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Implications of Ethiopian water development for Egypt and Sudan

Giorgio Guariso and Dale Whittington

This paper examines the implications for Egypt and Sudan of the development of Blue Nile water resources by Ethiopia. The long-term development progamme produced between 1958 and 1963 by the Ethiopian government in collaboration with the US Bureau of Reclamation is summarized. A linear programming model is used to examine the effects on Egypt and Sudan of implementing this programme. It is found that water for agricultural use in Egypt and Sudan would actually increase, though there would be some adverse consequences for Egypt.

From 1958 to 1963 the United States Bureau of Reclamation (Department of Interior) and the Ethiopian Ministry of Public Works and Communications collaborated on a major study of the development potential of the water resources of the Ethiopian portion of the Blue Nile for irrigation and hydroelectric power generation. At the time of the study Ethiopia was allied with the United States and Egypt with the Soviet Union. Today the alliances have reversed and, perhaps as a result, the findings of the study have received little attention from students of Nile water management (see Waterbury, 1982, for an exception).

The subject of this paper is the implications for Egypt and Sudan of the likely long-term development of the Blue Nile resources in Ethiopia. Our discussion of the Blue Nile's investment potential for Ethiopia is based on the Bureau of Reclamation's study. We first summarize the long-term investment programme it recommended. The regulatory projects described in that investment plan would have important effects on the flow of the Blue Nile throughout its course, and on the Main Nile downstream. We then present a linear programming model which we use for examining the consequences of such changes for Egypt and Sudan, and discuss the results of our analysis. Our conclusions are somewhat speculative, because the full-scale development of reservoirs on the Blue Nile in Ethiopia would certainly take several decades. Yet given the economic and population growth in the Nile basin, and its strategic importance, projects proposed for the Nile have a certain inevitability about them – particularly projects as economically attractive as those detailed in the Bureau of Reclamation study. It is thus perhaps useful to have a vision of the possible ultimate development of the Nile system when decisions are made on more short-term investment plans.

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Overview of the Bureau of Reclamation study

Blockage or diversion of the Blue Nile has been an enduring fear in Egypt and a persistent threat by Ethiopia (Waterbury, 1982), but until the Bureau of Reclamation reconnaissance study of the water resources of the Blue Nile Basin, the practicality of extensive reservoir development on the Blue Nile in Ethiopia was essentially unknown. Engineering proposals for the regulation of Lake Tana, at the headwaters of the Blue Nile (see Figures 1 and 2), date back at least to the early twentieth century (Dupuis, 1904), and several subsequent studies have

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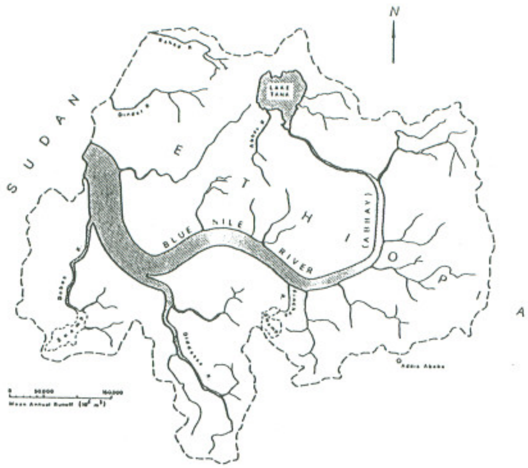

Figure 1. Blue Nile runoff distribution (flow-rate is proportional to the width of the line).

Source: Bureau of Reclamation (1964).

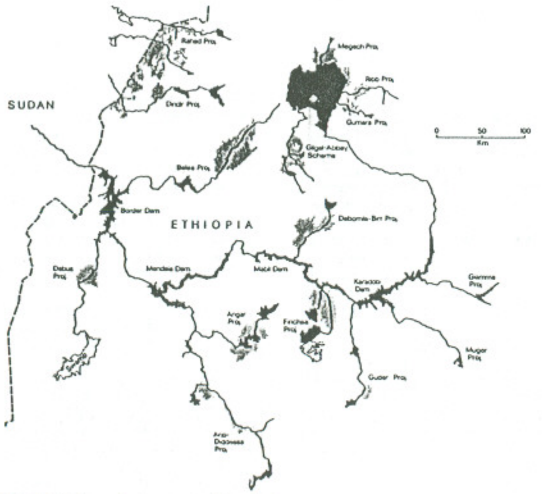

Figure 2. Main projects proposed for the Blue Nile in Ethiopia.

