sub-basins within the Nile Basin were identified and selected on the basis of watershed drainage divides, sub-basin characteristics, and the location of river gauging sites. All the calculations here are based on data stored in the NBHIS and the tools available in the MFS system are used. Therefore, since the basic resolution of the gridded data in the MFS is a METEOSAT pixel (5 km × 5 km in the sub-satellite point), we used it as the basic measure in our calculations. An area of 25 km² is used as the area for all pixels in our calculations, although due to the curvature of the earth, the pixel area grows slightly with the distance from the sub-satellite point. Thus we introduced an error in the calculation of the total area for particular sub-catchments, but the error can be ignored if we compare it to the errors of the available data in space and time. All the calculations are generally performed on the data time series for the 1940–1995 time period if not otherwise specified.

TABLE 1: THE MAIN CHARACTERISTICS OF THE SUB-BASINS.
PREGLEDNICA 1: GLAVNE ZNAČILNOSTI PODPOVODIJ.

Sub-BasinName	Outlet	No. of Pixels (km^2)	Area (mm/Year)	Avg. Rainfall (km^3/Year)	Total Rainfall (km^3/Year)	Avg. Runoff	Runoff/Rainfall Ratio (%)
1. Lake Victoria	Jinja	9546	238650	1295	309.05	30.97	10.02
2. Equatorial Lakes	Mongalla	7784	194600	1198	233.13	6.54	2.81
3. Sudd Area	Malakal	5577	139425	923	128.69	Loss of flow	
4. Bahr al-Ghazal	Lake No	13215	330375	970	320.46	0.5	0.16
5. Sobat River	Helit Dolieb	7451	186275	1057	196.89	13.66	6.94
6. Ethiopian Highlands	Diem	5676	141900	1346	191.00	47.44	24.84
7. Blue Nile in Sudan	Khartoum	4847	121175	573	69.43	2.00	2.88
8. Central Sudan	Khartoum	Semi-arid	Loss of 4.5 km^3				
9. Atbara River	Atbara Kilo3	6675	166875	553	92.28	10.93	11.84%
10. Entire Nile Catchment	Dongola	61100	1527500	1010	1542.78	84.71	5.49%

3.1. Lake Victoria

The Lake Victoria sub-basin is the area covering the lake surface itself and the catchment areas of all its tributaries. The outlet hydrological station is at Jinja. The lake's surface area is about 67,000 km² and occupies a large proportion of the entire sub-basin, which has 9,546 METEOSAT pixels. The corresponding total area (the number of METEOSAT pixels multiplied by 25) is about 238,650 km². The average annual precipitation is high with a bimodal seasonal distribution with peaks in March–May and November–December. It amounts to 1,295 mm and is slightly higher over the lake surface than over the adjacent land area. It varies considerably across the sub-basin from 688 mm in the southeastern part of the basin to more than 2,550 mm over the northwestern part of the lake. Figure 3 shows the spatial distribution of Yearly Average Areal Precipitation over the sub-basin.

Runoff is very much a function of the catchment climate, soil, land-use/land-cover, and topographic characteristics of the watershed and of the channel network. The yearly mean accumulated observed flow at Jinja is 30.97 km³, which is equivalent to 130 mm of average runoff over the whole catchment. Thus, the runoff/rainfall ratio is 0.10 or, in other words, only 10% of the total rainfall over the sub-basin is observed at the Jinja outlet. This relatively low runoff/rainfall ratio, compared to Europe and North America, is caused by the high evaporation rate from the lake's surface and by the moisture losses in a bimodal precipitation regime. Since the lake area does not differ considerably with the lake stage, it could be assumed that the hydrological cycle over the Lake Victoria Basin is without considerable anthropological impact.

However, we should point out that the outflow from Lake Victoria is controlled and therefore the yearly discharge or release at Jinja does not reflect the natural rainfall/runoff process in a particular year. The lake itself possesses huge storage. A difference of one meter in the lake level represents the volume generated by more than two years of average outflow. The data in the period since 1913 frequently shows a difference of close to half a meter between the lake level at the beginning and the end of the year. The above-mentioned runoff/rainfall ratio is therefore very approximate. A detailed study of the dynamics and hydrology of Lake Victoria is needed to get a more accurate estimate.

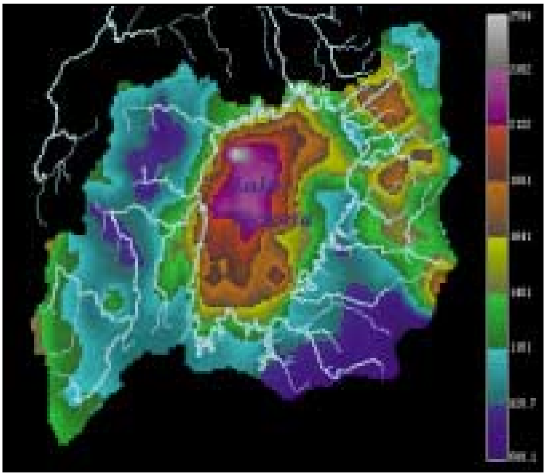

Figure 3: Average Annual Precipitation over the Lake Victoria watershed.
Slika 3: Povprečne letne padavine v prispevnem področju jezera Victoria.

3.2. Equatorial Lakes

From the outflow of Lake Victoria at the Owen Falls dam, the White Nile flows into Lake Kyoga, then into Lake Albert and northwards into southern Sudan. The Pakwach hydrological station would be the best outlet gauge to estimate the gain in runoff over this sub-basin, but there is not enough data for this station. Moreover, due to the lack of accurate measurements, it is not possible to determine the net runoff gains and losses in the Kyoga and Albert lakes with any certainty. Generally, it was observed that dry season flows at the Mongalla gauge downstream reflect the upstream lake levels, and wet season flows are affected by runoff from the torrential tributaries.

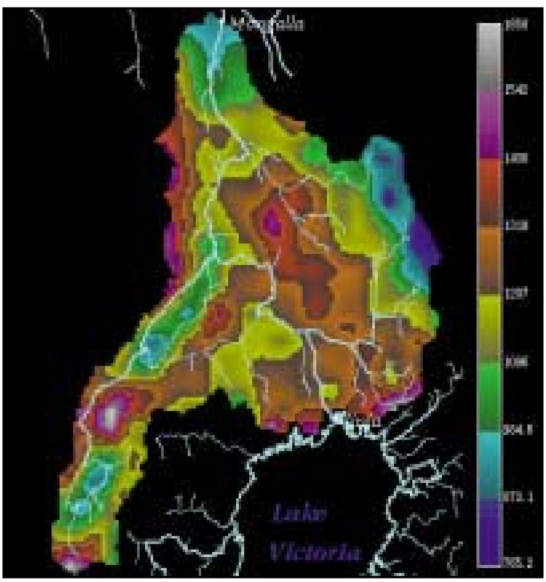

Figure 4: Average Annual Precipitation over the watershed upstream of Mongalla and downstream of Jinja.
Slika 4: Povprečne letne padavine v prispevnem področju med Mongallo in Jinjo.

For these reasons we chose the Mongalla gauge to estimate the gain in runoff over the Equatorial Lakes sub-basin. Figure 4 shows the average annual precipitation over the catchment on the stretch from Jinja to Mongalla. There is a good time series of data available for this station until 1981. Data since 1981 does not exist due to the civil war. In order to extend the data to 1995, we extrapolated it using the linear regression between Jinja and Mongalla in the years when the data exists for both stations. The catchment presented in Figure 4 has 7,784 METEOSAT pixels, which corresponds to an area of about 194,600 km^2. The average annual precipitation over the area is 1,198 mm, and the average yearly flow at Mongalla amounts to 37.51 km^3.

The net runoff gain between Mongalla and Jinja is therefore 6.54 km^3, which could be considered as the contribution of this particular sub-basin to the White Nile. The runoff/rainfall ratio is only 0.029, which is considerably lower than that of the Lake Victoria sub-basin. There are many reasons for this relatively low rainfall/runoff ratio: large areas of open water (lakes, marshes, etc.) with high evaporation as well as intensive vegetation with high evapotranspiration and groundwater losses.

3.3. Sudd

To the north from Mongalla, the White Nile is known as the Bahr el Jebel and flows into a vast complex of channels, lakes, and swamps in an enclosed basin. The entire area is very flat. From Mongalla to Malakal, the slope of the land averages only 10 cm/km. Figure 5 presents the average annual precipitation over this sub-basin.

The area counts 5,577 METEOSAT pixels, which corresponds to an area of about 139,425 km^2. The average annual precipitation over the area is 923 mm with a peak of over 1,470 mm in the southern part of the basin. Rainfall intensity decreases to the north where the annual average does not exceed 760 mm. Precipitation falls mostly in one season from April to October. This coincides roughly with the river flood period when the area is permanently flooded. Swamps expand in proportion to the magnitude of the inflow from the Mongalla and from local precipitation.

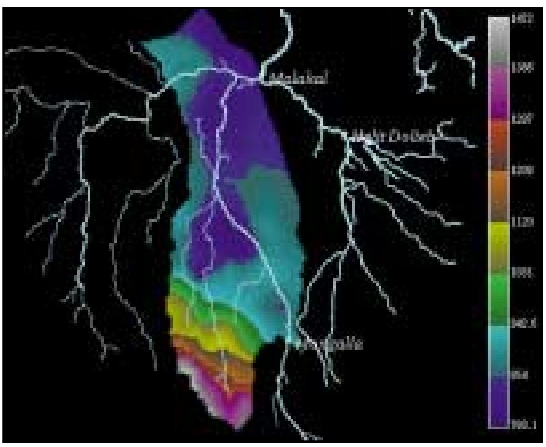

Figure 5: Average Annual Precipitation over the watershed upstream of Malakal and downstream of Mongalla.
Slika 5: Povprečne letne padavine v prispevnem področju med Malakalom in Mongallo.

A comparison of the historical inflow data at Mongalla (37.51 km^3) and outflow data at Malakal (30.47 km^3) shows a negative balance of 7.04 km^3. Taking into account that the Sobat River contributes on average 13.66 km^3 of water yearly to the flow at Malakal, one can easily conclude that more than 20 km^3 of water is diverted, mostly by evaporation, evapotranspiration, and groundwater losses, not taking into account the local precipitation over this sub-basin.

3.4. Bahr al-Ghazal

This sub-basin consists of a number of tributaries that run from the border of the Congo Basin to the Nile. Figure 6 presents the average annual precipitation over the area. This vast area counts 13,215 METEOSAT pixels, which corresponds to an area of about 330,375 km^2. The peak of rainfall intensity in the south-western part produces over 1,550 mm of average annual rainfall, which decreases toward the northeast where the annual precipitation does not exceed 500 mm. The average annual precipitation over the entire area is 970 mm.

It is practically impossible to get an estimate of flows over this section with any certainty due to the lack of data. The catchment is divided into many tributaries with bank overflow and flooding. In this large area of very low slope, nearly all the basin runoff and precipitation evaporates, so only about 0.5 km^3 (outflow from Lake No) leaves the basin annually.

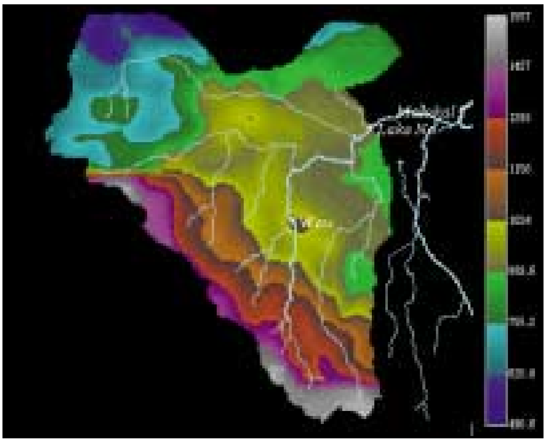

Figure 6: Average Annual Precipitation over the Bahr al-Ghazal watershed upstream of Lake No.
Slika 6: Povprečne letne padavine v prispevnem področju Bahr al-Ghazal gorvodno od jezera No.

3.5. Sobat

The Sobat River includes the discharge from two tributaries: the Baro River from the Ethiopian Highlands and the Pibor River from southern Sudan and northern Uganda. Figure 7 presents the average annual precipitation over this sub-basin.

This sub-basin is 7,451 METEOSAT pixels large, which corresponds to 186,275 km^2. The rainfall regime tends to unimodal with a rainfall season from April to October. The highest rainfall intensity is over the Baro basin in the east of the sub-basin where the average annual precipitation almost reaches 2,000 mm. The lowest intensity is over the southeast over a tributary of the Pibor River with an annual precipitation only slightly over 300 mm. The average annual precipitation over the entire sub-basin amounts to 1,057 mm.

Shortly upstream of the junction of the Baro and Pibor rivers, the Helit Dolieb profile reflects the flow of Sobat River. The Baro is the larger of the two and is highly torrential and seasonal. The Pibor is less seasonal. Many of the tributaries of the Sobat tend to overflow and form swamps when they reach the flat plains of Sudan from the Ethiopian Highlands. The area of flooding and spillage into seasonal and permanent swamps is large and includes the Marchar Marshes. There are only estimates of losses within the basin. Horst (1950) put the losses at 30% of the Baro and 14% of the Pibor.

There is data for Helit Dolieb in the NBHIS only up to 1983. We therefore used the data from the 1940–1983 period. The average annual flow amounts to 13.66 km^3, and the runoff/rainfall ratio is 0.069.

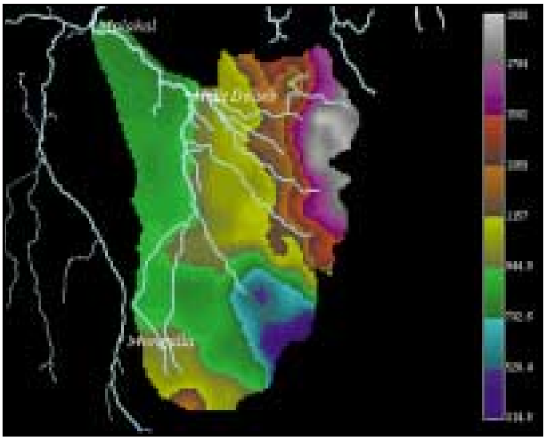

Figure 7: Average Annual Precipitation over the watershed of Sobat River upstream of Malakal.
Slika 7: Povprečne letne padavine v prispevnem področju reke Sobat gorvodno od Malakala.

3.6. Ethiopian Highlands

The source of the Blue Nile is the Little Abbay River in the Ethiopian Highlands. The Little Abbay flows into Lake Tana, which discharges into the Blue Nile and runs 900 km down through the highlands into Sudan. Figure 8 presents the average annual precipitation over the Blue Nile Basin in Ethiopia.

The area contains 5,676 METEOSAT pixels, which corresponds to an area of about 141,900 km^2. The average annual precipitation over the sub-basin is 1,346 mm, making it the highest among all the sub-basins of the Nile. The lowest rainfall is recorded over the eastern part of the sub-basin where the average annual precipitation does not exceed 800 mm. The highest values are over the southern part of the catchment (Didesa tributary) with the values exceeding 1,900 mm.

The average annual discharge at the Sudanese-Ethiopian border (Roseires until 1965 and Diem afterward) is 47.44 km^3. Therefore, the runoff/rainfall ratio over this basin is 0.248, which is the highest among all the sub-basins.

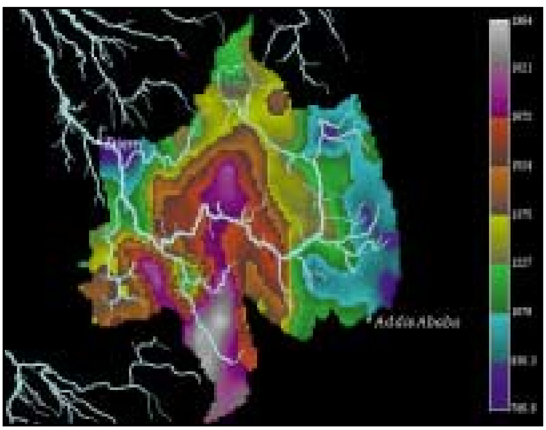

Figure 8: Average Annual Precipitation over the watershed of the Blue Nile upstream of Diem.
Slika 8: Povprečne letne padavine v prispevnem področju Plavega Nila gorvodno od Diema.

3.7. Blue Nile in Sudan

From the Sudanese-Ethiopian border the Blue Nile flows north from humid to semi-arid conditions, and there is usually little additional runoff north of Roseires. The exceptions are the two tributaries, the Dinder and the Rahad. They join the main flow downstream of Roseires and have their headwaters in the Ethiopian Highlands. Figure 9 shows the average annual precipitation over this stretch.

The sub-basin contains 4,847 METEOSAT pixels, which is equivalent to 121,175 km^2. The relatively high values (1,300 mm) of the average annual precipitation around the Sudanese-Ethiopian border decrease rapidly downstream. Around Khartoum the average annual precipitation is below 180 mm. The average annual precipitation over this sub-basin is 573 mm.

Since the end of the 1950's, this area has become intensively irrigated, and it is therefore difficult to estimate the gain of river flow over this stretch. The data for the 1912–1960 time period shows that the gain of flow is almost lost by evaporation.

3.8. Central Sudan

On the stretch from Malakal to Khartoum, the White Nile flows into increasingly semi-arid conditions. There are no permanent tributaries and it is only in years of very heavy precipitation that there is any addition of importance to the river flow. There are only losses. On average, there is a loss to evaporation of about 2 km^3 of the total discharge as measured at Malakal. The Jebel Aulia dam built forty kilometers upstream of Khartoum in 1937 to store water for later use in Egypt has added approximately a further 2.5 km^3 to the evaporation losses along this stretch.

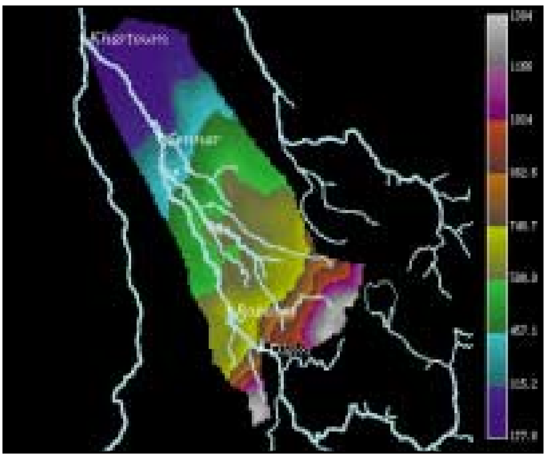

Figure 9: Average Annual Precipitation over the watershed of the Blue Nile in Sudan upstream of Khartoum and downstream of Diem.
Slika 9: Povprečne letne padavine v prispevnem področju Plavega Nila v Sudanu gorvodno od Khartouma in dolvodno od Diema.

3.9. Atbara

The Atbara River is the most northern tributary to join the Nile. Its headwaters originate in the northwestern Ethiopian Highlands. The nature of the river is extremely torrential. The majority of the river discharge is derived upstream of the Khashm El Girba reservoir. Downstream, the conditions change to semi-arid and then arid. Figure 10 presents the average annual precipitation over this sub-basin.

The entire Atbara sub-basin is quite large. It counts 6,675 METEOSAT pixels, which corresponds to 166,875 km^2. The average annual precipitation over the area is 553 mm, the lowest among the Nile sub-basins. The relatively high value of more than 1,300 mm of annual rainfall over the Ethiopian Highlands decreases to less than 90 mm downstream at the junction of the Atbara River with the Main Nile.

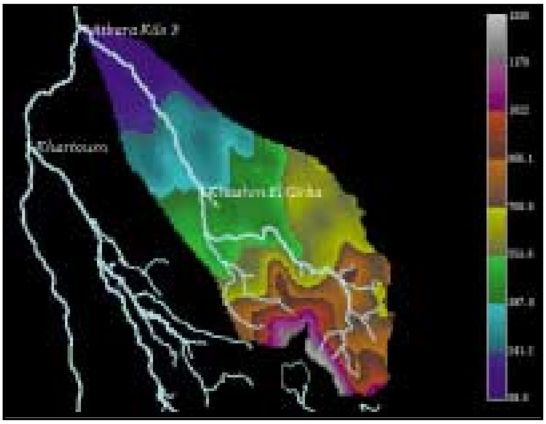

Figure 10: Average Annual Precipitation over the watershed of the Atbara River upstream of its junction with the Nile.
Slika 10: Povprečne letne padavine v prispevnem področju reke Atbara gorvodno od sotočja z Nilom.