Source: Bureau of Reclamation (1964).

focused on the feasibility of regulating its outflow, most of them concerned largely with the benefits of such regulation for Egypt.

For several reasons, however, the development of the Blue Nile downstream from Lake Tana was largely ignored. First, the area from Lake Tana to the Ethiopian–Sudanese border was inaccessible and poorly mapped. The first recorded journey down the full course of the Ethiopian Blue Nile was made during 1926–29 by the English consul Major Cheesman (Bureau of Reclamation, 1964). He was the first to suggest two possible reservoir sites along the Blue Nile, but neither seemed to him very promising. It was known, for example, that the Blue Nile flowed through deep canyons, which suggested that high dams would be required, with probably small capacities (Hurst, Black and Simaika, 1951). Second, Nile water resource planners as early as Garstin (1904) worried that the huge volumes of sediment carried by the Blue Nile would rapidly silt up any major reservoir. Third, Egyptian interest in regulation of the Blue Nile was limited to increased,

Table 1. Summary data on US Bureau of Reclamation's proposed irrigation and power projects in the Blue Nile Basin.

Item	Project	Purpose	Reservoir: Source (river)	Reservoir: Initial capacity (million m³)	Construction cost (Eth $1000)	Irrigable area (hectares)	Annual water requirement (million m³)	Installed kilowatts	Benefit/cost ratio
1	Megech Gravity	Irrigation	Megech	225.3	76 028	6 940	93		0.46 to 1
2	Ribb River	Irrigation	Ribb	312.6	78 405	15 270	194		0.95 to 1
3	Gumara River	Irrigation	Gumara	236.7	79 633	12 920	163		0.83 to 1
4	West Megech Pump	Irrigation	Lake Tana	12 987.0	12 617	7 080			1.49 to 1
5	East Megech Pump	Irrigation	Lake Tana	12 987.0	11 488	5 890	101		1.36 to 1
6	Northeast Tana Pump	Irrigation	Lake Tana	12 987.0	9 634	5 000			1.47 to 1
7	Upper Beles[a]	Multipurpose	Lake Tana	12 987.0	346 717	63 200	994	200 000	3.04 to 1
8	Middle Beles[b]	Power	Beles	3 974.0	213 737			168 000	2.58 to 1
9	Upper Birr	Irrigation	Birr	537.4	140 718	24 350	299		1.00 to 1
10	Debohila	Irrigation	Debohila	50.1	43 531	4 200	56		0.59 to 1
11	Lower Birr	Irrigation	Birr	Run of river	12 300	6 600	85		3.30 to 1
12	Giamma River[b]	Power	Giamma	3 169.0	269 040			60 000	0.72 to 1
13	Muger River[b]	Power	Muger	300.7	31 088			26 000	2.42 to 1
14	Upper Guder	Irrigation	Bello	70.6	13 962	5 100	51		1.54 to 1
15	Lower Guder[a]	Power	Guder	2 557.0	126 848			50 000	1.21 to 1
16	Finchaa[a]	Multipurpose	Finchaa	464.0	86 127	15 000	210	80 000	3.44 to 1
17	Amarti-Neshe[a]	Multipurpose	Amarti and Neshe	847.6	123 020	8 490	116	80 000	2.38 to 1
18	Arjo-Diddessa[a]	Multipurpose	Diddessa	2 130.0	161 211	16 800	183	30 000	2.11 to 1
19	Dabana[a]	Multipurpose	Dabana	1 617.0	358 368	6 100	86	85 000	0.93 to 1
20	Angar[a]	Multipurpose	Angar	3 572.0	469 935	30 200	416	185 000	1.93 to 1
21	Lower Diddessa[a]	Power	Diddessa	4 862.0	404 885			320 000	2.09 to 1
22	Dabus	Irrigation	Dabus	Direct diversion	23 433	15 000	205		3.03 to 1
23	Dabus[a]	Power	Dabus	Run of river	9 622			7 500	2.08 to 1
24	Dinder[b]	Multipurpose	Dinder	3 690.0	448 472	58 300	1 145	40 000	1.22 to 1
25	Galegu	Irrigation	Galegu	798.8	211 706	11 600	225		0.45 to 1
26	Rahad	Irrigation	Rahad	1 902.0	243 130	53 100	1 043		1.55 to 1
27	Karadobi[b]	Power	Blue Nile	32 500.0	1 031 002			1 350 000	3.16 to 1
28	Mabil[b]	Power	Blue Nile	13 600.0	851 079			1 200 000	3.65 to 1
29	Mendaia[b]	Power	Blue Nile	15 930.0	1 003 829			1 620 000	4.35 to 1
30	Border[b]	Power	Blue Nile	11 074.0	942 805			1 400 000	3.74 to 1
31	Addis Ababa-Assab Trans[a]	Power			84 891			–	–
32	Jiga Spring Pilot	Irrigation	Turkar Spring	Direct diversion	210	224	3	–	–
33	German Gilgel Abbay[a]	Multipurpose	Jema, Koga, Gilgel Abbay	1 017.0	Not available	62 390	693	63 665	–
	Totals			118 427.8	7 919 525	433 754	6 367	6 965 165	

[a] Present century, power facilities.
[b] Next century, power facilities.
Source: Bureau of Reclamation (1964).

reliable water supply for irrigation downstream. The tremendous hydroelectric potential of such reservoirs for Ethiopia was not a primary concern, and throughout the twentieth century Ethiopia itself has not been in a position to utilize large additional supplies of electricity effectively because of its limited economic development.

The scope of the Bureau of Reclamation study included the entire Blue Nile Basin in Ethiopia, not simply the main channel, and provided the first detailed account of the Blue Nile region, including its hydrology, water quality, geology, physiography, mineral resources, sedimentation, land use, groundwater and local economy. Of particular importance for water planning was the establishment of streamflow measurements throughout the basin (59 gauging stations) and extensive aerial surveys and mapping.

The irrigation and hydroelectric projects recommended in the Bureau's investment programme are summarized in Table 1 and Figure 2. The Bureau concluded that there are no lands along the Blue Nile which can be irrigated; the proposed irrigation schemes are located primarily in the plateau valleys at elevations between 335 and 920 m, chiefly (1) around Laka Tana, (2) on the Sudanese–Ethiopian border, and (3) on the Angar and Finchaa tributaries (see Figure 2). The total area of the proposed projects would be about 434 000 ha (about 17% of the current irrigated area of Egypt) with an annual water requirement of roughly 6 billion m^3 (1 billion $= 10^9$).

The major hydroelectric projects, however, lie on the Blue Nile between Lake Tana and the Sudanese border. Figures 2 and 3 show the location of the four dams proposed for the Blue Nile downstream of Lake Tana: Karadobi, Mabil, Mendaia and the Border Project. Together these four dams would have an initial active storage capacity of about 51 billion m^3 and an estimated annual electricity generation of over 25 billion KWh, about three times the actual production of the Aswan High Dam. The annual mean flow of the Blue Nile at the Sudanese–Ethiopian border is about 50 billion m^3; thus the combined active storage would be approximately equal to the mean annual flow. The storage capacity of the Karadobi Dam, the largest of the four, would be twice the mean annual flow of the Blue Nile at the site. Other hydroelectric and multipurpose projects included in the Bureau's plan would add an additional 5 billion to 10 billion KWh per year. As noted in Table 1, the Bureau estimated that all four of the major hydropower projects on the Blue Nile would have benefit/cost ratios greater than 3, based solely on hydroelectric benefits.

The Bureau's report does not include a detailed economic analysis of the optimal scheduling of the investment projects. It suggests, however, that the Finchaa, Dabana, Upper Beles, Dabus, Lower Diddessa, Lower Guder, Arjo-Diddessa, Angar, Amarti-Neshe and Gilgel Abbay projects would be the most desirable for the remainder of the twentieth century. It was believed that the four major hydroelectric dams on the Blue Nile were all too large to be efficiently integrated with the Ethiopian economy in the near term and would be more profitably delayed until the next century. In this sense the Bureau was probably overly optimistic.