The NBHIS contains monthly discharge data for the Atbara Kilo 3 profile, which observes the flow before the junction with the Main Nile, from 1912 to the present. However, data analyses show that the accuracy of measurements deteriorated during the 1980's and 1990's. We therefore took the data for the 1940–1982 period into account. The average annual flow during this time period was 10.93 km^3; thus the runoff/rainfall ratio was 0.118.

3.10. Entire Nile Catchment

As we already mentioned, we took into account only those areas where the rainfall contributes to the runoff and Nile flow. Thus, the entire Nile Basin area in our case is simply the sum of all the sub-basins presented above. The areas in the so-called »Nile countries« whose runoff is diverted to other river basins and arid areas in Sudan and Egypt where there is no rain at all are not counted. This way, the entire Nile Basin amounts to 61,100 METEOSAT pixels, which corresponds to 1,527,500 km^2. This figure is lower than those

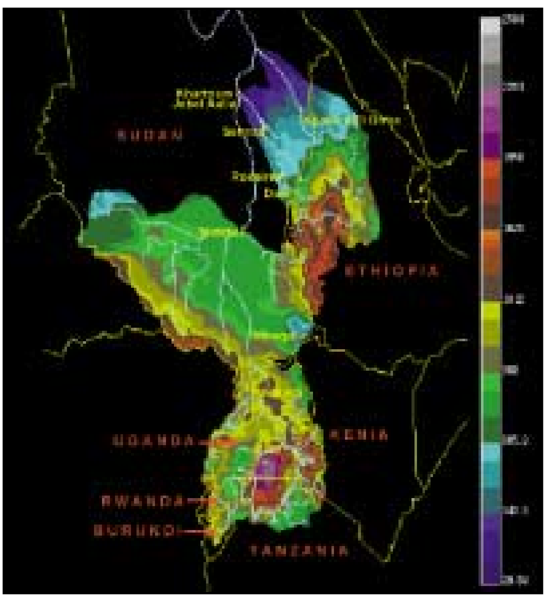

Figure 11: Average Annual Precipitation over the entire Nile watershed.
Slika 11: Povprečne letne padavine v celotnem prispevnem področju Nila.

usually found in references to the Nile Basin area. Figure 11 presents the spatial distribution of the average annual rainfall over the entire basin, which averages spatially to 1,010 mm.

The best station to estimate the runoff/rainfall ratio over the Nile catchment as defined above would be the one immediately downstream of the junction of the Atbara River with the Main Nile. Unfortunately, data from such a station does not exist. We therefore chose the inflow at Aswan as an estimate of the yield for the entire Nile catchment. This is the station with the longest historical records. In the NBHIS, monthly data is available from 1871 for the gauge located at Aswan. From the construction of the Old Aswan Dam (completion of Phase I in 1902) to the completion of the Aswan High Dam, the gauge at Wadi Halfa served as a station monitoring inflow at Aswan and the gauge at Dongola was used as a measuring station afterward. To analyze the behaviour of the inflow at Aswan for the entire time period, data from all tree gauges was combined into a single time series. Since the second half of the 1050's onward, there has been considerable usage of water for irrigation in Sudan. Therefore, the so-called »naturalized« flow is taken into account for this time period.

Calculated this way, the average annual inflow at Aswan during the 1940–1995 time period was 84.71 km^3; thus, the runoff/rainfall ratio was 0.055. In other words, only approximately 6% of the total estimated rainfall over the Nile Basin is observed at the Aswan site.

4. Rainfall/Runoff time analysis

In the previous chapter we based our discussion on the data from the 1940–1995 time period. Moreover, to show the behaviour of the various sub-basins, we based our presentation on the average annual values of rainfall and flow. However, the flow in a particular year is usually far from average values. The Nile is generally known as a river with very high inter-annual variability. Although one may detect high frequency variability in any record independent of length, it is more reliable to identify falling and rising trends if we consider records consisting of long time series.

4.1. Rainfall

Let us consider first the behaviour of the Mean Areal Rainfall (MAP). Figure 12 shows the yearly data for the 1940–1995 time period for some chosen profiles. Generally, the MAP over the Blue Nile (Khartoum on the Blue Nile and Diem) triggers the MAP over the entire Nile catchment, here presented as Dongola. It is an interesting discovery that there is a very similar trend comparing the Blue Nile basin and the Equatorial plateau: a higher MAP over Jinja corresponds to a higher MAP over the Blue Nile and vice versa. Certainly, there are some exceptions, for example, the years 1945, 1946, 1951, 1971–1978, and 1992–1995.

Figure 12 does not directly show any periodic behaviour of the MAP. We used monthly MAP data over the entire basin (upstream of Dongola) to see if there is any periodicity or at least if we could find some periodic tendency.

Fourier analysis was applied in order to find the periodic behaviour. It is a mathematical tool that decomposes a time series of data into a sum of waveform elements. Each decomposed element has its own wavelength, which corresponds to a certain frequency. The waveform elements are usually denominated as wave numbers $k_0 \dots k_n$, where k_0 represents the waveform element with the longest wave cycle in the data series and the k_n the shortest. Because the number of input data for the Fourier transformation should be a power of 2, we chose the latest 512 months of data. Thus, the data in the May 1953–December 1995 period was used.

Figure 13 shows the result. The green line on the graph presents twelve months' moving averages or yearly averages. The highest magnitude of power (69,642) is for the cycle of 44 months and the second highest (2,402) is for the cycle of 86 months. Thus, the highest magnitude is considerably higher than the white

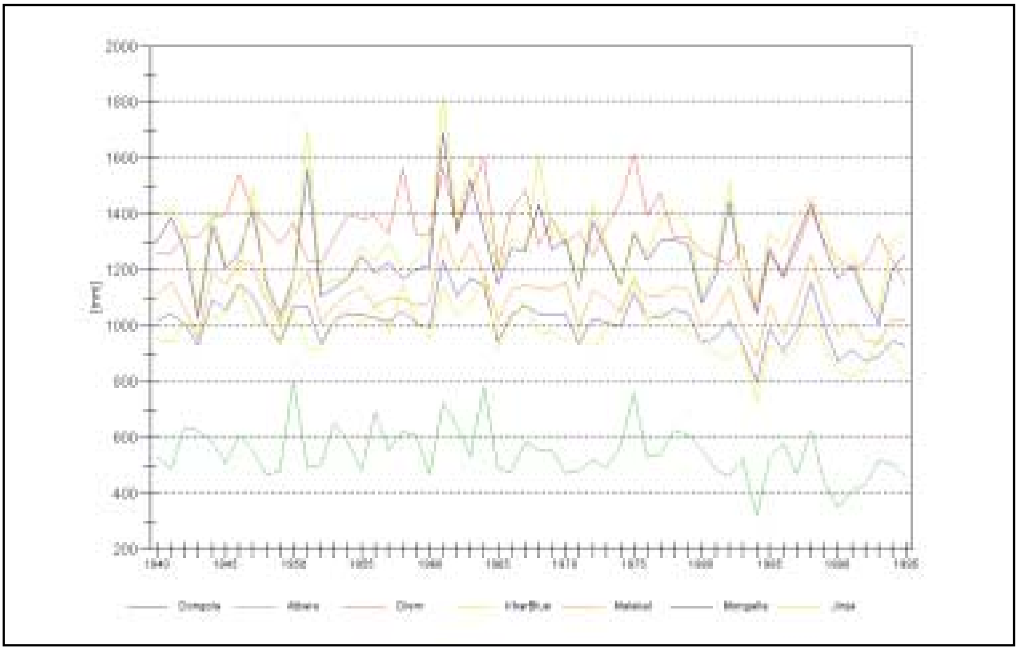

Figure 12: Comparison of the yearly MAP at chosen Nile profiles.
Slika 12: Primerjava povprečnih letnih ploskovnih padavin za izbrane točke vzdolž Nila.

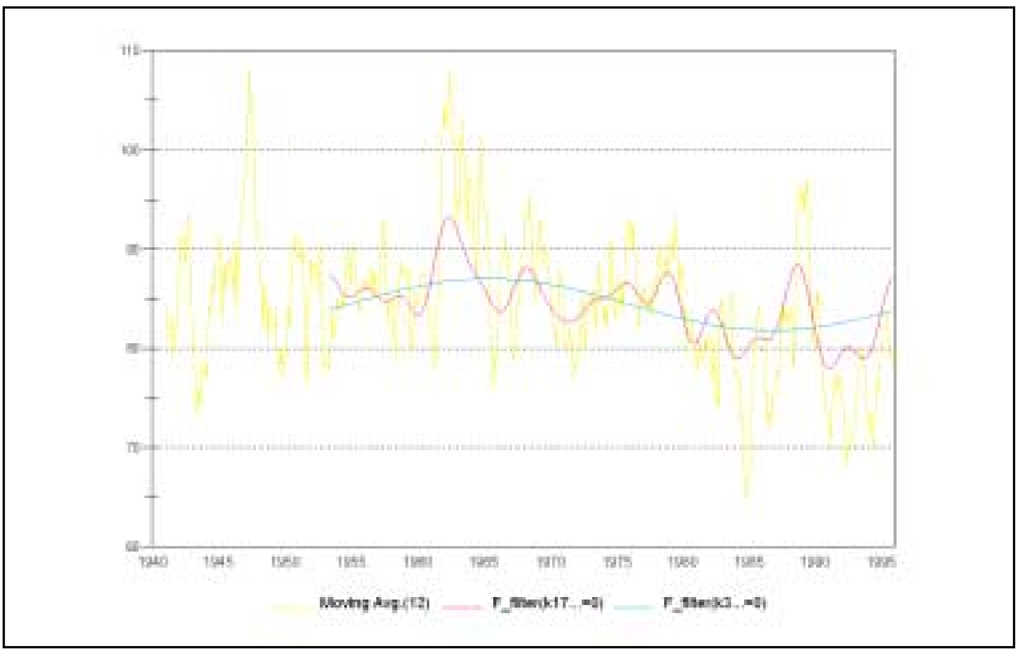

Figure 13: Monthly MAP [mm] over the entire Nile upstream of Dongola, 1940–1995 period.
Slika 13: Povprečne mesečne ploskovne padavine [mm] za celotno prispevno področje Nila gorvodno od Dongole v obdobju 1940–1995.

noise, and there is a clear cycle of 44 months (3.67 year), the first higher harmonic of 86 months (7.17 year), and so forth. The red line on the graph presents the inverse transformation where all the frequencies corresponding to k > 16 are filtered out. Roughly, we filtered out all the waves with wavelengths shorter than 34 months. To get only the basic sine wave, we filtered out all the waves corresponding to k > 2, that is, waves shorter than 256 months. The thick blue line presents this wave. It is worth mentioning that 256 months correspond to 21.33 years, which is twice the estimated average sunspot cycle period. Moreover, the 3.67-year dominant cycle is well within the estimated range of the cycles of the ENSO phenomenon (3–7 years). Based on the above, we can conclude that there exists a periodicity of the MAP over Dongola with a basic cycle of 44 months and at least few higher harmonics. The result matches the high flood years during the first half of the 1960's and the drought during the 1980's. A wave with a longer period may exist, but unfortunately we do not have a long enough time series of data to see it.

Figure 12 shows the yearly MAP for some profiles but does not clearly present the time relationship among various profiles, i. e., basins. To see the difference between the Equatorial and Ethiopian basins as the most important contributors to the Nile waters, that is, between the time behaviour of the MAP over the Victoria Lake basin and the MAP over the Blue Nile upstream of Diem, we plotted the following two trends for the Dongola (green lines), Jinja (blue lines), and Diem (red lines) hydrological stations on Figure 14:

- the inverse Fourier transformation–trend, where all the frequencies corresponding to k > 16 are filtered out (thin lines);
- the inverse Fourier transformation, the basic sine wave (thick lines).

One can see that the basic waves for Jinja and Diem are very similar, although the one for Diem has a higher amplitude (and thus a higher variability). This generally means that if there is a low MAP in subsequent years upstream of Jinja, there is a relatively low MAP upstream of Diem as well in the same time period. However, if we look at the waves with higher wave numbers, we can find time periods with the opposite behaviour, i. e., the low MAP upstream of Jinja and the high MAP upstream of Diem (second half of the 1950's, mid 1970's, and first half of the 1990's).

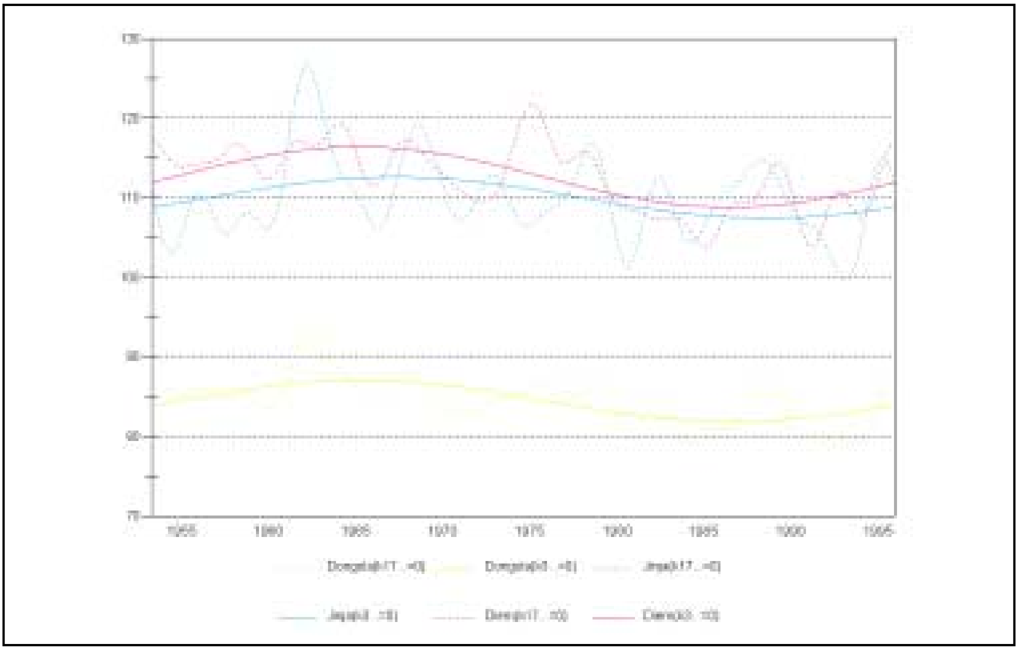

Figure 14: Comparison of monthly MAP trends [mm], May 1953–December 1995 time period.
Slika 14: Primerjava trendov povprečnih mesečnih ploskovnih padavin v obdobju maj 1953–december 1995.

The curves for Dongola show that the basic trend follows those of Diem and Jinja. The thin curve shows that there is a considerable attenuation of the amplitude compared to Diem and Jinja, and that the MAP over the entire basin should be triggered by the same natural global phenomenon, perhaps the Indian monsoon as result of global circulation, particularly in the Equatorial belt.

4.2. Runoff

It is well known that runoff is a function of rainfall, potential evapotranspiration, soils, land-use/land-cover, the topological and geometrical characteristics of the channel network, and the topographical characteristics of a watershed. Based on the availability of data in the NBHIS, we illustrate the properties of the runoff over the Nile catchment using time series of various record lengths. Thus, for the comparison of runoff on the main Nile profiles, the time series for the 1912–1995 time period is used; for the analysis of periodicity at Aswan, the series for the 1871–1998 period is used; and for the comparison of runoff and rainfall, the 1940–1995 period is used.

To show the behaviour of the yearly runoff and to compare it over the entire Nile Basin, the following outlets of the main sub-basins were chosen:

- Mongalla for the Equatorial Lakes sub-basin,
- Helit Dolieb for the Sobat River sub-basin,
- Malakal for the contribution of the White Nile, Sobat River, and Bahr al-Ghazal,
- Diem for the Ethiopian Highlands sub-basin;
- Khartoum on the Blue Nile for the contribution of the Blue Nile,
- Atbara Kilo 3 for the Atbara sub-basin, and
- Aswan for the yield of the entire Nile.

Certainly, to compare the data on the above outlets we would like to show data for a time period as long as possible, and the 1912–1995 time period was chosen. Because the amount of time series data available in the NBHIS is not the same for all the above-mentioned stations, we extrapolated the missing data as follows:

a) Mongalla: Extrapolation for the 1983–1995 period using the linear regression relationship based on data from 1912–1982 time period between Mongalla and Jinja (coefficient of correlation, R = 0.98);
b) Helit Dolieb: Extrapolation for the 1983–1995 period using linear regression relationship based on data from the 1912–1982 time period between Helit Dolieb and Malakal (R = 0.66);
c) Atbara Kilo 3: Analysis revealed that the data for this profile is very inaccurate since 1983. Therefore, the extrapolation was performed for the 1983–1995 time period using a linear regression relationship based on data from the 1912–1982 time period between Atbara Kilo 3 and Diem (R = 0.74).

In order to compare the flow among various profiles along the course of the Nile, anthropological influences should be excluded. We cannot exclude the influence of Lake Victoria's multi-year storage and the fact that the releases at Jinja from Lake Victoria are fully controlled. Downstream from Jinja, only Sudan has developed a water control structure for considerable water usage. The impact of the water usage in Sudan should be taken into account at Khartoum and Aswan. We therefore used the so-called »naturalized« flow data for Aswan and corrected the data for the Khartoum station on the Blue Nile in the 1956–1995 time period using linear regression relationship based on data from the 1912–1955 time period (R = 0.95). The data, extrapolated and corrected as described above, is presented in Figure 15, which presents ten years moving averages for the above-mentioned profiles, plotted so that the values for each year present the average during the preceding ten years. For instance, the values for 1930 are the averages over the 1921–1930 time period.

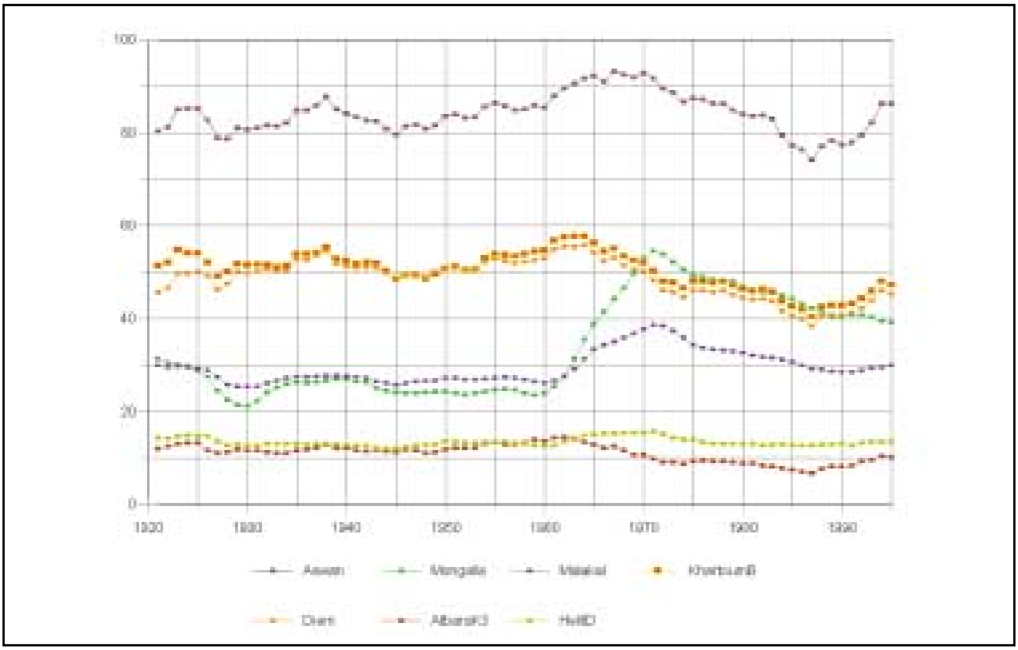

Figure 15: Comparison of yearly discharge at selected Nile stations [km^3].
Slika 15: Primerjava letnega pretoka na izbranih postajah vdolž Nila [km^3].

On the graph, one can easily distinguish three groups of curves: the two curves representing the Atbara Kilo 3 (Atbara sub-basin) and Helit Dolieb (Sobat sub-basin) stations, the two curves representing Mongalla and Malakal (White Nile), and the two curves representing Diem and Khartoum (Blue Nile). Certainly, the curve representing Aswan is somehow a composite of the others. Although the Blue Nile sub-basin and the Equatorial Lakes sub-basin are geographically quite far apart and without common tributaries, it is obvious that there is a common general trend for both. The relatively uniform flow since the beginning of the century increased at the beginning of the 1960's for few years and afterward abated. We already observed the same behaviour when considering the MAP. The peak at the beginning of the 1960's is highest at Mongalla, attenuated by the vast open waters in Sudd, but is still very clear at Malakal. However, there was a peak at Khartoum on the Blue Nile as well.