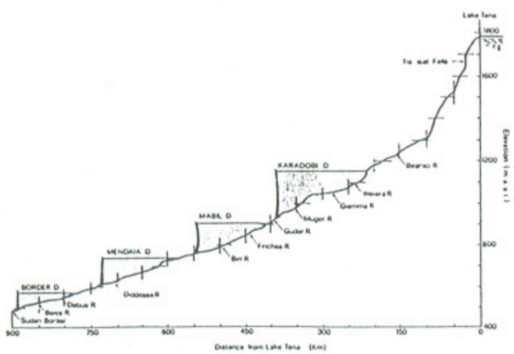

Figure 3. Profile of proposed Ethiopian hydroelectric dams on the Blue Nile.

Source: Bureau of Reclamation (1964).

Twenty years after the release of the study, only one of the proposed projects has been completed. The Finchaa hydropower plant was appraised by the World Bank in 1969 and has been in operation since 1972. The European Economic Community is presently financing a diversion of the Amarti river which will increase the available flow and thus increase hydropower generation at Finchaa (Whittington and Haynes, 1985).

Although the Bureau's plan for the operation of the reservoirs was not based on explicit optimization studies, the simple routing calculations supplied in its report illustrate the dramatic effects that the four hydroelectric dams on the Blue Nile would have on the fluctuations of the river flow. Figure 4 presents the monthly flows of the Blue Nile at Roseires in Sudan (100 km from the Ethiopian border) for high, mean and low years. Because the reservoirs would be operated to maximize firm hydropower, management policy during a normal year would be to store as much of the late summer and early autumn floodwaters as possible for release the following winter and spring. Figure 5 presents the results of the Bureau's regulation plan for the four reservoirs. Projections were based on the 1911–17 hydrology, a sequence containing one very low and two high floods. For this sequence of years, the flow reaching Sudan is almost constant, both throughout the year and over the multiyear period. As projected, the annual Nile flood would be effectively eliminated. The pattern of flows entering Sudan during a series of years with consecutive high floods would show more variation, but the dampening effect on the seasonal flood would still be very strong. From the 1911–17 data the Bureau concluded that total annual flows of the Blue Nile reaching Sudan would be reduced 8.5% as a result of Ethiopian development (both irrigation withdrawals and evaporation losses from the reservoirs).

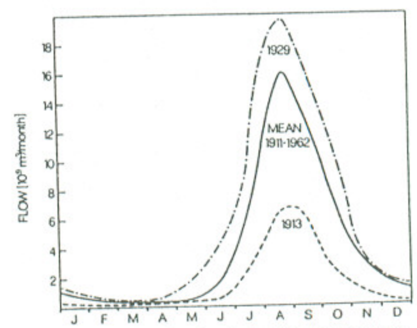

Figure 4. Blue Nile at Roseires during high, mean and low years.

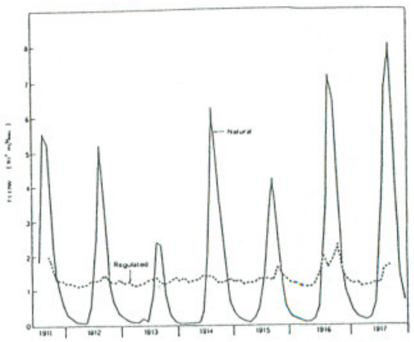

Figure 5. Hydrograph of Blue Nile flows below Border Dam (Sudanese–Ethiopian border) before and after water development projects in Ethiopia.

Source: Bureau of Reclamation (1964).

Model formulation

We have constructed a classical multiobjective programming model to explore the impact of potential Ethiopian developments on Sudanese and Egyptian uses of Nile water. Our basic assumptions are that the operation of the four projected Ethiopian reservoirs on the Blue Nile (see Figure 2) can be approximated by a single reservoir with their combined capacities, and that the Ethiopian objective in managing this reservoir is to maximize hydropower production, which we assume can be approximated by maximizing the volume of water released in the monthly pattern of future power needs, as estimated by the Bureau of Reclamation (1964).

Two points are worth emphasizing about these assumptions. First, the release of water in a given pattern is only one of the two principal factors affecting hydropower production; the second is the head on the turbines, which is not included in our formulation. Second, assuming the existence of a single large reservoir instead of four separate ones gives the reservoir manager more freedom to shift volumes of water from one season to another than actually exists. However, because the total active storage in the four Ethiopian reservoirs would be larger than the mean annual inflow volume, the reservoir manager with four separate reservoirs should have considerable flexibility to utilize their combined storage capacity effectively. Moreover, evaporation rates and surface-to-volume relationships of the three upstream reservoirs (Karadobi, Mabil and Mendaia) are quite similar. The fourth reservoir (Border) is located in the Blue Nile plain and thus differs substantially from the other three, but it also has the smallest volume. We examine the problem of the annual operation of the system of reservoirs: how a certain annual inflow should be allocated between the different months.

The objective functions of Egypt and Sudan are assumed to be the maximization of the volumes of water released from their major reservoirs (Aswan and Roseires respectively) in the patterns of their respective agricultural needs. Their separate objectives are, however, linked in the model by the requirement of the 1959 Nile Waters Agreement (signed by the two countries, but never recognized by Ethiopia) that any increases or decreases in Nile water availability must be shared equally by Egypt and Sudan. Thus maximizing water to Egypt or Sudan corresponds to maximizing the share of the other party, and the overall problem can be reduced to two objectives: maximizing hydropower in Ethiopia, and maximizing the water supply in the agricultural pattern downstream.

The model can de defined as follows. Let P be the volume of water released by the Ethiopian reservoir in the pattern of future power consumption, described by the monthly coefficients α_t^1, $t = 1,\ldots,12$ and $\sum_{t=1}^{12} \alpha_t^1 = 1$. Let A be the mean annual volume of the Blue Nile water used by Sudan according to the pattern of monthly agricultural requirements given by the coefficients α_t^2, $t = 1,\ldots,12$ and $\sum_{t=1}^{12} \alpha_t^2 = 1$. The fulfilment of the Nile Waters Agreement is assured by increasing the Egyptian share, defined by the coefficients α_t^3, $\sum_{t=1}^{12} \alpha_t^3 = 1$ by the same amount supplied to Sudan.

The formulation is thus

$$\text{Max}\ \{R_t^i, V_t^i\} \mid P\,A \mid i = 1,2,3;\ t = 1,\ldots,12 \qquad (1)$$

$$V_t^i + 1 = V_t^i + I_t^i - R_t^i - L_t^i \qquad (2a)$$

$$m^i \leq V_t^i \leq M^i \qquad (2b)$$

$$V_{13}^i = V_1^i \qquad (2c)$$

$$R_t^1 \geq \alpha_t^1 P \qquad (3a)$$

$$R_t^2 \geq \alpha_t^2 A \qquad (3b)$$

$$R_t^3 \geq \alpha_t^3 (59.4 + E) \qquad (3c)$$

$$E = A - (22.4 - W^s) \qquad (4)$$

$$R_t^i, V_t^i, P, A \geq 0 \qquad (5)$$

where i = 1,2,3 represents each reservoir (1 = Ethiopian, 2 = Roseires, and 3 = Aswan High Dam Reservoir); V_t^i, I_t^i and R_t^i are the monthly volumes, inflows and releases, m^i and M^i are the limits of their active storages; L_t^i are reservoir losses; and 59.4 and 22.4 are the Egyptian and the Sudanese shares (in billion m^3) according to the Nile Waters Agreement, supplemented by water development projects on the White Nile. A sketch of the complete system of reservoirs and water uses represented by the model is given in Figure 6.

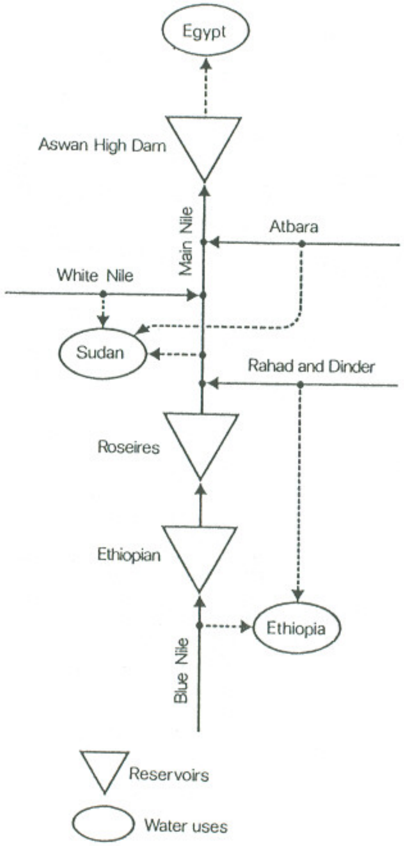

Figure 6. A scheme of reservoirs and consumptive water uses considered in the model.