The question now is how long the falling trend that began in the mid-1960's will continue and is the rising trend since the end of the 1980's an indication of an opposite trend? We tried to answer these questions with a Fourier analysis of the yearly inflow data for Aswan using a 128-year time period (1871–1998). Before looking at the results of this analysis, consider first the yearly naturalized data for Aswan. Presented in Figure 16, it is quite informative. In addition to the yearly data, we plotted the ten-year moving average, the average over the entire 128-year period (yellow line: 86.81 km^3), thirty-year averages for the 1871–1900, 1901–1930, 1931–1960, and 1961–1998 periods (red line: 100.61 km^3, 82.92 km^3, 84.38 km^3, and 87.09 km^3 respectively), and the 1901–1998 average (violet line: 84.99 km^3). With the exception of the extremely high flow during the last thirty years of the 19th century, the thirty-year averages for this century show a fairly uniform long-term trend. Certainly, the yearly fluctuations are considerable. The Nile River is known as a river with extremely high variability, but there is still a discussion about the accuracy of data measured during the previous century. The huge decline in the 30-year average for the 1901–1930 period compared to that of the 1871–1900 period is really hard to justify. Do the rising trend during the last ten years of the 20th century and the highest flow of the century recorded in 1998 validate the values measured in the 1871–1900 time period?

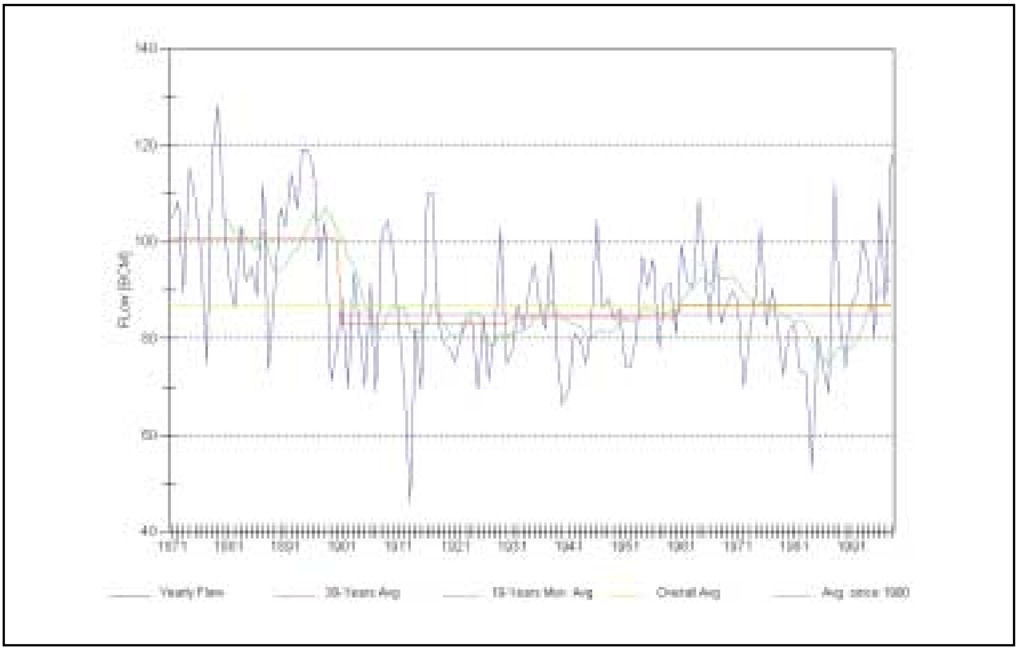

Figure 16: Yearly naturalized discharge at Aswan [km^3], 1871–1998 time period.
Slika 16: Letni naturaliziran pretok v Asuanu [km^3] v obdobju 1981–1998.

Figure 17: Yearly inflow at Aswan [km^3], 1871–1998 time period.
Slika 17: Letni pretok v Asuanu [km^3] v obdobju 1871–1998.

The answer to these questions is of crucial importance for water managers in all the riparian countries and particularly in Egypt, which lies at the very end of the Nile's course. With the construction of the Aswan High Dam as a multi-year storage, Egypt can manage the short-term year-to-year variability of Nile's flow. But what if the long-term trend is changing as well? The time analyses mentioned above illustrate the issue, and Figure 17 shows the basic results. The green line on the graph presents the yearly inflow at Aswan. The red and blue curves have the same meaning as we described in the case of the MAP analysis (see Figure 13) with the difference that in this case we use yearly data. The blue line presents the basic sine wave for the period of 128 years. The sequence of extremely high flood years during last thirty years of the 19th century abated at the turn of century. The year 1913 was the lowest on record with only 46 km^3 of inflow. The sine wave reached the minimum around 1940 and afterward rose. The year 1998, the last on record, is the highest in the century, and the sine wave is about to reach another peak. The magnitude of power at $n = 9$ has a peak of 82,506 and a second one at $n = 20$ (65,654). The peaks of magnitude are consistently higher than other values although the level of white noise is relatively high. The runoff therefore has much weaker periodic behaviour with basic cycles of 9 and 20 years if we compare it to the periodicity of the MAP.

If the sine curve representing the long-term trend has reached its peak, it means that it can only abate in the near future. The sequence of relatively high flood years recorded since 1988 is most likely to be followed by a series of years with moderate or low floods. Hypothesizing that in future the periodic behaviour of the inflow at Aswan will remain the same as on Figure 17, we produced the projection of the future flow shown on Figure 18. Generally, the sine wave has a doubled period (256 years) and will reach the minimum around 2011. The red curve (a doubled period size as well of around 18 years) shows that the local peak in 1999 will be followed by a series of years with an abating flood trend. We would like to emphasize once again that this is <u>not</u> a prediction but rather a projection based on the assumption that the past trend will continue in the future. We know very well that this is not always the case in nature, but we do not have a long enough time series of data to determine the waves for longer periods. However, there is a high likelihood that the floods during the next ten years will be closer to those recorded in the 1980's and 1970's than in the 1990's.

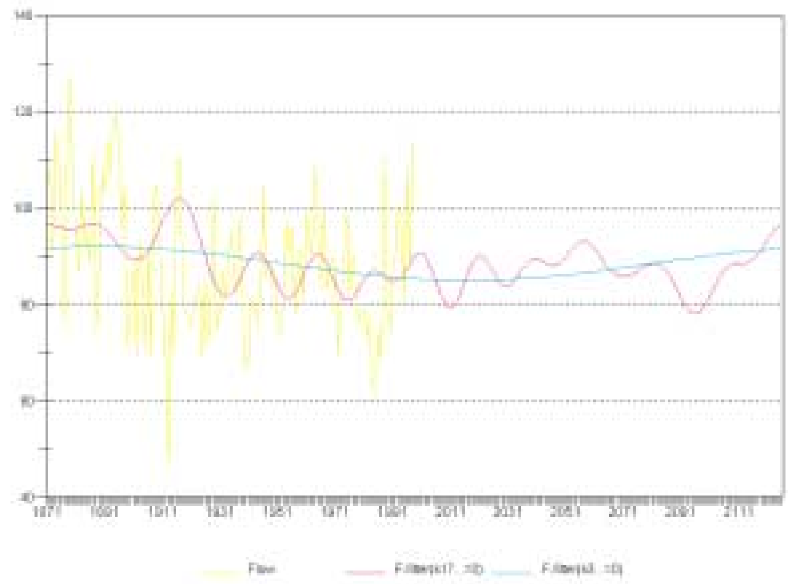

Figure 18: Projection of inflow at Aswan [km^3], 1871–2126 time period.
Slika 18: Projekcija pretoka v Asuanu [km^3] v obdobju 1871–2126.

IV.3. Rainfall/Runoff process

In the preceding two chapters we discussed Mean Areal Precipitation and Runoff primarily in terms of averages and long-term trends. To assess the water potential realistically, we have to analyze the year-to-year variability of the MAP and flow and address the relationship between MAP and flow, that is, the Rainfall/Runoff process. In this sense we have to analyze the MAP in a different way than we used in section IV.1. To analyze the Rainfall/Runoff process above a particular station, we must take the MAP over the entire area upstream of the station into account and the data for both MAP and flow for the same time period. We used the 1940–1995 time period, and the basic results are summarized in Table 2. As mentioned above, the releases from Lake Victoria at Jinja are 100% controlled and the lake itself is a huge water storage. Therefore, one may expect that the relationship between the yearly MAP and the total yearly releases at Jinja is very weak. The results are presented in the second row of the table. The correlation coefficient between yearly MAP and total yearly releases is 0.13, showing there is no relation between the two variables. A simple experiment was performed: we assumed that the lake has a constant area, i. e. constant evaporation losses, and to the total yearly releases we added the difference of lake storage to get the hypothetical runoff. It would be the natural discharge from the lake in the natural environment. The results are in the first row of the table. As expected, there is a high correlation of 0.83 between the yearly MAP and the hypothetical runoff. The relatively low coefficient of variability (STD/Mean) of the MAP (0.1242) compared to the coefficient of variability of the hypothetical runoff (0.6688) shows that a small difference in the MAP produces great differences in the hypothetical runoff and that there is a high variability of runoff in subsequent years. Certainly, the lake serves as a buffer and considerably attenuates the variability.

The results for the Mongalla profile downstream, which is considered an outlet from the Equatorial region, show a similar behaviour. Because the majority of the runoff is generated over the Lake Victoria basin and the outflow from the lake is 100% controlled, there is no linear relationship between the yearly MAP and the runoff at Mongalla. The coefficient of correlation is only 0.14, similar to the one at Jinja taking into account the total yearly releases. There is also no considerable change in the variability of the MAP and the runoff compared to Jinja. The scattergram on Figure 19 additionally illustrates the relationship between the MAP and the runoff at Mongalla.

TABLE 2: SUMMARIZED RAINFALL/RUNOFF FOR THE TIME PERIOD 1940–1995.
PREGLEDNICA 2: PREGLED PADAVIN/ODTOKA ZA OBDOBJE 1940–1995.

Hydrological Station	MAP (mm/Year)	Coeff. of Variation MAP	Total Runoff (km^3/Year)	Coeff. of Variation Runoff	Corr. Coeff. MAP/Runoff
1. Jinja (level diff.)	1295	0.1242	31.88	0.6688	0.83
2. Jinja (releases)	1295	0.1242	30.97	0.3207	0.13
3. Mongalla	1254	0.1061	37.51	0.3275	0.14
4. Malakal	1096	0.0823	30.48	0.1700	0.12
5. Diem	1346	0.0855	47.44	0.1790	0.72
6. Khartoum on the Blue Nile	984	0.0928	49.21	0.1738	0.73
7. Atbara Kilo 3	553	0.1760	10.93	0.3453	0.55
8. Aswan	1010	0.0809	84.71	0.1311	0.48

The data from the Malakal station presents the yield from four major sub-basins: Equatorial, Sudd, Sobat River, and Bahr al-Ghazal. The vast areas of open water with considerable evaporation losses in Sudd and Sobat River additionally attenuate the runoff. Thus, the correlation coefficient between the MAP and the runoff is the lowest among all the basins (0.12) and proves that there is no relationship between these two variables. The MAP declines considerably compared to Mongalla, as does the variability of the MAP and the runoff. The low correlation coefficient could be explained by the fact that the open water areas in the Sudd and Sobat River basins and Lake Victoria serve as multi-year storage. Our calculations are based on the yearly data.

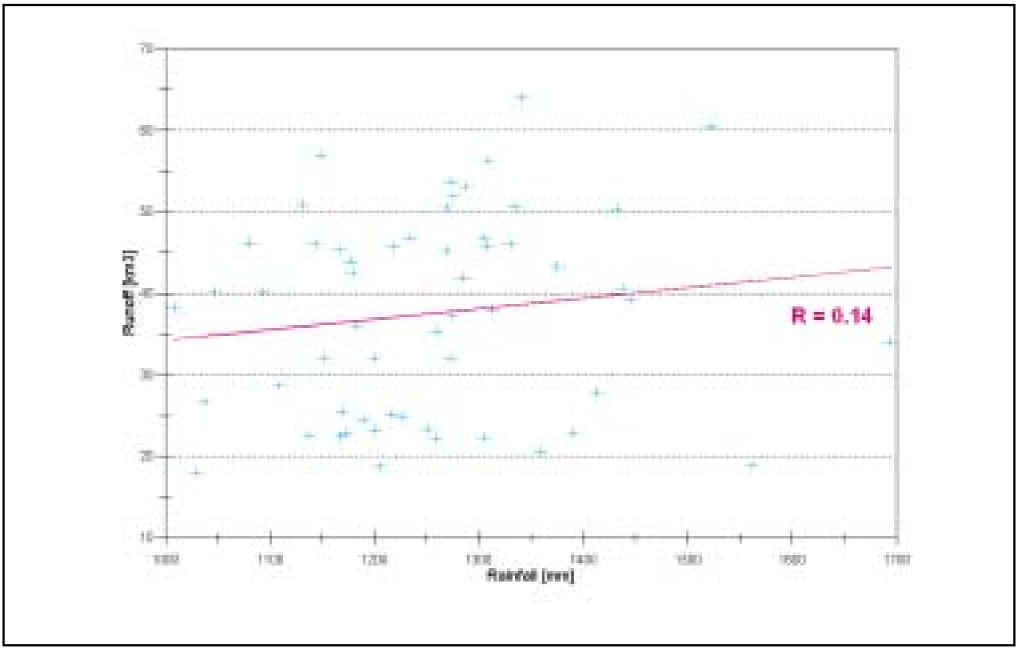

Figure 19: Rainfall/Runoff relationship at Mongalla station, 1940–1995 time period.
Slika 19: Odvisnost med padavinami in odtokom gorvodno od Mongalle v obdobju 1940–1995.

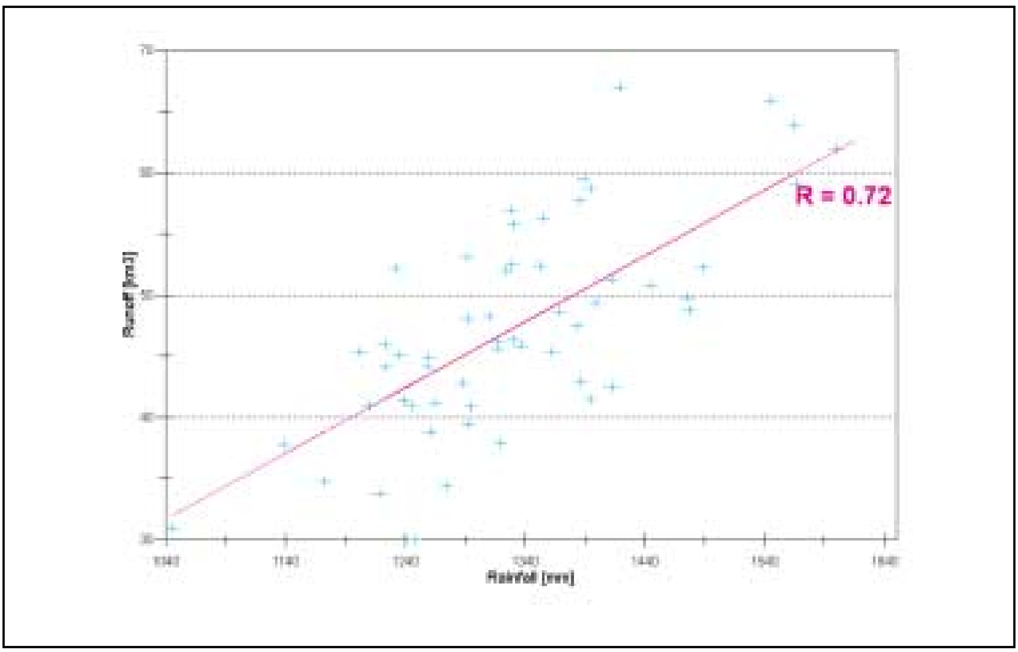

Figure 20: Rainfall/Runoff relationship at Diem station, 1940–1995 time period.
Slika 20: Odvisnost med padavinami in odtokom gorvodno od Diema v obdobju 1940–1995.

As expected, the correlation coefficient between the yearly MAP and the runoff at the Sudanese-Ethiopian border (Diem) is relatively high (0.72). Because the majority of precipitation over the Blue Nile Basin comes from convective clouds, the steep orography and high slopes give the Blue Nile a torrential behaviour; therefore, one would expect a high variability for MAP and runoff. There is high variability if we consider daily data, but in terms of yearly data, the variability is relatively low for both MAP and runoff, very close to that at the Malakal profile.

The scattergram for rainfall/runoff at Diem on Figure 20 shows a much stronger relationship between the MAP and the runoff compared to the one at Mongalla. The MAP over the Ethiopian Highlands is the highest in the entire Nile catchment. Surprisingly, the variation of MAP and runoff at Diem is very close to the results at Malakal. As said before, we expected a relatively small factor of variability at Malakal because the flow at Malakal is attenuated by large losses on one hand and by the impact of the vast open waters that serve as multi-year storage on the other. The result supports our finding that the MAP's over the White Nile basin and the Blue Nile basin have a somewhat similar behaviour (see section IV.1).

At the Khartoum station on the Blue Nile, which serves as the station for estimating the yield over the Blue Nile basin, we see that the variability of the MAP and the runoff is close to that at Diem. The same conclusion is valid for the correlation coefficient between the MAP and the runoff as well. Since downstream of the Ethiopian border the Blue Nile flows through semi-arid and arid areas, the MAP upstream of Khartoum decreases consistently compared to the MAP upstream of Diem.

Since the beginning of the 1950's, particularly with the construction of the dam at Roseires, Sudan has developed a considerable irrigation structure along the stretch from the Sudanese border to Khartoum. In order to get information about water use along this stretch, we plotted on Figure 21 the difference of measured discharges between Khartoum on the Blue Nile and Diem. The graph clearly shows the rising water use since 1955. Assuming that the gain in discharge along this reach is on average equal to evaporation losses, the graph clearly presents the tendency of higher water use, in terms of absolute values, in

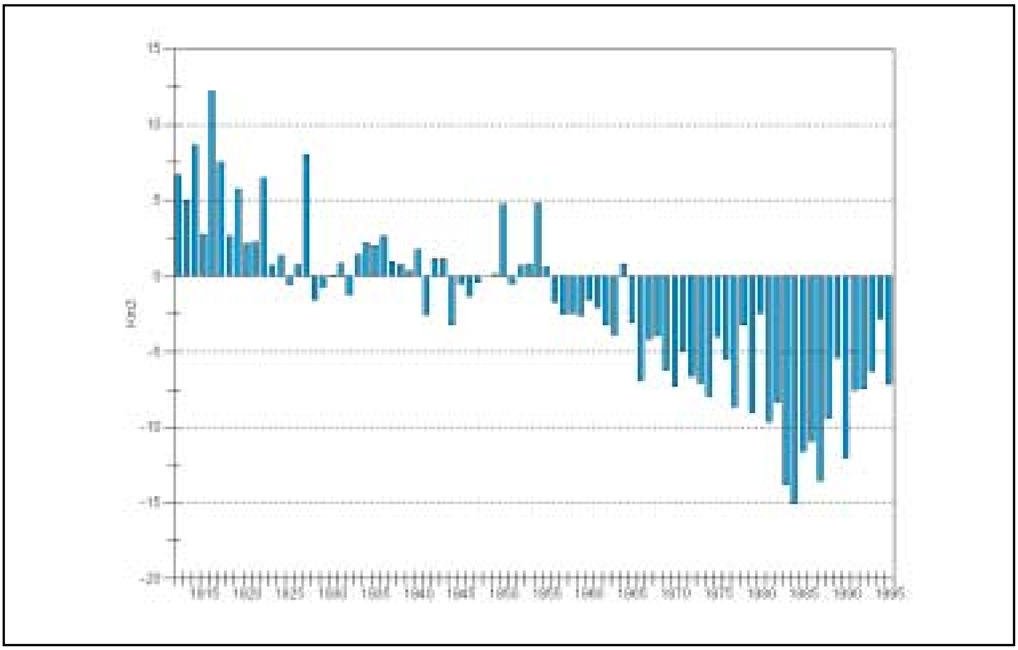

Figure 21: Difference in the yearly flow between Khartoum on the Blue Nile and Diem, 1912–1995 time period.
Slika 21: Razlika letnega pretoka med Khartoumom in Diemom v obdobju 1912–1995.

the dry years. For instance, the highest negative difference of 15.02 km^3 was recorded in 1984 when the second lowest inflow between 1912 and 1995 was recorded at Aswan. Certainly, these figures can only be taken as a rough approximation since there is simply not enough data available for the entire water usage and other losses that obviously considerably vary from year to year.