The mathematical program is constructed on a monthly basis. The decision variables are the monthly releases and volumes of the Aswan High Dam Reservoir, Roseires, and the Ethiopian reservoir. Several constraints are applied: continuity equations (2a) and the capacities of the three reservoirs (2b); a guarantee that downstream water requirements are met from inflows and not from reservoir volumes (2c) (the solution can be repeated for any number of years provided the annual sequence of inflows remains the same); the pattern of water requirements for agriculture and hydropower generation (3); and the fulfilment of the 1959 Nile Waters Agreement (4). The increased supply to Egypt (E) is in fact set equal to the increased supply to Sudan, which in turn is equal to its share under the agreement (22.4 billion m^3) minus abstractions from the White Nile (W^s). According to Sudanese development plans for the White Nile region, these abstractions are estimated to increase to 8.1 billion m^3 annually. The continuity equations (2a) differ for the values of the inflows I^i and of the losses L^i. I_t^1 is simply the mean monthly flow of the Blue Nile at the Egyptian–Sudanese border, I_t^2 is a fraction of β_t^i ($\beta_t^i < 1$, $t = 1,\ldots,12$, to account for losses) of the release R_t^1 from Ethiopia, and $I_t^2 = \beta_t^2 (R_t^2 - \alpha_t^2 A) + W_t^E$ (inflows to the Aswan High Dam Reservoir are a percentage β_t^2, which again accounts for losses, of what is released from Roseires and not used by Sudan, plus an addition W_t^E due to flows from the White Nile and the Rahad, Dinder and Atbara rivers). Losses (in equations 2a–c) from the reservoirs are computed by assuming three linear relationships between surface area and storage multiplied by three sets of monthly evaporation loss coefficients.

Because the development of the Ethiopian reservoirs is some time away, all the data used in the program have been modified to depict future conditions in the Nile Basin. For example, it is assumed that the Jonglei Canal and the Machar Marshes projects on the White Nile have been completed, yielding an increased mean annual flow of 3.8 million and 4.0 million m^3 respectively, shared equally by Egypt and Sudan. (A detailed discussion of the assumptions used to represent future conditions appears in one of our earlier publications; see Whittington and Guariso, 1983, Chapter 7).

Results of the analysis

The solution of the model, associated with a sequence of inflows for an average year, shows that the objectives of Ethiopian hydropower production and Sudanese and Egyptian agricultural water use are not conflicting. There is less than 1% variation in the results between the cases in which A and P are maximized separately. Thus even if Ethiopia were simply to pursue its own objective of managing its reservoir to maximize hydropower production, without considering the interests of Egypt and Sudan, the amount of water available to the downstream riparians would not be substantially affected.

For purposes of illustration, we have arbitrarily selected a point of the Pareto optimal set for which a cubic metre of water has the same value in Ethiopia, Sudan and Egypt. Other points with different relative values of water yield only marginally different results. If the Bureau of Reclamation's plans were completed, which implies water consumption in Ethiopia of about 6 billion m^3, mainly abstracted from the Blue Nile, the Rahad and the Dinder (see Table 1), Ethiopia would be able to gain full control of the Blue Nile during a mean year, and thus release 46.9 billion m^3 in its desired pattern. Roughly 3% of the total inflow would be lost to evaporation in Ethiopia or to flows outside the desired pattern. During mean conditions only half of the active capacity of the Ethiopian reservoir would be used; the maximum level would be reached in November at the end of the flood. Figure 7a summarizes these results by comparing the actual pattern of Blue Nile flows and the optimal releases from the Ethiopian reservoir.