Atbara is the only tributary of the Nile on the stretch between Khartoum and Lake Nasser. Table 2 shows a fairly low MAP over the Atbara Kilo 3 sub-basin and a high yearly variability of the MAP and the runoff. The correlation between the MAP and the runoff shows a weak relationship between the two variables.

Finally, the last row in Table 2 gives the results for the entire Nile Basin. Certainly one could argue about the figure of 1,010 mm we estimated for the MAP. Let us note again that this figure displays the MAP over the basin as it is presented in Figure 21. Vast arid areas in Sudan and Egypt with an average annual precipitation less than 50 mm, which without any doubt belong to the Nile Basin, are not taken into consideration. The coefficient of variability for MAP and runoff show a fairly low likelihood that an extreme difference in the yearly flow could appear in subsequent years. Therefore, based on these results, there is a low probability that an extremely high flood year will be followed by an extremely low flood year. It is obvious that the relatively high inter-seasonal variability of the MAP and the runoff over the Equatorial region is attenuated by the huge storage of Lake Victoria and the vast open water areas in the Sudd and Sobat River basins. The relatively low coefficient of correlation between the MAP and the runoff shows a weak relationship between the two variables and indicates that the impact of controlled releases from Lake Victoria affects the inflow to Lake Nasser as well.

Considering the inflow to Lake Nasser and the fact that there are two main regions with a high MAP, the Equatorial basin and Ethiopian Highlands, a natural question arises: how much of the inflow to Lake Nasser is contributed by the White Nile and how much by the Blue Nile. To answer this question we did not take the official data for natural flow at Aswan. The routine procedure for calculating the natural flow at Aswan, as it is applied in Egypt, adds to the discharge in Dongola the constant evaporation losses due to the enlarged

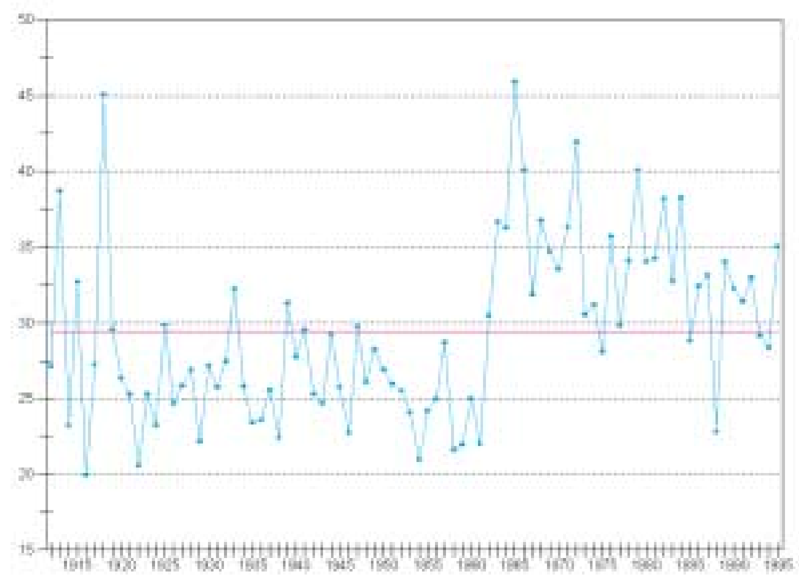

Figure 22: Percentage of the contribution of the White Nile to the Nile at Aswan, 1912–1995 time period.
Slika 22: Procent prispevka Belega Nila k pretoku Nila v Asuanu v obdobju 1912–1995.

water areas behind the dams in Sudan and the anticipated constant value of the water consumption in Sudan. As shown on Figure 21, there is a considerable yearly fluctuation of water usage only along the Blue Nile downstream from the Sudanese-Ethiopian border. Therefore, to get a more realistic estimate of the contribution of the White Nile to the inflow to Lake Nasser we made the following calculation: to estimate the total yield of the Nile, we summarized the accumulated yearly flow at Malakal as the contribution of the White Nile reduced by 4.5 km^3 (see scetion III.8), the naturalized flow at Khartoum on the Blue Nile (see section IV.2), and the flow at Atbara Kilo 3. In this way, the flow at the Malakal station includes the water yield of the Sobat River. The percentage of the contribution of the White Nile, including the Sobat River, against the total yield is presented in Figure 22.

The red line presents the average (29.4%) contribution of the White Nile in the 1912–1995 time period. The entire time period can be divided into three periods: the 1912–1920 period when the contribution of the White Nile fluctuated around the average, the 1921–1961 period when contribution was below average, and the period since 1962 with the contribution of the White Nile considerably above average. Following the sudden jump in the White Nile's flow at the beginning of the 1960's, there has been a clear falling trend of the contribution of the White Nile since 1966.

5. Aswan High Dam as over-year storage

After the completion of the Old Aswan Dam in 1902 many suggested its further heightening for flood protection in Egypt and for increased water storage that could be utilized by both Egypt and Sudan. In contrast, the idea was born to build a new dam upstream of Aswan that would serve as over-year storage, and its construction was finished in 1970. Although there were many controversial and opposing opinions about the impact of the dam on the environment, agriculture has flourished in Egypt since that time. The experience after 30 years is relatively positive, but there are still questions such as whether it is pos-

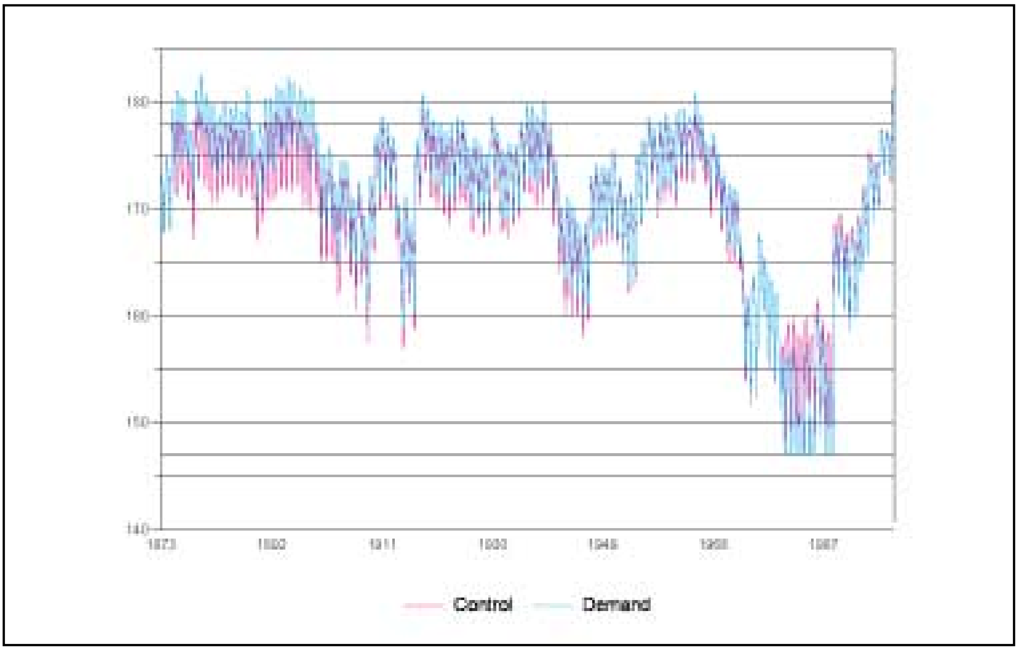

Figure 23: HAD levels simulated in Control and Demand mode for the 1872–1998 time period.
Slika 23: Višine vodne gladine asuanskega jezera simulirane v kontrolnem in zahtevnem modu za obdobje 1872–1998.

sible to manage the releases from the HAD in a way to avoid any harm to Egypt's water supply, assuming that the future inflow to Nasser Lake behind the dam will have similar fluctuation behaviour as in the past.

To answer this question we used the control-simulation model of the HAD developed during the implementation of the MFS project. The basic feature of the model is that it optimizes future releases in a time horizon, usually one year, under the condition that irrigation demand is always satisfied when the lake level is above the bottom level. The model: 1) minimizes surface evaporation, 2) minimizes spillage through the emergency spillway, which runs the water into the desert when the lake level approaches the top, and 3) delays the decreasing of releases when the lake level is close to bottom. The model can run on monthly or ten-daily time steps. We ran it on the ten-daily time step. For each 10-day period of the selected historical time horizon, the inflow forecasting model is activated first to generate multiple ensemble forecast traces for a lead-time of one year. As input we used the ten-daily natural flow at Aswan for the 1872–1998 time period. For the Sudanese abstractions we used a constant value of 16.6 km^3 per year. For irrigation demand in Egypt, a constant value of 55.6 km^3 per year was applied. Two runs were performed, one in control mode that optimizes the releases and the second in demand mode that forces the releases according to the irrigation demand. The spillage level was set to 178 m, while the bottom level was set to 147 m because we wanted to simulate the response of the lake to the current operational parameters. The maximum daily release was set to 260 km^3.

Figure 23 shows the simulated HAD levels for both runs. It shows clearly that using the optimization of releases in the sense we described above, almost all circumstances could be managed successfully. In the cases when the lake level is somewhere in the middle of the active lake area, the optimization approach would release slightly more water compared to the irrigation demand. This would reduce the evaporation from the lake surface and enable more power production. However, the use of the optimization approach would bring the biggest benefit when lake level runs close to the top or close to the bottom over a sequence of years. Spillage would be reduced to the minimum even in the event of a long series of consecutive high flood years such as occurred during the last thirty years of the 19^{th} century. Figure 24 illustrates this case.

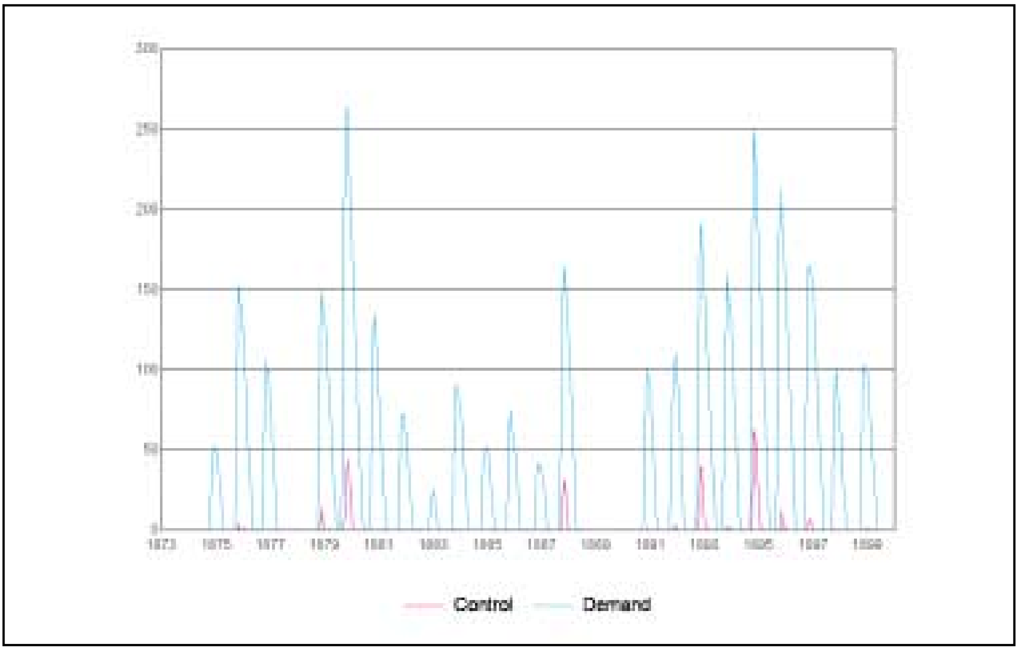

Figure 24: Spillage [millions m^3/day] simulated for the last thirty years of the 19^{th} century.
Slika 24: Preliv vode [milijon m^3/dan] simuliran za zadnjih trideset let 19. stoletja.

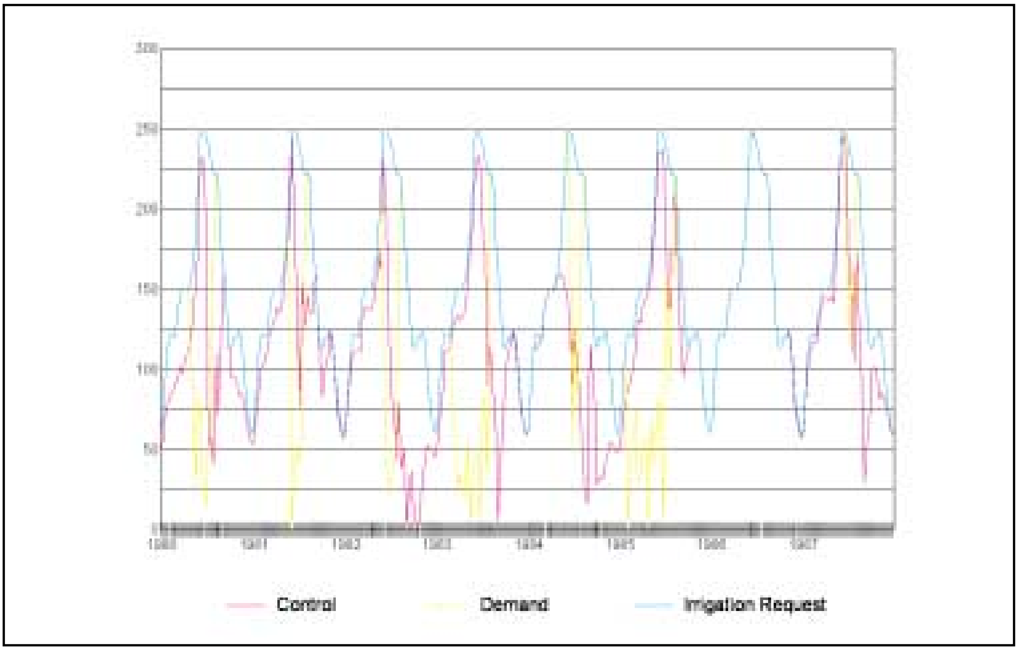

Figure 25: Releases [millions m^3/day] simulated for the 1980–1988 time period.
Slika 25: Izpusti vode [milijon m^3/dan] simulirani za obdobje 1980–1988.

On the other hand, the harm done by the series of low flood years in the 1980's is minimized. Figure 25 shows the releases for this case. The blue line represents the irrigation demand. The yellow line, which presents the simulation in demand mode, shows that releases could even reach zero if the level depleted to the bottom of the lake. In this case, only the inflow could be released. However, the optimization approach takes into account the one-year ensemble forecast of inflow to the lake and the fact that the most important harvest is over by the end of August. It therefore reduces releases below the irrigation demand toward the end of the year and saves water for the vegetation cycle the following year.

TABLE 3: SOME BASIC RESULTS OF BOTH RUNS.
PREGLEDNICA 3: OSNOVNI REZULTATI ZA OBA POSKUSA.

Mode	Annual avg. Inflow (km^3)	Annual avg. Outflow (km^3)	Annual avg. Spillage (km^3)	Annual avg. Deficit (km^3)	Spillage Freq.	Irrigation Deficit Freq.	Average Annual Evap. (km^3)
Control Mode	88.49	58.82	0.170	0.915	0.025	0.107	12.10
Demand Mode	88.49	54.72	3.640	0.785	0.164	0.016	12.64

As expected, the outflow is higher in the case of control mode because the model increases releases in order to avoid spillage. The corresponding spillage frequency is therefore lower than in the case of demand mode. Pertaining to the irrigation deficit, there is a higher irrigation deficit relative frequency in the control mode because it decreases releases earlier by a small value to avoid zero releases as happens in the case of irrigation demand mode. The model tends to spread the deficit over a longer time frame. Smaller deficits are applied over several time periods. In this way, the model avoids the harsh consequences of a total shortage.

The answer to the question set at the beginning of this section is positive: yes, it is possible to manage the HAD so that any potential harm to Egypt's water supply can be avoided. If we assume the similar distribution of inflow patterns in future as in the past, the above experiment confirms the following:

- In the event of high floods, releases could be increased in time to some extent, usually up to 260 km^3/day, in order to optimize power production and minimize the spillage over the emergency spillway;
- In the event of low floods, the total irrigation deficit could be spread over a longer time period and therefore minimize damage to crops.

The growing populations in all the Nile countries are causing a growth in water consumption as well. Therefore, the coordination of water management among the Nile countries is essential. Being at the end of the pipe, however, Egypt is the most vulnerable. Let us assume that in general Egypt cannot increase water consumption and that it must meet its growing water needs by improvement of the irrigation system and wise water management. Moreover, it is realistic to expect that increased water consumption in the countries upstream will decrease the inflow to the HAD. The question arises of how much the upstream water consumption can increase without doing harm to Egypt's current water supply.

To find the answer to this question, we ran a series of control-simulation models in control mode, each run with a slightly increased consumption upstream of Nasser Lake to find the amount by which the current agreed consumption in Sudan (18.5 km^3) could be increased without considerable harm to the Egyptian water supply. In each run we used the historical ten-daily natural flow at Aswan for the 1872–1998 time period. Our objective was related strictly to fulfilling the Egyptian water demand, and we therefore set the bottom level of the HAD at 142 m. Moreover, we assumed that the turbines would stop if the level dropped below 160 m. The tests show that with an upstream consumption of around 25 km^3, an approximately 50% increase over the current situation, the wise management of releases from the HAD could meet the current Egyptian demand. Figure 26 shows the simulated HAD levels get in this experiment.

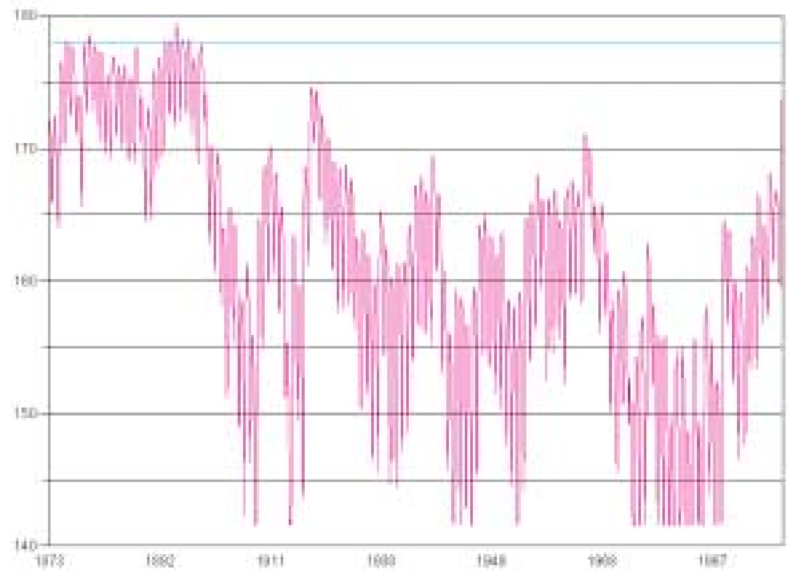

Figure 26: Simulated HAD levels.
Slika 26: Simulirane višine Asuanskega jezera.

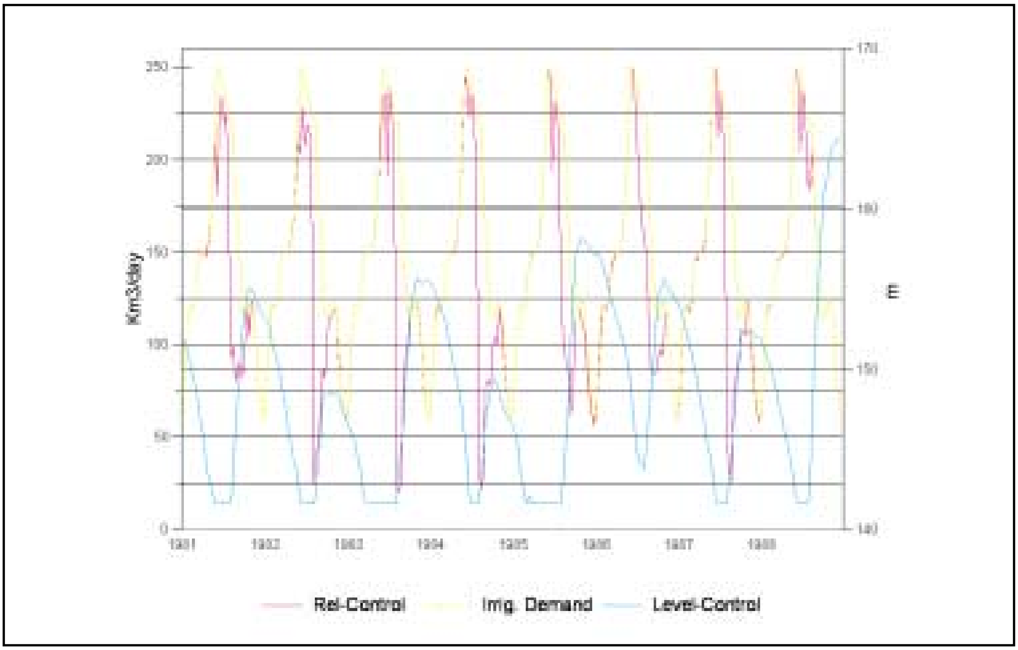

Figure 27: Simulated releases and corresponding lake levels.
Slika 27: Simulirani izpusti in njim ustrezni vodostaji jezera.

Figure 26 shows considerably lower lake levels compared to the simulated levels in the control mode on Figure 23. According to this experiment, the lake level would decrease to the bottom only in a few ten-daily periods over the entire time period of the simulation. The relatively small increase in the average irrigation deficit, only by about 1 km^3/year when average total inflow is lower by about 10%, is the consequence of smaller evaporation losses (9.00 km^3 against 12.6 km^3). The most sensitive period in the historical time period was the 1981–1987 period. The simulated releases in all other years are very close to the irrigation demand. To illustrate that Egypt could satisfy its irrigation demand even in this quite long period of low floods and with the increased upstream consumption, we plotted the for this time period on Figure 27. The yellow line on the graph represents the anticipated irrigation demand, the red line the simulated releases, and the blue line the simulated levels. The results clearly show that wise management of HAD releases using control-simulation models like one developed by the MFS project could assure the water supply in even the most critical situations.

6. Concluding remarks

6.1. Mean areal precipitation

In section IV.1. we showed that in general the MAP over the entire Nile Basin has a similar periodic behaviour, although there are quite large differences in MAP amplitudes among the Nile sub-basins. Table 1 shows some basic characteristics of the sub-basins as they were derived in this study. The yearly MAP varies from around 500 mm over the Atbara and Blue Nile in Sudan to more than 1,300 mm over the Ethiopian Highlands and Victoria Lake sub-basins. With the exception of the Atbara sub-basin, there is a relatively low inter-seasonal/yearly variation for the entire catchment. Since we considered huge areas, the low inter-seasonal variability does not mean that a particular smaller sub-basin could not suffer from drought while other sub-basins are over-flooded at the same time. Based on the monthly MAP data over Dongola, thus the entire Nile Basin, we found a periodic behaviour with a basic cycle of 44 months. The comparison of the basic sine waves for the MAP over the Jinja, Diem, and Dongola basins show a similar long-term periodic behaviour; thus, the rainfall over the entire Nile Basin is driven by a common global natural phenomenon.

6.2. Runoff

Considering the 1912–1995 time period, we found that there is a common runoff trend for each of the sub-basins. For instance, the 10-year moving averages of total yearly runoff for the Equatorial plateau and the Ethiopian Highlands as the main sources of flow have similar trends. The amplitudes are higher for the Equatorial plateau due to the higher variability of the MAP, and there is some delay in the runoff from the Equatorial plateau compared to the Ethiopian Highlands because the entire basin upstream of Malakal behaves like a multi-year storage.

The overall average of total yearly natural flow at Aswan in the 1871–1998 time period is 86.81 km^3 with a coefficient of variability (CV) of 0.13. The rather low CV could be misleading because the amplitudes of fluctuations are not uniformly distributed. The trend of the flow shows that the yield of high or low years tends to group during consecutive years. Thus, the average for the 1871–1900 time period is 100.61 km^3, and 82.92 km^3, 84.38 km^3, and 87.09 km^3 are the averages for the subsequent 30-year time periods. The frequency analysis shows a weak periodicity of the total yearly natural flow at Aswan with cycles of nine and twenty years.

The frequency analysis for the coming 128 years with the assumption that the natural flow at Aswan will have the same periodic behaviour in the future as in the past 128 indicates there is a high likelihood that the flow during the coming ten years may be closer to that of the 1970's and 1980's than that of the 1990's.

6.3. Rainfall/runoff process

The coefficient of variation (CV) for the yearly MAP abates from 0.12 for the basin above Jinja to 0.11 for the basin upstream of Mongalla and 0.08 for the basin upstream of Malakal. On the other hand, the CV of the total yearly runoff abates from 0.32 for the runoff at Jinja and Mongalla to 0.17 at Malakal. Generally, a relatively small variation in the MAP over Jinja produces a high variation of runoff. The coefficient of correlation between the yearly MAP and the total yearly runoff is 0.13 at Jinja, 0.14 at Mongalla, and 0.12 at Malakal. Therefore, there is no relationship between the yearly MAP and the total yearly runoff along the White Nile downstream of Jinja.

On the Sudanese-Ethiopian border at Diem and at Khartoum on the Blue Nile, we obtained the same CV of 0.09. The CV's for runoff are very close as well: 0.18 for Diem and 0.17 for Khartoum. The coefficients of correlation between the yearly MAP and the total yearly runoff are 0.72 for Diem and 0.73 for Khartoum. Thus, there is a considerable difference comparing the relationship between MAP and runoff over the Blue Nile against that over the White Nile. While there is no relationship between the two variables for the White Nile, there is a fairly significant relationship for the Blue Nile. This means that all the runoff driven by the rainfall occurring during a particular hydrological year over the Blue Nile Basin is reflected in the Khartoum profile during the same hydrological year, while the White Nile Basin, being a multi-year storage, spreads the runoff over several hydrological years.

In calculating the natural flow at Aswan, a constant figure is used for Sudanese abstractions or water usage in Sudan. The comparison of flow at Khartoum on the Blue Nile and Diem shows that there are considerable variations from year to year (see Figure 21). The differences can not be attributed to rainfall alone but are rather the consequence of various abstractions. The absolute deficit of flow at Khartoum compared to Diem tends to be lower during high flood years and higher in low flood years.

We found that the White Nile with the Sobat River contributed 29.4% on average to the total runoff of the Main Nile or to the Nasser Lake in the 1912–1995 time period (see Figure 22). Two distinct time periods were found: the first from 1912 to the beginning of the 1960's and the second afterward. During the first period the average contribution was lower, only about 25%. At the beginning of the 1960's, the White Nile contributed almost 40%; but the percentage has decreased steadily since that time.

6.4. Aswan High Dam as over-year storage

The experiment simulating the HAD parameters over the historical 1871–1998 time period, that is, over 128 years, using actual parameters (spillage crest, maximum release, water abstraction in Sudan, etc.) showed that it is possible to manage HAD releases to avoid any harm to Egypt's water supply if its irrigation demand remains within the current range (55.6 km^3/year) and if we assume that the inflow patterns in future will continue their past statistical and periodic behaviour. Certainly, the application of a control-simulation model will optimize the water management.

The experiment employing increased upstream water consumption shows that it is possible to secure the water supply for Egypt in the range of current irrigation demand if the upstream consumption in Sudan increases from the current 18.5 km^3/year to 25 km^3/year. Certainly, the wise management of HAD releases requires a control system for the HAD such as the one designed during the implementation of the MFS project that could spread the irrigation deficit over a longer time period to avoid the severe damage of a sudden total deficit.

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8. Summary in Slovene – Povzetek

Ocena vodnega potenciala reke Nil na osnovi razpoložljivih podatkov, zbranih v Prognostičnem centru za Nil v Kairu

Jožef Roškar

1. Uvod

Ni samo dolžina tista, ki loči Nil od vseh njegovih velikih tekmecev. S svojimi 6671 km od izvira do izliva je najdaljša reka na svetu. Vendar ta podatek lahko dopolnimo z nekaj še mnogo bolj izrednimi dejstvi. Prvo je, da nobena druga reka ne prečka tako raznovrstnih pokrajin, take mešanice kultur, takega spektra ljudstev kot Nil. In nobena reka ni skozi zgodovino imela tako velikega vpliva na tiste, ki živijo ob njenih bregovih, predstavljala razlike med obiljem in lakoto ter življenjem in smrtjo za množice že od začetka življenja.

Reka Nil izvira v Viktorijinem jezeru v vzhodni centralni Afriki. Večinoma teče proti severu: skozi Ugando, Sudan in Egipt v Sredozemsko morje, kar je razdalja 5584 km. Če pa ga merimo od njegovega najbolj oddaljenega pritoka, reke Luvironza v Burundiju, je dolg 6671 km. Vplivno področje obsega več kot 2.590.000 km^2.

Izvir Nila je eden gornjih pritokov reke Kagera v Tanzaniji. Kagera sledi meji Ruande na severu, zavije po meji z Ugando ter se izlije v Viktorijino jezero. Ko pri sedaj potopljenih Ripon Falls zapusti jezero, se Nil vije 483 km med visokimi skalnatimi bregovi ter preko brzic in slapov najprej proti severozahodu in nato proti zahodu, dokler se ne izlije v Albertovo jezero. Del reke med dvema jezeroma se imenuje Viktorijin Nil. Reka zapusti severni del Albertovega jezera kot Albertov Nil in teče nato skozi severno Ugando ter na meji s Sudanom postane Bahr al-Jabal. Na sotočju z Bahr al-Ghazal reka postane Bahr al-Abyad ali Beli Nil. Mnogo pritokov teče skozi področje Bahr al-Ghazala. Pri Kartumu se Belemu Nilu pridruži Modri Nil, Bahr al-Azraq. Oba sta dobila ime po barvi vode. Modri Nil, dolg 1529 km, izvira v jezeru Tana v Etiopskem višavju, kjer je poznan kot Abbai. Iz Kartuma teče Nil proti severovzhodu; 322 km pod mestom se mu pridruži reka Atabarah (Atbara). Preden je bil zgrajen Visoki Asuanski jez, so se črne usedline, ki jih prinaša ta reka, usedale v delti Nila, ki je bila zato zelo rodovitna. Med svojo potjo od sotočja z Atbaro skozi Nubijsko puščavo naredi reka dva globoka zavoja. Pod Kartumom je navigacija po reki nevarna zaradi slapov – prvi je severno od Kartuma, šesti pa blizu Asuana. Nil se izliva v Sredozemsko morje v obliki delte, ki jo tvorita rokava Rosetta in Damietta.

Povodje Nila sega od 4° južno do 31° severno in vključuje deset različnih držav: Burundi, Egipt, Eritrejo, Etiopijo, Kenijo, Ruando, Sudan, Tanzanijo, Ugando in Demokratično republiko Kongo. Ne le da Nil s tekočo vodo preskrbuje milijone, v njegovem povodju je tudi pet večjih jezer s površino več kot 1000 km^2 (Viktorijino, Edvardovo in Albertovo jezero, ter jezeri Kyoga in Tana), obsežne površine stalno močvirnatih tal in sezonskih poplav (Sudd, Bahr El Ghazal in Machar), pet večjih jezov za rezervoarje (Asuanski jez, Roseires, Khashm El Girba, Sennar in Jebel Aulia) ter trije jezovi za hidrocentrale (Tis Isat, Finchaa in Owen Falls). Nil teče iz više ležečih območij z obilico vlage v nižavja s polsuhim ali suhim podnebjem. Celotno prispevno področje Nila je razdeljeno na osem večjih podpodročij z zelo različnimi fizikalnimi, hidrološkimi in podnebnimi značilnostmi.

Egipt je zadnja država ob spodnjem toku Nila in je praktično popolnoma odvisen od njegove vode. Podnebje je suho in letna količina padavin ne preseže maksimuma 200 mm ob severni Sredozemski obali. Kmetijstvo v Egiptu je mogoče samo s pomočjo namakanja. Na svoji poti skozi Egipt je Nil popolnoma reguliran z Visokim Asuanskim jezom, dokončanim leta 1970. Če se vodna gladina jezera za jezom približa

180 metrom, ima jezero prostornino okrog 170 km^3. Ocenjujejo, da je bil v obdobju od 1900 do 1990 povprečen pretok Nila ob njegovem vstopu v Egipt pri Asuanu 84 km^3 na leto. Ta številka temelji na sporazumu o Nilu iz leta 1959, sklenjenim med Egiptom in Sudanom, ki dodeljuje Egiptu 55,5 km^3, Sudanu 18,5 km^3 in izgubam 10 km^3 vode na leto. Čeprav je bilo na samem začetku gradnje Visokega Asuanskega jezu v javnosti mnogo nasprotujočih si mnenj o njegovi koristnosti, je njegova izgradnja prinesla Egiptu brezmejne socialno-ekonomske koristi. Odkar je bil jez dokončan, je Egipt zelo povečal učinkovitost porabe vode, medtem ko se je kmetijski pridelek povečal za več kot 200 %.

Vendar pa sta edina podpisnika sporazuma o Nilu Egipt in Sudan. Ostale gorvodne države se pogodbi niso pridružile in jim njenih odločb ni treba niti priznati niti po njih delovati. V preteklosti so vodne zaloge zadostovale za obstoječe in novo nastajajoče potrebe različnih sektorjev držav v povodju Nila. Danes ni več tako. Vsaka država ob Nilu načrtuje in pričakuje različne koristi od nadzora in upravljanja vodnih virov Nila. V mnogih točkah kompleksnega ekonomskega in socialnega razvoja v porečju Nila je voda poglaviten strateški faktor.

Možno pomanjkanje vode, napovedano za Egipt, se bo nedvomno zrcalilo tudi v Sudanu, medtem ko bodo države, kot so Etiopija, Kenija in Tanzanija, tradicionalno odvisne pri pridelavi hrane od kmetijstva, namočenega z dežjem, potrebovale precejšnjo količino vode, da bodo lahko zadostile prehrambenim potrebam rastočega števila prebivalstva. Če bi po skrajno hipotetičnem scenariju vsaka država ob Nilu, ne glede na pravice drugih v spodnjem toku in druge pomisleke, uporabila vso razpoložljivo vodo na svojem območju za namakanje primerne zemlje, ne bi v povprečju sploh nič vode doseglo rezervoarja Visokega Asuanskega jezu. Obstaja torej velika možnost meddržavnih sporov glede uporabe vode na tem območju. To je razlog, da je doseg izpopolnjenega regionalnega razvoja vodnih virov na trdni podlagi kritičen pogoj za skladen socialno ekonomski razvoj držav ob Nilu. Do danes je bil trud, da bi sklenili vodni sporazum o Nilu med vsemi državami ob reki, brezuspešen zaradi večih razlogov. Najbolj izrazit je pomanjkanje celovite razvojne strategije vodnih virov za celotno prispevno področje Nila ter odsotnost zanesljivega orodja za natančno ocenjevanje različnih možnosti in projektov za razvoj vodnega gospodarstva Nila. Tako orodje je bistvenega pomena, saj bi državam ob Nilu omogočilo oceniti različne scenarije razvoja vodnega gospodarstva z visoko stopnjo zaupanja in s tem pomagalo najti splošno sprejemljive rešitve.

Tehnologijo s takimi lastnostmi so začeli razvijati v Egiptu aprila 1991 v načrtovalnem sektorju Ministrstva za javna dela in vodne vire z izvajanjem projekta *Monitoring, Forecasting and Simulation* (MFS) reke Nil v Egiptu. Pričakujejo, da bo MFS, upirajoč se tradicionalnim klišejem, intenzivneje pospeševal tehnične in znanstvene povezave z državami ob zgornjem toku Nila, tako kot tudi povezave s pomembnimi regionalnimi in/ali državnimi projekti na tem področju. MFS poskuša tudi uvesti ali pa se pripravlja na vzpostavitev regionalnega sodelovanja na področjih hidrometeorologije, poljedelstva, hidroloških analiz in prognoz ter razvoja vodnih virov.

Namen tega priepevka je oceniti vodne potenciale v povodju Nila z uporabo vseh podatkov, zbranih v preteklosti in podatkov, zbranih v realnem času v času izvajanja MFS projekta. Podatki so organizirani v NBHIS (*Nile Basin Hydrometeorological Information System*) Prognostičnega centra za Nil. NBHIS predstavlja najpomembnejši dosežek projekta MFS od začetka njegovega obstoja. Seveda smo uporabili tudi osnovna orodja za upravljanje in rokovanje s podatki, ki so jih razvili med izvajanjem projekta MFS. Avtor je želel pojasniti tudi nekatere druge točke in poskušal najti odgovore na postavljena vprašanja z uporabo razpoložljivih podatkov in orodij. Pogosta vprašanja so: kako se obnašata časovni vrsti količin padavin in pretokov ter kakšno povezavo ali odvisnost lahko najdemo med količino padavin in pretoki na glavnih podpovodjih; kako se je v preteklosti reka odzivala na podnebne spremembe padavinskega režima in kaj lahko pričakujemo v bližnji prihodnosti; ali lahko Visoki Asuanski jez zaščiti Egipt pred nevšečnimi dogodki, ki bi jih povzročile spremembe podnebja.

2. Viri podatkov

Vsi podatki, uporabljeni v tem referatu, izvirajo iz NBHIS, ki so ga v Prognostičnem centru za Nil ustanovili med izvajanjem projekta MFS.

2.1. Podatki o padavinah

V NBHIS so zbrali veliko raznovrstnih opazovanj količine padavin za razna pretekla obdobja. Za sedaj baza podatkov vključuje večinoma mesečne količine padavin za časovno obdobje pred izvajanjem MFS projekta. Dnevne podatke so zbirali med izvajanjem projekta MFS od junija 1992 naprej in k temu dodali še nekaj let v sedemdesetih letih. Datoteka postaje, ki vsebuje identifikacijske podatke postaj, vključuje 282 dnevnih in 577 mesečnih postaj za količino padavin (glej Ref. 5).

Podatki o padavinah so shranjeni v časovnih serijah in ploskovnih formatih. Že leta star hidrološki problem je, kako pretvoriti točkovne vrednosti v ploskovne vrednosti. Ploskovne vrednosti padavin smo dobili z uporabo klimatološke statistike in podatkov časovnih serij opazovanih padavin (glej Ref. 2,3,4). Da bi pokrili čim daljše časovno obdobje, smo za glavni vir podatkov o padavinah izbrali mesečne podatke. Mesečna ploskovna polja padavin za obdobje od januarja 1940 do decembra 1995, ki temeljijo na dobljenih podatkih o količini padavin, so izračunana za sledeče vodomerske postaje: Jinja (izliv iz Viktorijinega jezera), Mongalla (Beli Nil), Helit Dolieb (reka Sobat), Malakal (Beli Nil), Diem (Modri Nil), Kartum (Modri Nil), Atbara Kilo 3 (reka Atbara) in Dongola (dotok v jezero izza Visokega Asuanskega jezu).

2.2. Hidrološki podatki

Zbrali so opazovane vodostaje rek in jezer za 40 postaj na celotnem področju Nila. Z uporabo kar se da natančnih umeritvenih krivulj smo vodostaje spremenili v pretoke. Vsi podatki so shranjeni v NBHIS. Za posamezne postaje so dostopni dnevni podatki, ki pokrivajo časovno obdobje od leta 1945 do danes z različno dolgimi zapisi podatkov za posamezne postaje (glej Ref. 1). Razen dnevnih podatkov so dostopni tudi desetdnevni in mesečni podatki za daljša časovna obdobja kot dnevni; v NBHIS so podatki glavnih postaj dostopni od leta 1912 dalje z izjemo Asuana, kjer se podatki začnejo z letom 1871. Da bi analizirali obnašanje rečnega toka na posameznih postajah za čim daljše časovno obdobje ter zaradi dejstva, da so za daljše časovno obdobje dostopni le mesečni podatki o količini padavin, smo kot osnovni vir podatkov v tem prispevku izbrali mesečne podatke. Obravnavali smo sledeče glavne postaje:

- **Asuan**, končna postaja, ki predstavlja celotno vplivno področje Nila izven meja Egipta;
- **Atbara Kilo 3**, zadnja postaja na reki Atbara kmalu pred sotočjem z glavnim Nilom;
- **Diem**, hidrološka merilna postaja na sudansko-etiopski meji, ki prikazuje pritok Modrega Nila iz Etiopskih višavij v Sudanske nižine;
- **Kartum na Modrem Nilu**, zadnja postaja na Modrem Nilu kmalu pred njegovim sotočjem z Belim Nilom;
- **Malakal**, hidrološka postaja na Belem Nilu, ki prikazuje prispevek Belega Nila, reke Sobat in povodja Bahr El Ghazel;
- **Helit Dolieb** na reki Sobat gorvodno od Malakala, ki prikazuje prispevek reke Sobat;
- **Mongalla**, postaja, ki prikazuje pretok Belega Nila s področja Ekvatorijalnih jezer, pred vstopom Belega Nila v razsežna območja močvirij in barij;
- **Jinja**, pretok iz prispevnega področja Viktorijinega jezera.