The model solution also shows that Sudan would receive an annual allocation of 25.1 billion m^3, 2.7 billion more than its current share under the Nile Waters Agreement, and suggests that Roseires should be filled at the beginning of the calendar year, when water requirements in both Egypt and Sudan are low, for release during the spring and summer period of low flow. More precisely (see Figure 7b), the highest release should be in May, so as to reach Egypt before the period of highest water requirements and yet spare as much as possible the high evaporation losses of the Aswan High Dam Reservoir. In turn the Aswan reservoir should be kept relatively high from November through March, and reach its minimum level in September after the peak of summer agricultural water use.

This deterministic, periodic solution of the management problem would use less than 10% of the active storage of the Aswan High Dam Reservoir; the minimum level corresponds to dead storage. Obviously this is an unrealistic operating policy because of the threat of low floods. But it is interesting to compare this solution with that for the case in which Ethiopia would not implement any of the Bureau's investment plan. In the latter case,

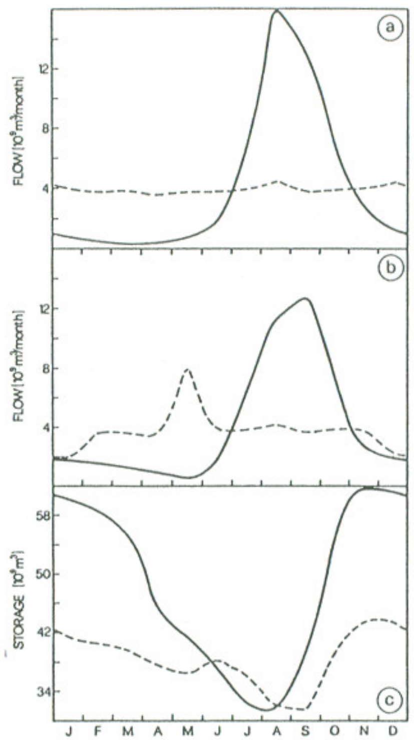

Figure 7. Optimal management of the Nile system during a mean year with (dashed lines) and without (solid lines) the Ethiopian reservoir: (a) flows at the Ethiopian border; (b) releases from Roseires; (c) storage in the Aswan High Dam reservoir.

both the releases from Roseires (solid line, Figure 7b), and consequently the storage in the Aswan High Dam Reservoir (solid line, Figure 7c), would vary more widely. Up to 23% of the active storage of the Aswan reservoir would be used, implying higher evaporation losses which would reduce the Sudanese and Egyptian allocation to 22.9 billion and 59.9 billion m^3 respectively. That both Sudanese and Egyptian allocations could still be higher than their share under the Nile Waters Agreement is simply due to the Aswan reservoir's being operated at relatively low levels, thus reducing evaporation losses below the estimates in the treaty. In fact Egypt could have withdrawn about 6 billion m^3 more water in its agricultural water pattern (and certainly would have), but Sudan would have been limited by the capacity of the Roseires reservoir (which we have assumed is heightened to 490 m). The significance of this capacity constraint at Roseires is confirmed by examining its shadow value in the two cases. When Ethiopian development is assumed, the shadow value is negligible, but it is quite substantial if there is no upstream storage in Ethiopia.

Other model solutions show that if Ethiopia developed only its hydropower facilities (but not the proposed irrigation schemes), Sudan and Egypt could increase their allocation by 3.9 billion m^3 each. The model was also solved for a very high year (1929), but there was no substantial change in the overall management policy (though clearly the values of the objectives would change). Even in a high year Ethiopia would be able to utilize all its inflows effectively without being constrained by reservoir capacity. Dealing with very low years would involve the adoption of some policy to decrease agricultural water consumption (see Whittington and Guariso, 1983, Chapter 6), a complication that cannot be adequately addressed in this simple model.