Treba je poudariti, da NBHIS v Prognostičnem centru za Nil zaenkrat še nima dovolj podatkov, da bi načeli ali obravnavali probleme kot na primer:

- vloga dinamičnih procesov evapotranspiracije pri večletni akumulaciji vode v Ekvatorijalnih jezerih in barjih Belega Nila (je voda izgubljena ali shranjena);
- ocena izgub v močvirjih in vodnih površinah Nila zaradi izhlapevanja v polsuhem in suhem podnebju;
- področja, kjer se polnijo podzemne vode Belega in Modrega Nila; in
- vpliv strukture tal in rabe zemljišč na nastanek odtoka.

Analiza zgoraj omenjenih problemov je bistvenega pomena za izčrpno razumevanje hidrološke slike in vodne bilance vzdolž Nila. Zato smo v tem prispevku zasnovali svoje zaključke le na podatkih površinskih pretokov, njihovih prostorskih ter časovnih odnosih in odnosih med količinami padavin in pretoki.

3. Pregled osmih večjih podpovodij

Osem večjih podpovodij v prispevnem področju Nila smo določili in izbrali na podlagi razvodnic, značilnosti podpovodij in lokacij merilnih postaj ob reki. Vsi izračuni v prispevku temeljijo na podatkih, shranjenih v NBHIS, uporabili pa smo orodja iz sistema MFS. Ker je v MFS osnovna enota ploskovnih podatkov METEOSAT piksel (5 km × 5 km v točki na površju pod satelitom), smo to ločljivost v naših izračunih uporabili kot osnovno mero. Površino 25 km^2 smo posplošili kot površino za vse piksle, čeprav se površina pikslov zaradi Zemljine ukrivljenosti rahlo veča z razdaljo od podsatelitske točke. Na ta način smo vnesli napako pri izračunu površine posameznih podpovodij, ki pa jo lahko zanemarimo, če jo primerjamo z drugimi napakami, ki jih imajo razpoložljivi podatki v prostoru in času. Vse izračune smo v glavnem izvedli na časovnih vrstah podatkov za časovno obdobje 1940–1995, razen če ni napisano drugače. Glavne značilnosti podpovodij so razvidne v preglednici 1.

3.1. Viktorijino jezero

Prispevno področje Viktorijinega jezera je območje, ki pokriva površino jezera sámo ter pripadajoča področja vseh njegovih pritokov. Hidrološka postaja, ki meri iztoke iz jezera, je pri Jinji. Površina jezera meri približno 67.000 km^2 in zavzema velik del celotnega povodja, ki ima 9546 METEOSAT pikslov. Celotno odgovarjajoče območje (opomba: število METEOSAT pikslov pomnoženo s 25) meri približno 238.650 km^2. Povprečna letna količina padavin je visoka in ima dva sezonska vrha: v obdobju od marca do maja in novembra do decembra. Znaša do 1295 mm in je na površini jezera rahlo višja kot na okoliškem ozemlju. Po področju precej niha – od 688 mm na jugovzhodnem delu povodja do več kot 2550 mm nad severozahodnim delom jezera. Slika 3 prikazuje prostorsko porazdelitev letne povprečne količine ploskovnih padavin v povodju.

Odtok je v precejšnji meri funkcija podnebja povodja, sestave tal, rabe tal in vegetacije ter topografskih značilnosti povodja in mreže vodotokov. Letno povprečje opazovanega pretoka pri Jinji je 30,97 km^3, kar je enako 130 milimetrom povprečnega odtoka v celotnem povodju. Razmerje odtok/padavine je torej 0,10 ali z drugimi besedami, pri iztoku Jinja je zabeleženih le 10 % celotne količine padavin v povodju. Do tega, v primerjavi z Evropo in Severno Ameriko relativno nizkega razmerja odtok/padavine, pride zaradi visokega odstotka izhlapevanja s površine jezera ter izgube vlage v padavinskem režimu, ki ima letno dva vrhova. Ker se površina jezera ne spreminja veliko z vodostajem jezera, lahko domnevamo, da se hidrološki cikel v povodju Viktorijinega jezera odvija brez človekovega vpliva.

Vendar pa moramo upoštevati, da je iztok iz Viktorijinega jezera nadzorovan in da torej letni izpust pri Jinji ne pokaže naravnega procesa odtok/padavine v določenem letu. Jezero samo predstavlja ogromno akumulacijo. Razlika enega metra v vodostaju jezera predstavlja količino vode, ki zadošča povprečnemu izpustu v več kot dveh letih. Podatki za obdobje od leta 1913 naprej pogosto kažejo, da je razlika med vodostajem jezera na začetku in koncu istega leta blizu pol metra. Zgoraj omenjeno razmerje odtok/padavine je torej zelo približno. Da bi dobili bolj natančno oceno, bi bila potrebna natančna študija dinamike in hidrologije Viktorijinega jezera.

3.2. Ekvatorialna jezera

Iz iztoka Viktorijinega jezera pri jezu Owen Falls teče Beli Nil v jezero Kyoga, nato v Albertovo jezero ter proti severu v južni Sudan. Hidrološka postaja Pakwach bi bila najboljša za pridobitev ocene, kolikšen je v tem podpovodju prispevek k pretoku. Vendar za to postajo nimamo dovolj podatkov. Še več: zaradi pomanjkanja natančnih meritev ne moremo z gotovostjo določiti pritokov ali izgub v Albertovem in jezeru Kyoga. Na splošno smo opazili, da pretoki v sušnem obdobju pri Mongalli odsevajo vodostaje jezer v zgornjem toku ter da na tokove v deževnem obdobju vpliva odtok iz hudourniških pritokov.

Zato smo za oceno prispevka k pretoku v povodju Ekvatorijalnih jezer izbrali meritve Mongalle. Slika 4 prikazuje povprečno letno količino padavin na delu med Jinjo in Mongallo. Za to postajo obstaja dobra časovna vrsta podatkov do leta 1981. Od tega leta dalje ni podatkov zaradi državljanske vojne. Da bi razširili podatke do leta 1995, smo prišli do njih z uporabo linearne regresije med podatki v Jinji in Mongalli v letih, ko za obe postaji obstajajo podatki. Vplivno področje, predstavljeno na slika 4, ima 7784 METEOSAT pikslov, kar odgovarja površini okoli 194.600 km^2. Povprečna letna količina padavin na tem območju je 1198 mm, povprečni letni pretok pri Mongalli pa znaša 37,51 km^3.

Prispevek k pretoku med Mongallo in Jinjo je torej 6,54 km^3, kar lahko vzamemo kot prispevek tega podpovodja k Belemu Nilu. Razmerje odtok/padavine znaša samo 0,029, kar je precej nižje od tistega v povodju Viktorijinega jezera. Za to relativno nizko razmerje je mnogo razlogov: velike vodne površine (jezera, barja, itd) z močnim izhlapevanjem ter bujno vegetacijo z intenzivno evapotranspiracijo in izgubami v podzemnih vodah.

3.3. Sudd

Severno od Mongalle je Beli Nil poznan kot Bahr El Jebel in teče po razsežnih kompleksih vodotokov, jezer in barij v zaprtem bazenu. Celotno območje je zelo položno. Od Mangalle do Malakala je povprečni padec zemljišča le 10 cm/km. Slika 5 predstavlja povprečno letno količino padavin v tem prispevnem področju.

Področje znaša 5577 METEOSAT pikslov, kar odgovarja površini velikosti približno 139.425 km^2. Povprečna letna količina padavin na tem področju je 923 mm z maksimumom več kot 1470 mm v južnem delu povodja. Pogostost padavin se zmanjšuje proti severu, kjer letno povprečje ne preseže 760 mm. Padavine padajo pretežno v obdobju od aprila do oktobra. To v grobem sovpada s poplavnim obdobjem reke, ko je področje stalno poplavljeno. Močvirja se razširjajo in krčijo v sorazmerju z količino dotoka iz Mongalle in lokalnimi padavinami.

Primerjava med zgodovinskimi podatki pretokov pri Mongalli (37,51 km^3) in podatki o pretokih pri Malakalu (30,47 km^3) kaže negativno bilanco 7,04 km^3. Če upoštevamo, da reka Sobat v povprečju prispeva 13,66 km^3 vode letno k pretoku v Malakalu, lahko z lahkoto zaključimo, da se več kot 20 km^3 vode izgubi, večinoma zaradi izhlapevanja, evapotranspiracije in izgub v podtalne vode, ne da bi upoštevali lokalne padavine v tem povodju.

3.4. Bahr El Ghazal

To povodje sestavljajo številni pritoki, ki tečejo od meje povodja reke Konga proti Nilu. Slika 6 prikazuje povprečno letno količino padavin na tem področju. To obsežno območje meri 13.215 METEOSAT pikslov, kar ustreza področju velikosti okoli 330.375 km^2. Maksimum intenzitete padavin v jugozahodnem delu prinaša v povprečju več kot 1550 mm povprečne letne količine padavin, ki upada proti severovzhodu, kjer letna količina padavin ne preseže 500 mm. Povprečna letna količina padavin na celotnem območju znaša 970 mm.

Zaradi pomanjkanja podatkov je skoraj nemogoče dobiti zanesljivo oceno pretokov na tem področju. Povodje je razdeljeno na mnogo pritokov, ki prestopajo bregove in poplavljajo. Na tem velikem področju z zelo majhnim padcem skoraj ves pretok in padavine izhlapijo, tako da letno zapusti povodje le okoli 0,5 km^3 vode (iztok iz jezera No).

3.5. Sobat

Reka Sobat vsebuje pretok dveh pritokov: reke Baro iz Etiopske planote ter reke Pibor iz južnega Sudana in severne Ugande. Slika 7 prikazuje povprečno letno količino padavin na tem povodju.

Prispevno področje meri 7451 METEOSAT pikslov, kar ustreza področju velikosti 186.275 km^2. Padavinski režim teži k enojnemu, z deževnim obdobjem od aprila do oktobra. Padavine so najintenzivnejše v povodju Baro na vzhodu podpovodja, kjer povprečna letna količina padavin doseže skoraj 2000 mm. Najmanj intenzivne so na jugovzhodu na prispevnem področju pritoka Pibor, kjer letna količina padavin seže le malo prek 300 mm. Povprečna letna količina padavin na celotnem povodju znaša 1057 mm.

Malo navzgor od sotočja obeh rek, Baro in Pibor, je postaja Helit Dolieb, ki odraža pretok reke Sobat. Baro je daljša od obeh rek ter izredno hudourniška in sezonska. Pibor je manj sezonska. Mnogo pritokov reke Sobat rado poplavlja in tvori močvirja, ko iz Etiopskega višavja dosežejo položne planote Sudana. Področje poplavljanja in razlitja v sezonska in stalna močvirja je veliko in vključuje tudi močvirje Marchar Marches. Za to področje so ocenjene le izgube. Horst (1950) pripisuje 30 % izgub povodju reke Baro in 14 % povodju reke Pibor.

V NBHIS obstajajo podatki za Helit Dolieb le do leta 1983. Zato smo uporabili podatke za obdobje 1940–1983. Povprečni letni pretok znaša 13,66 km^3, razmerje odtok/padavine pa je 0,069.

3.6. Etiopsko višavje

Izvir Modrega Nila je reka Little Abbay v Etiopskem višavju. Little Abbay teče v jezero Tana, ki se izliva v Modri Nil, ta pa nato teče 900 km navzdol skozi višavje v Sudan. Slika 8 prikazuje povprečne letne padavine v prispevnem področju Modrega Nila v Etiopiji.

Prispevno področje ima 5676 METEOSAT pikslov, kar ustreza velikosti okoli 141.900 km^2. Povprečna letna količina padavin v povodju znaša 1346 mm in je torej med vsemi podpovodji Nila najvišja. Najnižjo količino padavin so zabeležili na vzhodnem delu področja, kjer povprečna letna količina ne preseže 800 mm. Najvišja je v južnem delu povodja (pritok Didesa), kjer presega 1900 mm.

Povprečni letni pretok na sudansko-etiopski meji (Roseires do leta 1965 in Diem po tem) znaša 47,44 km^3. Razmerje odtok/padavine je v tem povodju 0,248, kar je med vsemi podpovodji najvišje.

3.7. Modri Nil v Sudanu

Od sudansko-etiopske meje teče Modri Nil proti severu iz vlažnih v polsuhe podnebne pogoje; severno od Roseiresa običajno dobi malo dodatnega pretoka. Izjemi sta dva pritoka, Dinder in Rahad. Glavnemu toku se pridružita nizvodno od Roseiresa, njune glavne vode pa izhajajo iz Etiopskega višavja. Slika 9 prikazuje povprečno letno količino padavin na tem delu.

Prispevno področje vsebuje 4847 METEOSAT pikslov, kar je enako 121.175 km^2. Relativno visoke vrednosti (1300 mm) povprečne letne količine padavin v okolici sudansko-etiopske meje se po toku navzdol hitro zmanjšujejo. V okolici Kartuma je povprečna letna količina padavin manjša od 180 mm. Povprečna letna količina padavin v tem povodju znaša 573 mm.

Od konca petdesetih let je to področje intenzivno namakano. Zato je težko oceniti, koliko v tem pasu rečni tok pridobi. Podatki za časovno obdobje 1912–1960 kažejo, da se skoraj vse, kar rečni tok pridobi, izgubi zaradi izhlapevanja.

3.8. Centralni Sudan

V pasu od Malakala do Kartuma teče Beli Nil v vse bolj suhe pokrajine. Tu ni nobenih stalnih pritokov in edini omembe vreden prispevek k rečnemu toku se pojavi le v letih intenzivnih padavin. Sicer pa reka samo izgublja vodo. Kot so izmerili pri Malakalu, se zaradi izhlapevanja povprečno izgubi okoli 2 km^3 celotnega pretoka letno. Jez Jebel Aulia, zgrajen 40 km gorvodno od Kartuma leta 1937, da bi shranil vodo za kasnejšo uporabo v Egiptu, dodaja nadaljnjih približno 2,5 km^3 k izgubam zaradi izhlapevanja v tem pasu.

3.9. Atbara

Reka Atbara je najsevernejši pritok Nila. Njene glavne vode izvirajo v severozahodnem Etiopskem višavju. Po naravi je reka izredno hudourniška. Večina rečnega pretoka se nabere gorvodno od rezervoarja Khashm

El Girba. Nizvodno od rezervarja, se podnebje spremeni v polsuho in nato suho. Slika 10 prikazuje povprečno letno količino padavin na tem povodju.

Celotno povodje Atbare je precej veliko. Šteje 6675 METEOSAT pikslov, kar ustreza 166.875 km^2. Povprečna letna količina padavin na tem področju znaša 553 mm in je najnižja med vsemi podpovodji Nila. Relativno visoka vrednost (več kot 1300 mm) letne količine padavin v etiopskem višavju se nizvodno zmanjša na pod 90 mm pri sotočju Atbare in glavnega Nila.

NBHIS vsebuje podatke o mesečnih pretokih za postajo Atbara Kilo 3, ki beleži pretok Atbare pred sotočjem z glavnim Nilom v obdobju od leta 1940 do danes. Toda analize podatkov kažejo, da je natančnost meritev nazadovala v osemdesetih in devetdesetih letih. Upoštevali smo torej samo podatke za obdobje 1940–1982. Povprečni letni pretok v tem časovnem obdobju je znašal 10,93 km^3, razmerje odtok/padavine pa je bilo 0,118.

3.10. Celotno povodje Nila

Kot smo že omenili, smo upoštevali samo področja, kjer padavine prispevajo k pretoku Nila. V našem primeru je torej celotno prispevno področje Nila enostavno vsota vseh podpovodij, ki so predstavljena zgoraj. Področij v državah ob Nilu, katerih odtok je usmerjen v druge reke in suha področja v Sudanu in Egiptu, kjer sploh ni dežja, nismo upoštevali. Tako celotno prispevno področje Nila znaša 61.100 METEOSAT pikslov, kar ustreza 1.527.500 km^2. Ta številka je nižja od tistih, ki jih običajno najdemo v podatkih za velikost povodja Nila. Slika 11 predstavlja prostorsko porazdelitev povprečne letne količine padavin v celotnem povodju, ki znaša povprečno 1010 mm.

Najboljša postaja za oceno razmerja odtok/padavine v povodju Nila, kot je definiran zgoraj, bi bila postaja takoj nizvodno od sotočja Atbare z Nilom. Na žalost podatkov s take postaje ni. Kot oceno rezultatov za celotno povodje Nila smo torej izbrali dotok v Asuan. To je postaja z najdaljšo zgodovino opazovanj. V NBHIS so dostopni mesečni podatki za meritve v Asuanu od leta 1871 naprej. Od izgradnje starega Asuanskega jezu (faza I dokončana leta 1902) do dokončanja Visokega Asuanskega jezu je postaja v Wadi Halfi služila kot postaja, ki je opazovala dotok v Asuan, medtem ko so kasneje postajo pri Dongoli uporabili kot merilno postajo. Da bi analizirali obnašanje dotoka v Asuan v celotnem časovnem obdobju, smo podatke vseh treh postaj združili v eno samo časovno vrsto. Od druge polovice petdesetih let dalje so v Sudanu precej vode uporabili za namakanje. Za to časovno obdobje smo torej upoštevali tako imenovani naturalizirani pretok.

Tako je bil v časovnem obdobju 1940–1995 povprečni letni dotok v Asuan 84,71 km^3, razmerje odtok/padavine pa 0,055. Z drugimi besedami, v Asuan pride le približno 6 % celotne ocenjene količine padavin v povodju Nila.

4. ČASOVNA ANALIZA PADAVIN IN PRETOKOV

V prejšnjem poglavju je naša razprava temeljila na podatkih iz časovnega obdobja 1940–1995. Da bi pokazali lastnosti različnih podpovodij, smo našo predstavitev zasnovali na povprečnih letnih vrednostih količine padavin in pretokov. Vendar pa je pretok v nekem določenem letu običajno daleč od povprečne vrednosti. Govorijo, da je Nil reka z zelo veliko medletno spremenljivostjo. Čeprav lahko odkrijemo visoko frekvenčno spremenljivost v poljubnem časovnem nizu podatkov ne glede na dolžino, je identifikacija padajočih in naraščajočih trendov bolj zanesljiva, če proučujemo nize podatkov, sestavljene iz daljših časovnih serij.

4. Padavine

Najprej poglejmo lastnosti povprečnih ploskovnih padavin (MAP). Slika 12 nam kaže letne podatke za časovno obdobje 1940–1995 za nekaj izbranih postaj. Na splošno je MAP na celotnem povodju Nila, ki ga v našem primeru predstavlja postaja Dongola odvisen od MAP nad Modrim Nilom (Kartum na Modrem

Nilu in Diem). Zanimivo je odkritje, da najdemo podoben trend, če primerjamo povodji Modrega Nila in Ekvatorijalne planote: višji MAP v Jinji ustreza višjemu MAP nad Modrim Nilom in obratno. Seveda je nekaj izjem, kot na primer leta 1945, 1946, 1951, 1971–1978 in 1992–1995.

Slika 12 direktno ne kaže nobenega periodičnega obnašanja MAP. Da bi videli, če kakšna periodičnost obstaja ali če lahko najdemo vsaj kakšno težnjo k periodičnosti, smo uporabili mesečne podatke o MAP na celotnem vplivnem področju Nila (gorvodno od Dongole).

Za analizo periodičnosti smo uporabili Fourierjevo analizo. To je matematično orodje, ki časovno serijo podatkov razgradi v vsoto valovnih elementov. Vsak razgrajen element ima svojo valovno dolžino, ki ustreza določeni frekvenci. Valovni elementi so ponavadi označeni kot valovna števila $k_o \dots k_n$, kjer k_o predstavlja valovni element z najdaljšo valovno dolžino v seriji podatkov in k_n element z najkrajšo. Ker mora biti število vhodnih podatkov za Fourierjevo transformacijo potenca števila 2, smo izbrali podatke zadnjih 512 mesecev. Tako smo uporabili podatke za obdobje od maja 1953 do decembra 1995.

Slika 13 prikazuje rezultat Fourierjeve analize. Zelena črta na grafu predstavlja premikajoča 12-mesečna povprečja oziroma letna povprečja. Najvišja gostota spektra (69642) ima periodo 44-ih mesecev, druga najvišja (2402) pa periodo 86-ih mesecev. Tako je najvišja gostota spektra precej višja od belega šuma. Pojavi se torej jasna perioda 44-ih mesecev (3,67 leta), prvi višji harmonij 86-ih mesecev (7,17 leta) in tako dalje. Rdeča črta na grafu predstavlja inverzno transformacijo, kjer se vse frekvence, ki ustrezajo valovnim številom $k > 16$, izločene. V grobem, izločili smo vse valove z valovnimi dolžinami krajšimi od 34 mesecev. Da bi dobili le osnovni sinusni val, smo izločili vse valove z valovnim številom $k > 2$, torej valove, krajše od 256 mesecev. Debela modra črta predstavlja ta osnovni sinusni val. Naj omenimo še, da 256 mesecev ustreza 21,33 letom, kar je dvakrat toliko kot povprečna perioda sončnih peg. Še več, 3,67 letno periodo brez težav primerjamo z ocenjeno periodo fenomena ENSO (3–7 let). Glede na povedano lahko zaključimo, da v Dongoli obstaja periodičnost MAP z osnovno periodo 44-ih mesecev in vsaj nekaj višjimi harmoniki. Rezultat se ujema z leti velikih poplav v prvi polovici šestdesetih in sušami v osemdesetih letih. Lahko da obstaja val z daljšo periodo, vendar na žalost nimamo dovolj dolgih časovnih vrst podatkov, da bi to videli.

Slika 12 kaže MAP za nekatere postaje, vendar ne pokaže jasno časovne odvisnosti med različnimi postajami, t. j. med različnimi prispevnimi področji. Da bi pokazali razliko med ekvatorijalnim in etiopskim prispevnim področjem, ki najpomembneje prispevata k vodam Nila, torej med časovnim obnašanjem MAP na povodju Viktorijinega jezera in MAP nad Modrim Nilom od Diema navzgor, smo na sliki 14 narisali sledeča dva trenda za hidrološke postaje Dongolo (zelene črte), Jinjo (modre črte) in Diem (rdeče črte):

- inverzno Fourierjevo transformacijo – trend, kjer so vse frekvence, ki ustrezajo $k > 16$, izločene (tanke črte);
- inverzno Fourierjevo transformacijo z osnovnim sinusnim valom (debele črte).

Vidi se, da sta osnovna valova za Jinjo in Diem zelo podobna, čeprav ima val za Diem višjo amplitudo (torej višjo spremenljivost). V splošnem to pomeni, da če je MAP gorvodno od Jinje v zaporednih letih nizek, bo tudi gorvodno od Diema relativno nizek v istem časovnem obdobju. Toda če pogledamo valove, ki pripadajo višjim valovnim številom, lahko najdemo časovna obdobja z nasprotnim obnašanjem, t. j. nizek MAP gorvodno od Jinje in visok MAP gorvodno od Diema (druga polovica petdesetih, sredina sedemdesetih in prva polovica devetdesetih let 20. stoletja).

Krivulje za Dongolo kažejo, da osnovni trend sledi trendoma Diema in Jinje. Tanka krivulja nam kaže, da je amplituda v primerjavi z Diemom in Jinjo precej manjša in da je MAP na celotnem prispevnem področju posledica istega globalnega pojava, morda indijskega monsuna, še posebno v ekvatorskem pasu.

4.2. Pretoki

Znano je, da je pretok produkt količine padavin, potencialne evapotranspiracije, prsti, rabe tal/površja, topologije in geometričnih značilnosti mreže kanalov ter topografskih značilnosti povodja. Na osnovi razpoložljivih podatkov v NBHIS bomo pokazali lastnosti pretokov celotnega povodja Nila z uporabo časovnih vrst različnih dolžin. Tako smo za primerjavo pretokov glavnih postaj ob Nilu uporabili časovno vrsto za obdobje 1912–1995, za analizo periodičnosti pri Asuanu vrsto za obdobje 1871–1998, za primerjavo pretokov in količine padavin pa obdobje 1940–1995.

Da bi pokazali obnašanje letnih pretokov in jih primerjali s celotnim prispevnim povodjem Nila, smo izbrali sledeče postaje glavnih povodij:

- Mongalla za prispevno področje Ekvatorialnih jezer,
- Hekit Dolieb za prispevno področje reke Sobat,
- Malakal za prispevek Belega Nila, reke Sobat in Bahr el Ghazal,
- Diem za prispevno področje Etiopske planote,
- Kartum na Modrem Nilu za prispevek Modrega Nila,
- Atbara Kilo 3 za povodje Atbare in
- Asuan za povodje celotnega Nila.

Seveda bi za primerjavo podatkov zgoraj navedenih postaj radi uporabili podatke za čim daljše časovno obdobje. Izbrali smo časovno obdobje 1912–1995. Ker dolžina časovne vrste podatkov dostopnih v NBHIS ni enaka za vse zgoraj omenjene postaje, smo manjkajoče podatke ekstrapolirali, kot sledi:

a) Mongalla: ekstrapolacija za obdobje 1983–1995 z uporabo linearne regresije, ki temelji na podatkih iz časovnega obdobja 1912–1982 med Mongallo in Jinjo (koeficient regresije R = 0,98);
b) Helit Dolieb: ekstrapolacija za obdobje 1983–1995 z uporabo linearne regresije, ki temelji na podatkih iz časovnega obdobja 1912–1982 med Helit Dolieb in Malakalom (R = 0,66);
c) Atbara Kilo 3: analiza kaže, da so podatki za to postajo zelo nenatančni od leta 1983 naprej. Zato smo ekstrapolirali obdobje 1983–1995 z uporabo linearne regresije, ki temelji na podatkih iz časovnega obdobja 1912–1982 med Atbara Kilo 3 in Diemom (R = 0,74).

Za primerjavo pretokov na različnih postajah ob Nilu bi morali izključiti vse antropološke vplive. Ne moremo izključiti vpliva večletne akumulacije Viktorijinega jezera in dejstva, da je pri Jinji spuščanje vode iz Viktorijinega jezera popolnoma kontrolirano. Dolvodno od Jinje je edino Sudan razvil pomembnejši sistem za namakanje. Vpliv namakanja v Sudanu bi morali upoštevati za pretoke v Kartumu in Asuanu. Zato smo za Asuan uporabili podatke t. i. naturaliziranih pretokov, podatke v časovnem obdobju 1956–1995 za postajo v Kartumu na Modrem Nilu pa popravili s pomočjo linearne regresije, ki temelji na podatkih iz obdobja 1912–1995 (R = 0,95). Podatki, ki smo jih dobili z ekstrapolacijo ali popravili, so predstavljeni na sliki 15. Ta kaže 10 letna premikajoča povprečja za zgoraj omenjene postaje, ki so zasnovana tako, da vrednosti za vsako leto predstavljajo povprečje v prejšnjih 10-ih letih. Npr. vrednosti za leto 1930 so povprečja za časovno obdobje 1921–1930.

Na grafu lahko z lahkoto razločimo tri skupine krivulj: dve krivulji predstavljata postaji Atbara Kilo 3 (prispevno področje Atbare) in Helit Dolieb (prispevno področje reke Sobat), dve krivulji predstavljata Mongallo in Malakal (Beli Nil) ter dve krivulji Diem in Kartum (Modri Nil). Krivulja, ki predstavlja Asuan, je seveda nekakšna kompozicija drugih. Čeprav sta prispevni področji Modrega Nila in Ekvatorialnih jezer geografsko precej oddaljeni druga od druge ter nimata skupnih pritokov, je očitno, da se pri obeh pojavlja skupni splošni trend. Relativno enakomeren tok od začetka stoletja je v začetku šestdesetih let za nekaj let narasel in se nato znižal. Z istim obnašanjem smo se srečali že, ko smo govorili o MAP. Vrh v začetku šestdesetih let je pri Mongalli najvišji, obsežne vodne površine v Suddu so ga zmanjšale, v Malakalu pa je kljub temu še vedno zelo jasen. Vendar se vrh pojavlja tudi pri Kartumu na Modrem Nilu.

Vprašanje je, kako dolgo se bo padajoči trend, ki se je začel v sredini šestdesetih let, še nadaljeval, in ali je naraščajoči trend od konca osemdesetih let znak nasprotnega trenda? Na ta vprašanja smo skušali odgovoriti s pomočjo Fourierjeve analize podatkov o letnem pretoku pri Asuanu z uporabo podatkov časovnega obdobja 128-ih let (1871–1998). Preden se posvetimo rezultatom teh analiz, si najprej poglejmo letne naturalizirane podatke za Asuan. Predstavlja jih slika 16 in je zelo nazoren. Razen letnih podatkov smo prikazali še: desetletno premikajoče povprečje, povprečje celotnega 128-letnega obdobja (rumena črta: 86,81 km^3), 30-letna povprečja za obdobja 1871–1900, 1901–1930, 1931–1960 in 1961–1998 (rdeča črta: 100,61 km^3, 82,92 km^3, 84,38 km^3 in 87,09 km^3) ter povprečje obdobja 1901–1998 (vijolična črta: 84,99 km^3). Z izjemo izredno visokega toka v zadnjih tridesetih letih 19. stoletja, 30 letna povprečja za to stoletje kažejo precej enoten dolgoročen trend. Seveda pa so letna nihanja precejšnja. Reka Nil je znana po svoji spremenljivosti. Ostaja nam še, da povemo nekaj o natančnosti podatkov, izmerjenih v prejšnjem stoletju. Res je težko opravičiti ogromen odklon 30-letnega povprečja za obdobje 1901–1930 od povprečja za obdobje 1871–1900. Sta naraščajoči trend v zadnjem desetletju 20. stoletja in najvišji pretok stoletja zabeležen leta 1998 znamenje, da so vrednosti, izmerjene v časovnem obdobju 1871–1900, pravilne?

Odgovori na ta vprašanja so bistvenega pomena za vodno gospodarstvo v vseh državah ob Nilu in še posebno v Egiptu, ki leži ob koncu toka Nila. Izgradnja Velikega Asuanskega jezu kot večletne akumulacije je Egiptu omogočila, da z lahkoto preseže kratkoročno spremenljivost pretokov Nila, ki se spreminjajo iz leta v leto. Toda kaj, če se spreminja tudi dolgoročen trend? To vprašanje osvetljujejo časovne analize, omenjene zgoraj. Slika 17 podaja osnovne rezultate. Zelena črta na grafu predstavlja letni dotok v Asuan. Rdeča in modra krivulja imata enak pomen, kot smo ga opisali v primeru analize MAP (glej sliko 13), z razliko, da smo v tem primeru uporabili letne podatke. Modra črta predstavlja osnovni sinusni val za obdobje 128-ih let. Zaporedje izredno velikih pretokov v zadnjih tridesetih letih 19. stoletja se je na prelomu stoletja umirilo. Leto 1913 beleži najnižji dotok, samo 46 km^3. Sinusni val je dosegel minimum okoli leta 1940 in se kasneje dvignil. Leto 1998, ki je zabeleženo zadnje, je najvišje v 20. stoletju in sinusna krivulja bo kmalu spet dosegla vrh. Gostota spektra pri n = 9 ima vrh 82506, drugi vrh je pa pri n = 20 (65654). Obe gostoti sta višji od drugih vrednosti, čeprav je stopnja belega šuma relativno visoka. Odtok ima torej v primerjavi s periodičnostjo MAP mnogo šibkejše periodično obnašanje z osnovnima periodama 9-ih in 20-ih let.

Če torej sinusna krivulja, ki predstavlja dolgoročen trend, doseže vrh, pomeni, da se lahko v bližnji prihodnosti le zniža. Zaporedju let z relativno visokimi pretoki, zabeleženimi od leta 1988 naprej, bo najverjetneje sledilo zaporedje let z zmernimi ali nizkimi pretoki. Z domnevo, da bo bodoče periodično obnašanje pretoka v Asuanu ostalo podobno kot na sliki 17, smo izdelali projekcijo bodočih pretokov. Rezultat je prikazan na sliki 18. Na splošno je osnovni sinusni val dvakrat daljši (256 let). Minimum bo dosegel okoli leta 2011. Rdeča krivulja (tudi z dvojno periodo – okoli 18 let) kaže, da bo lokalnemu vrhu leta 1999 sledilo zaporedje let s padajočim trendom pretokov. Ponovno bi radi poudarili, da to ni napoved, temveč le projekcija na osnovi domneve, da se bo pretekli trend nadaljeval v prihodnosti. Zelo dobro vemo, da v naravi ni tako in nimamo dovolj dolgih časovnih vrst podatkov, da bi videli valove z daljšimi periodami. Kljub temu pa obstaja velika verjetnost, da bodo pretoki v naslednjih desetih letih bolj podobni tistim, zabeleženim v osemdesetih in sedemdesetih letih, kot tistim v devetdesetih letih 20. stoletja.

4.3. Proces padavine/odtoki

V prejšnjih dveh poglavjih smo govorili o povprečnih letnih ploskovnih padavinah (MAP) in pretokih v smislu povprečkov in dolgoročnih trendov. Da bi pa ocenili vodni potencial realno, moramo analizirati spremenljivost MAP in pretokov v zaporednih letih ter pogledati medsebojno povezavo med MAP in pretoki, t. j. proces padavine/odtoki. Zaradi tega moramo analizirati MAP drugače, kot v poglavju IV.1. Za analizo procesa padavine/odtoki za določeno postajo moramo upoštevati MAP nad celotnim prispevnim področjem gorvodno od postaje ter podatke o MAP in pretokih v istem časovnem obdobju. Uporabili smo časovno obdobje 1940–1995. Osnovne rezultate povzema preglednica 2. Kot smo že omenili, je izpuščanje vode iz Viktorijinega jezera pri Jinji 100 % kontrolirano in jezero samo predstavlja ogromno akumulacijo. Lahko torej pričakujemo, da je povezanost med letnim MAP in letnimi izpusti pri Jinji zelo slaba. Rezultate smo predstavili v drugi vrsti tabele. Korelacijski koeficient med MAP in letnimi izpusti znaša 0,13; med obema spremenljivkama torej ni nobene povezave. Naredili smo enostaven poskus: predpostavimo, da je površina jezera konstantna glede na vodostaj, kar pomeni konstantne izgube zaradi izhlapevanja – letnim izpustom smo dodali razliko akumulirane vode in dobili hipotetični odtok. Tak bi bil odtok iz jezera v naravnih okoliščinah. Rezultati so podani v prvi vrsti tabele. Kot smo pričakovali, se je med MAP in hipotetičnim odtokom pojavila visoka korelacija 0,83. Relativno nizek koeficient spremenljivosti (standardna deviacija/povprečje) MAP (0,1242) v primerjavi s koeficientom spremenljivosti hipotetičnega odtoka (0,6688) kaže, da majhna sprememba MAP povzroči velike razlike v hipotetičnem odtoku in da je na splošno spremenljivost odtokov v zaporednih letih velika. Jezero vsekakor blaži spremenljivost.

Rezultati za postajo Mongalla, ki predstavlja odtok iz Ekvatorialne regije, kažejo podobno obnašanje. Ker se večina odtoka proizvede v prispevnem področju Viktorijinega jezera in je iztok iz jezera 100 % kontroliran, med letnimi MAP in pretoki pri Mongalli ni nobene linearne povezave. Koeficient korelacije znaša le 0,14, podoben je torej tistemu pri Jinji. V primerjavi z Jinjo tudi ni posebne razlike v spremenljivosti MAP in pretokov. Prikaz na sliki 17 še dodatno osvetljuje povezanost med MAP in pretoki pri Mongalli.

Podatki za postajo Malakal prikazujejo prispevek štirih prispevnih področij: Ekvatorialnega, Sudda, reke Sobat in Bahr El Ghazala. Ogromne vodne površine s precejšnjimi izgubami zaradi izhlapevanja v Suddu in ob reki Sobat še dodatno zmanjšujejo odtok. Koeficient korelacije med MAP in pretokom je torej najnižji med vsemi prispevnimi področji (0,12), kar dokazuje, da med tema dvema spremenljivkama ni povezave. V primerjavi z Mongallo, MAP precej odstopa in spremenljivost MAP in pretokov ravno tako. Nizek koeficient korelacije bi lahko pojasnilo dejstvo, da vodne površine v prispevnih področjih Sudda in reke Sobat ter Viktorijino jezero služijo kot večletna akumulacija. Naši izračuni temeljijo na letnih podatkih.

Kot smo pričakovali, je koeficient korelacije med MAP in pretoki na sudansko-etiopski meji (Diem) relativno visok (0,72). Ker večina padavin v prispevnem področju Modrega Nila izvira iz konvektivnih nevihtnih oblakov, dajo strma orografija in visoka pobočja Modremu Nilu hudourniško obnašanje. Pričakovali bi, da bo zato spremenljivost MAP in pretokov velika. Če upoštevamo dnevne podatke, je spremenljivost velika. Toda če pogledamo letne podatke, je spremenljivost obeh, MAP in pretokov, relativno majhna in zelo podobna tisti za Malakal.

Prikaz padavine/pretoki za Diem na sliki 20 kaže v primerjavi z Mongallo mnogo trdnejšo povezavo med MAP in pretoki. MAP v Etiopskem višavju je najvišji v celotnem povodju Nila. Presenetljivo je pa spremenljivost MAP in pretokov pri Diemu zelo podobna rezultatom pri Malakalu. Kot smo že rekli, smo pri Malakalu pričakovali relativno majhen faktor spremenljivosti, ker je pretok pri Malakalu zaradi velikih izgub na eni strani in vpliva razsežnih vodnih površin, ki služijo kot večletna akumulacija na drugi strani, zmanjšan. Rezultat podpira naš zaključek, da imajo povprečne letne površinske padavine v prispevnih področjih Belega in Modrega Nila nekaj podobnih lastnosti (glej poglavje IV.1.).

Za postajo Kartum na Modrem Nilu, ki služi kot postaja za ocenjevanje pritoka s prispevnega področja Modrega Nila, lahko vidimo, da je spremenljivost MAP in pretokov podobna tisti pri Diemu. Isto velja tudi za koeficient korelacije med MAP in pretoki. Ker nizvodno od etiopske meje Modri Nil teče skozi polsuha in suha podnebna področja, je MAP gorvodno od Kartuma precej nižji v primerjavi z MAP gorvodno od Diema.

Od začetka petdesetih let, še posebno z izgradnjo jezu pri Roseiresu, je Sudan razvil obsežen namakalni sistem od sudansko-etiopske meje do Kartuma. Za prikaz informacije o porabi vode na tem razponu smo na sliki 21 narisali razlike med izmerjenimi pretoki v Kartumu na Modrem Nilu in Diemom. Graf razločno kaže naraščajočo porabo vode od leta 1955 naprej. Če predvidevamo, da je doprinos padavin v tem pasu v povprečju enak izgubam zaradi izhlapevanja, graf jasno predstavlja težnjo k absolutno večji porabi vode v sušnih letih. Na primer, najvišjo negativno razliko (15,02 km^3) so zabeležili leta 1984, ko je bil zabeležen drugi najnižji dotok v Asuan v časovnem obdobju 1912–1995. Seveda pa te številke lahko vzamemo le kot grobe približke, ker enostavno ni dostopnih podatkov o celotni porabi vode in drugih izgubah, ki se očitno iz leta v leto občutno spreminjajo.

Atbara je edini pritok Nila med Kartumom in Naserjevim jezerom. Preglednica 2 kaže razmeroma nizek MAP za prispevno področje postaje Atbara Kilo 3 ter veliko letno spremenljivost MAP in pretokov. Korelacija med MAP in pretoki kaže šibek odnos med tema dvema spremenljivkama.

In končno, zadnja vrsta v Tabeli 2 podaja rezultate za celotno prispevno področje Nila. Seveda bi lahko razpravljali o številki 1010 mm, ki smo jo dobili za MAP. Naj povemo še enkrat, da gornja številka velja za MAP v prispevnem področju, kot je prikazano na sliki 21. Vanj niso vključena razsežna suha področja v Sudanu in Egiptu s povprečno letno količino padavin manj kot 50 mm, ki brez dvoma pripadajo prispevnemu področju Nila. Koeficient spremenljivosti MAP in pretokov kaže razmeroma majhno verjetnost, da se lahko v zaporednih letih pojavi velika razlika v letnem pretoku. Na osnovi teh rezultatov je torej majhna verjetnost, da bo letu z izredno velikimi pretoki sledilo leto z izredno majhnimi pretoki. Očitno je, da ogromna akumulacija Viktorijinega jezera in razsežne vodne površine v povodjih Sudd in reke Sobat zmanjšujejo relativno veliko medsezonsko spremenljivost MAP in pretokov v Ekvatorialni regiji. Relativno nizek koeficient korelacije med MAP in pretoki kaže šibek odnos med obema spremenljivkama in potrjuje, da se učinek kontroliranih izpustov iz Viktorijinega jezera odraža tudi na dotoku v Naserjevo jezero.

Če upoštevamo dotok v Naserjevo jezero in dejstvo, da imamo dve glavni prispevni področji z visokim MAP (Ekvatorialno in Etiopsko višavje), lahko postavimo logično vprašanje: koliko dotoka v Naserjevo jezero prispeva Beli Nil in koliko Modri Nil? Odgovora na to vprašanje nismo iskali s pomočjo uradnih podatkov o naturaliziranih pritokih za Asuan. Rutinski postopek za izračunavanje naturaliziranih pretokov v Asuanu, kot ga izvajajo v Egiptu, dodaja pretoku v Dongoli konstantne izgube zaradi izhlapevanja zaradi povečanih vodnih površin za jezovi v Sudanu ter konstantno vrednost pričakovane porabe vode v Sudanu. Kot je razvidno na sliki 21, samo ob Modrem Nilu nizvodno od sudansko-etiopske meje prihaja do precejšnjega letnega nihanja porabe vode. Da bi torej prišli do bolj realne ocene o prispevku Belega Nila k dotoku v Naserjevo jezero, smo izračunali naslednje: za oceno skupnega prispevka Nila smo vzeli letne pretoke pri Malakalu kot prispevek Belega Nila, zmanjšane za 4,5 km^3 (glej poglavje III.8.), naturaliziran pretok pri Kartumu na Modrem Nilu (glej poglavje IV.2.) ter pretok pri Atbara Kilo 3. Tako pretok za postajo Malakal vključuje tudi doprinos reke Sobat. Odstotek prispevka Belega Nila, vključno z reko Sobat, k skupnemu doprinosu je predstavljen na sliki 21.

Bela črta predstavlja povprečni doprinos (29,4 %) Belega Nila v časovnem obdobju 1912–1995. Celotno časovno obdobje lahko razdelimo v tri obdobja: obdobje 1912–1920, ko je doprinos Belega Nila nihal okoli povprečja, obdobje 1921–1961, ko je bil pod povprečjem ter obdobje od leta 1962 naprej, ko je bil precej nad povprečjem. Od nenadnega porasta pretoka Belega Nila v začetku šestdesetih, je od leta 1966 naprej opaziti jasen padajoči trend doprinosa Belega Nila.

5. VELIKI ASUANSKI JEZ KOT VEČLETNA AKUMULACIJA

Po dokončanju Starega Asuanskega jezu leta 1902 so mnogi predlagali, da bi ga še dodatno povišali za zaščito Egipta pred poplavami in tako povečali akumulacijo vode, ki bi jo lahko uporabljali obe državi, Egipt in Sudan. Odločili pa so se za izgradnjo novega jezu gorvodno od Asuana, ki bi služil kot večletna akumulacija. Gradnja je bila končana do leta 1970. Od takrat naprej je poljedeljstvo v Egiptu cvetelo, čeprav je bilo mnogo kontroverznih in nasprotujočih si mnenj o vplivu jezu na okolje. Po tridesetih letih se zdi izkušnja še vedno pozitivna. Kljub temu pa ostajajo odprta vprašanja, kot na primer: če predpostavimo, da bo v bodočnosti nihanje dotoka v Naserjevo jezero za Velikim Asuanskim jezom ostalo podobno kot v preteklosti, ali je možno regulirati izpuste iz jezera na način, ki bi preprečil kakršnokoli škodo egiptovskemu vodnemu gospodarstvu?

Za odgovor na to vprašanje smo uporabili kontrolni simulacijski model za Veliki Asuanski jez, ki so ga razvili med izvajanjem projekta MFS. Osnovna značilnost modela je, da optimizira prihodnje izpuste pod pogojem, da je vedno zadoščeno potrebam namakanja. Časovno obdobje simulacije je ponavadi eno leto. Model: 1) minimizira površinsko izhlapevanje, 2) v primeru, ko je vodostaj jezera blizu vrha, minimizira pretok skozi zasilni kanal, ki usmerja vodo v puščavo, 3) upočasni zmanjšanje izpustov v primeru, da je vodostaj jezera blizu dna. Model deluje z mesečnim ali desetdnevnim časovnim korakom. Pognali smo ga z desetdnevnim časovnim korakom. Za vsak časovni korak desetih dni izbranega preteklega obdobja model najprej izračuna prognozo dotoka, tako da izračuna množico prognostičnih krivulj za čas enega leta. Za vhodne podatke smo uporabili desetdnevni naturaliziran pretok v Asuanu za časovno obdobje 1872–1998. Za uporabo vode v Sudanu smo uporabili konstantno vrednost 16,6 km^3 na leto, medtem ko smo za potrebe namakanja v Egiptu uporabili konstantno vrednost 55,6 km^3 na leto. Model smo pognali dvakrat, enkrat v kontrolnem načinu, ki optimizira izpuste, in enkrat v načinu, ki dosledno simulira izpuste glede na potrebe namakanja. Vodostaj zasilnega izpusta smo postavili na 178 m, dno jezera pa na 147 m, ker bi radi simulirali odziv jezera glede na trenutno veljavne parametre. Maksimalen dnevni izpust smo postavili na 260 km^3.

Slika 23 prikazuje simulirane vodostaje Velikega Asuanskega jezu za oba poskusa. Jasno se pokaže, da lahko skoraj v vseh okoliščinah uspešno upravljamo z jezom, tako da uporabimo optimizacijo izpustov, kot smo ga opisali zgoraj. V primeru, da je vodostaj jezera nekje na sredini aktivnega področja jezera, bi pristop z optimizacijo izpustil malo več vode kot je potrebno za namakanje. Bi pa zmanjšal izhlapevanje s površine jezera in tako omogočil večjo proizvodnjo elektrike. Kakorkoli že, optimizacija bi prinesla največji dobiček, če se vodostaj jezera približa vrhu ali dnu v zaporednih letih. Pretok skozi zasilni kanal bi se zmanjšal na minimum celo v primeru dolge vrste zaporednih let z velikimi dotoki, kot se je zgodilo v zadnjih tridesetih letih 19. stoletja. To nazorno prikazuje slika 24. Na drugi strani pa bi se je škoda povzročena zaradi vrste zaporednih let z majhnimi dotoki v osemdesetih letih 20. stoletja zmanjšala na minimum. Slika 25 prikazuje simulirane izpuste za ta primer. Modra črta predstavlja zahteve namakanja. Rumena črta, ki predstavlja izpuste v načinu, ki dosledno sledi namakalnim potzrebam kaže, da bi izpusti lahko dosegli celo 0, če se vodostaj spusti do dna jezera. V tem primeru bi iz jezera lahko izpustili le dotok. Toda optimizacija upošteva enoletno prognozo dotoka v jezero ter dejstvo, da je najpomembnejša žetev končana do konca avgusta. Tako optimizacija zmanjša izpuste pod potrebe namakanja proti koncu leta ter shrani vodo za ciklus rasti v prihodnjem letu. Preglednica 3 prikazuje osnovne rezultate za oba poskusa. Kot smo pričakovali, je iztok v primeru optimizacije višji, ker model povečuje izpuste, da bi se izognil iztoku po zasilnem kanalu. Ustrezna frekvenca iztokov po zasilnem kanalu je torej nižja, kot če dosledno sledimo potrebam namakanja. Nasprotno pa se pri kontrolnem načinu poveča relativna frekvenca primanjkljajev vode glede na potrebe namakanja. Optimizacija namreč zmanjšuje izpuste bolj zgodaj za manjše vrednosti. Tako se izogne ničelnim izpustom, kot bi se zgodilo v primeru, ko dosledno sledimo potrebam namakanja. Model torej raztegne primanjkljaj čez daljše časovno obdobje z manjšimi primanjkljaji v konkretnem časovnem koraku. Tako se model izogne hudim posledicam v primeru popolnega pomanjkanja.

Odgovor na vprašanje iz začetka tega poglavja je torej pozitiven. Da, možno je upravljati Veliki Asuanski jez tako, da se izognemo morebitni škodi za vodno gospodarstvo Egipta. Če v bodočnosti predvidimo podobno statistično porazdelitev dotoka kot je bila v preteklosti, je gornji poskus potrdil sledeče:

- v primeru velikih dotokov bi lahko izpuste do določene mere pravočasno povečali, ponavadi do 260 km^3 na dan, da bi optimizirali proizvodnjo elektrike in minimizirali odtok skozi zasilni kanal;
- v primeru majhnih dotokov bi se skupen primanjkljaj glede na potrebe namakanja razširil preko daljšega časovnega obdobja in škoda pri pridelkih bi se tako zmanjšala na minimum.

Rastoča populacija v vseh državah Nila povzroča tudi povečano porabo vode. Koordinacija upravljanja vodnih zalog v državah ob Nilu je torej neizbežna. Vendar pa je Egipt, ki je na koncu toka Nila, najbolj ranljiv. Predpostavimo, da Egipt na splošno ne more povečati porabe vode ter da mora shajati s svojimi vse večjimi potrebami po vodi z izboljšanjem namakalnega sistema in modrim upravljanjem z vodo. Realno je tudi pričakovati, da bo povečana poraba vode v gorvodnih državah zmanjšala dotok v Naserjevo jezero. Vprašanje je, do kolikšne mere se lahko poraba vode gorvodno poveča, ne da bi pri tem oškodovala trenutne potrebe Egipta.

Za odgovor na zgornje vprašanje smo izvedli serijo poskusov s kontrolno simulacijskim modelom, vsakič z rahlo povečano porabo vode gorvodno od Naserjevega jezera, da bi tako našli količino, za katero bi se lahko povečala trenutna dogovorjena potrošnja v Sudanu (18,5 km^3), ne da bi pri tem oškodovala potrebe po vodi v Egiptu. Vsakič smo uporabili podatke desetdnevnega naturaliziranega pretoka v Asuanu za časovno obdobje 1872–1998. Naš cilj je bil samo, kako zadostiti potrebam po vodi za namakanje v Egiptu. Zato smo postavili spodnji možni vodostaj na Velikem Asuanskem jezu na 142 m. Predvideli smo tudi, da bi se turbine ustavile, če bi vodostaj padel pod 160 m. Poskus kaže, da bi modro upravljanje z izpusti iz Velikega Asuanskega jezu lahko zagotovilo Egiptu izpolnitev njegovih trenutnih potreb tudi v primeru, če se poraba gorvodno poveča na okoli 25 km^3, kar pomeni okoli 50 % povečanje glede na trenutno stanje. Slika 26 kaže simulirane vodostaje Velikega Asuanskega jezu pri tem poskusu.

Slika 26 kaže v primerjavi s simuliranimi vodostaji v kontrolnem načinu na sliki 23 precej nižje vodostaje jezera. Glede na ta poskus bi se vodostaj jezera znižal do dna le v nekaj desetdnevnih obdobjih v celotnem časovnem obdobju simulacije. Relativno nizko povečanje povprečnega primanjkljaja glede na potrebe namakanja (le za okoli 1 km^3 na leto) je posledica manjših izgub zaradi izhlapevanja (9,00 proti 12,6 km^3), medtem ko je povprečen dotok nižji za okoli 10 %. Najbolj občutljivo obdobje v preteklem časovnem obdobju je obdobje 1981–1987. Simulirani izpusti v vseh drugih letih pa se zelo približujejo potrebam namakanja. Kot prikaz, da Egipt lahko zadosti svojim potrebam namakanja celo v takem razmeroma dolgem časovnem obdobju majhnih dotokov ter s povečano porabo v zgornjem toku, smo narisali simulirane izpuste in njim ustrezne vodostaje jezera za to časovno obdobje na sliki 27. Rumena črta na grafu predstavlja predpostavljene potrebe namakanja, rdeča črta simulirane izpuste ter modra simulirane vodostaje. Rezultat jasno kaže, da bi modro upravljanje z izpusti iz Velikega Asuanskega jezu z uporabo kontrolno simulacijskega modela, podobnega tistemu, ki so ga razvili med izvajanjem projekta MFS, lahko zagotovilo relativno dovolj vode celo v najbolj kritičnih situacijah.

6. ZAKLJUČNE MISLI

6.1. Povprečne ploskovne padavine

V poglavju IV.1. smo pokazali, da ima na splošno MAP v celotnem prispevnem področju Nila podobno periodično obnašanje, čeprav so v amplitudah MAP med posameznimi prispevnimi področji Nila kar velike razlike. Preglednica 1 podaja nekaj osnovnih značilnosti prispevnih področij, kot smo jih spoznali v tem prispevku. Letni MAP niha od okoli 500 mm nad Atbaro in Modrim Nilom v Sudanu do več kot 1300 mm v prispevnih področjih Etiopskega višavja in Viktorijinega jezera. Z izjemo prispevnega področja Atbare ima celotno povodje relativno majhno medletno spremenljivost. Ker smo obdelali velika področja, majhna medletna spremenljivost še ne pomeni, da določena manjša prispevna področja ne morejo imeti suše, ko so v istem času druga področja poplavljena. Na osnovi mesečnih podatkov o MAP v Dongoli (torej v celotnem prispevnem področju Nila) smo odkrili periodično obnašanje z osnovno periodo 44 mesecev. Primerjava osnovnih sinusnih valov za MAP v prispevnih področjih Jinje, Diema in Dongolle kaže podobno dolgoročno periodično obnašanje. Padavine v celotnem prispevnem področju Nila torej pogojuje nek skupni globalni naravni proces.

6.2. Pretoki

Analiza podatkov v časovnem obdobju 1912–1995 kaže, da lahko na vseh obravnavanih prispevnih področjih najdemo skupen trend pretokov. Na primer, desetletna premikajoča povprečja letnih pretokov za Ekvatorialno planoto in Etiopsko višavje, ki sta glavna vira pretokov, imajo podoben trend. Amplitude so višje na Ekvatorialni planoti zaradi večje spremenljivosti MAP. Ker se celotno prispevno področje gorvodno od Malakala obnaša kot večletna akumulacija, se v primerjavi z Etiopskim višavjem pojavlja zaostanek pri odtoku z Ekvatorialne planote.

Povprečje letnega naturaliziranega pretoka v Asuanu v časovnem obdobju 1871–1998 znaša 86,81 km^3 s koeficientom spremenljivosti (CV) 0,13. Razmeroma nizek CV lahko zavede, ker amplitude nihanja niso enotno porazdeljene. Trend pretokov kaže, da se visok ali nizek letni doprinos v zaporednih letih rad združi. Tako povprečje za časovno obdobje 1971–1990 znaša 100,61 km^3, medtem ko so 82,92 km^3, 84,38 km^3 in 87,09 km^3 povprečja za sledeča tridesetletna časovna obdobja. Frekvenčna analiza kaže šibko periodičnost letnih naturaliziranih pretokov v Asuanu s periodama 9-ih in 20-ih let.

Frekvenčna analiza za prihajajočih 128 let na osnovi predpostavke, da bo prihodnji naturalizirani pretok pri Asuanu imel isto periodično obnašanje kot v preteklosti, opozarja, da obstaja velika verjetnost, da bo pretok v prihodnjih desetih letih morda bolj podoben pretokom v sedemdesetih in osemdesetih letih kot pretoku v devetdesetih letih 20. stoletja.

6.3. Proces padavine/odtoki

Koeficient spremenljivosti CV za letni MAP se znižuje od 0,12 za prispevno področje Jinje do 0,11 za prispevno področje gorvodno od Mongalle ter 0,08 za prispevno področje gorvodno od Malakala. Po drugi strani pa se CV za letni pretok znižuje od 0,32 za pretok pri Jinji in Mongalli do 0,17 pri Malakalu. Na splošno relativno majhna spremenljivost MAP nad Jinjo povzroča veliko spremenljivost pretokov. Koeficient korelacije med letnimi MAP in letnimi pretoki pri Jinji znaša 0,13, pri Mongalli 0,14 ter pri Malakalu 0,12. Med letnimi MAP in letnimi pretoki ob Belem Nilu nizvodno od Jinje torej ni nobene povezave.

Na sudansko-etiopski meji pri Diemu ter pri Kartumu na Modrem Nilu smo dobili enak koeficient spremenljivosti 0,09. Zelo podoben je tudi CV za pretoke, in sicer 0,18 za Diem in 0,17 za Kartum na Modrem Nilu. Koeficienta korelacije med letnimi MAP in letnimi pretoki znašata 0,72 za Diem in 0,73 za Kartum na Modrem Nilu. Če torej primerjamo odnos med MAP in pretokom za Modri in Beli Nil, vidimo, da obstaja precejšnja razlika. Medtem ko ob Belem Nilu med tema dvema spremenljivkama ni nobene povezave, je ob Modrem Nilu povezava med njima precej tesna. To pomeni, da se ves odtok, ki ga povzročijo padavine v določenem hidrološkem letu v prispevnem področju Modrega Nila, odraža pri Kartumu v istem hidrološkem letu, medtem ko prispevno področje Belega Nila razporedi letni pretok preko več hidroloških let in deluje kot večletna akumulacija.

Pri izračunih naturaliziranega pretoka v Asuanu uporabljajo za porabo vode v Sudanu konstantno število. Primerjava pretokov pri Kartumu na Modrem Nilu in Diemu kaže, da od leta do leta prihaja do precejšnjih nihanj (glej sliko 21). Razlik ne moremo pripisati le padavinam, ampak so tudi posledica različne porabe vode. Absoluten primankljaj pretoka pri Kartumu v primerjavi z Diemom je v letih visokih pretokov nižji ter v letih manjših pretokov višji.

Ugotovili smo, da je v časovnem obdobju 1912–1995 Beli Nil z reko Sobat prispeval v povprečju 29,4 % k pretoku Nila ali pritoku v Naserjevo jezero (glej sliko 22). Našli smo dve značilni časovni obdobji: prvo od leta 1912 do začetka šestdesetih let ter drugo po tem. V prvem obdobju je bil povprečen prispevek nižji, le okoli 25 %. Ob začetku šestdesetih let pa je Beli Nil prispeval skoraj 40 %; ta odstotek od takrat enakomerno pada.

6.4. Veliki Asuanski jez kot večletna akumulacija

Poskus simulacije parametrov Velikega Asuanskega jezu za časovno obdobje 1872–1998, torej za časovno obdobje 128-ih let, z uporabo aktualnih parametrov (vodostaj za izpust po zasilnem kanalu, maksimalen izpust, uporaba vode v Sudanu, itd) kaže, da je možno upravljati izpuste iz Velikega Asuanskega jezu tako, da se izognemo morebitni škodi egiptovskemu vodnemu gospodarstvu, če njegove potrebe po namakanju ostanejo na trenutni stopnji (55,6 km^3 na leto) ter če predvidevamo, da bodo bodoči pretoki ohranili statistično in periodično obnašanje, kot so ga imeli v preteklosti. Uvedba kontrolno simulacijskih modelov nedvomno izboljša upravljanje.

Poskus z naraščajočo porabo vode gorvodno kaže, da je možno zagotoviti dovolj vode za Egipt s sedanjimi potrebami namakanja, če se poraba vode gorvodno v Sudanu poveča s sedanjih 18,5 km^3 na leto na 25 km^3. Modro upravljanje izpustov iz Velikega Asuanskega jezu nedvomno zahteva kontrolni sistem za Veliki Asuanski jez, kot so ga razvili med izvajanjem projekta MFS in ki lahko razširi primanjkljaj glede na potrebe namakanja preko daljšega časovnega obdobja, da se tako izogne hudi škodi v primeru nenadnega popolnega pomanjkanja.