Additional discussion

We have interpreted the management problem as one of balancing the interests of Ethiopia and the downstream states, Egypt and Sudan, but in fact the results show that there is very little conflict between their objectives as represented in the model. Contrary to Egyptian and Sudanese perceptions, everyone would benefit from increased regulation of the Blue Nile flood in Ethiopia. Both Egypt and Sudan would have more water available for agricultural development (though at a cost to Egypt of reduced hydropower from the Aswan High Dam and less secure control of its water supply). Interestingly, Egypt and Sudan could achieve such water savings without a cooperative agreement with Ethiopia on the operation of the system of Ethiopian reservoirs, provided Ethiopia can be counted on to act in its own interest. Of course, if Ethiopia were to act strategically and withhold water during a drought, the consequences for Sudan and Egypt would be disastrous. If Ethiopia attempted to maximize the water available for hydropower production, the resulting pattern of flows into Sudan and then Egypt would be a clear improvement for both downstream riparians. Indeed such a relatively constant inflow pattern (as evident in Figures 5 and 7a) would typically be ideal from the perspective of the

reservoir manager. The situation would be slightly less favourable for downstream riparians if Ethiopia decided to add agricultural uses to its development plans. The solution of the model shows, however, that even if the plans of the Bureau of Reclamation were to be fully implemented (6 billion m^3 of water used in Ethiopia), Egypt and Sudan would still benefit from construction of the reservoirs; losses and constraints in the systems would only entail a total reduction of 2.4 billion m^3 to Sudan and Egypt with respect to the *maximum* potential they could attain.

The regulation of the Blue Nile would be particularly beneficial for Sudan. Many of the current problems of operating the Roseires reservoir would be substantially reduced, if not eliminated. As previously mentioned, Roseires now functions as a seasonal storage reservoir to capture the tail of the annual flood, thus minimizing siltation problems. The storage is used to supplement flows in spring and summer to meet irrigation demands and low flow requirements at Khartoum, but the gates are completely opened in the flood season to flush out sediment. High flows during the late summer and early autumn thus reduce the available head for hydroelectric power generation and can dramatically reduce the available power in the Blue Nile grid, resulting in interruptions in supply throughout the region (including Khartoum). Moreover, debris from upstream has created problems for the hydroelectric facilities, requiring expensive removal operations. The model results show that with increased regulation upstream, Roseires could be filled later, and would essentially function as a barrage to raise water and as a hydroelectric generation facility.

Perhaps most importantly, the added storage upstream in Ethiopia is needed by Sudan for the long-term expansion of its gravity-fed irrigation area. Siltation is reducing the storage capacity of Roseires much more rapidly than originally anticipated. From the completion of the reservoir in 1964 until 1976, 75% of the reserved dead storage was filled (Blue Nile Consultants, 1978). The currently accepted solution is to heighten Roseires to 490 m, thus adding approximately 4 billion m^3 of storage. It is estimated that this additional storage would permit the maintenance of existing irrigation schemes and provide water for a modest expansion of the irrigated area. This is not, however, a long-term solution. On the basis of siltation estimates available in the mid-1970s, Blue Nile Consultants (1977) estimated that storage gains from heightening Roseires would be sufficient only until 2010. Regulation of the Blue Nile in Ethiopia would reduce the sediment loads reaching Roseires (as well as Aswan), preserving more storage for expansion of irrigation. This does not mean that Ethiopian reservoirs would 'solve' the siltation problem (except for some attenuation due to reduced speed and consequent reduced sediment load in the upstream stretches of the Blue Nile), but they would introduce more dead storage into the system, prolonging the life of existing reservoirs and distributing total siltation more evenly along the river channel.

Sudan is also a likely market for the tremendous amounts of electricity which could be generated in Ethiopia. It should prove to be in Sudan's and Ethiopia's interest to develop an integrated power development programme. In fact, there have recently been unofficial discussions going on between Sudan and Ethiopia regarding a link between the electricity networks of the two countries. Other markets for Ethiopian hydropower which are being considered are Djibouti and Aden (possibly linked by an undersea cable).

In addition, the more constant flow of the Blue Nile might change the water quality of the river, in ways which are difficult to foresee. Current minimum flows at Khartoum would be easier to maintain. Maghrabi (1983) has noted that macrophytes are now appearing in the Blue Nile farther north than they were previously found, and he speculates that this is due to reduced flows in the main channel. It is possible that improved regulation upstream would reverse this development.

On the other hand, one likely detrimental consequence of Ethiopian regulation would be reduced flows into Sudan from the Rahad and Dinder rivers (see Figure 1). The Dinder and Rahad irrigation projects proposed in the Bureau of Reclamation's investment programme for Ethiopia would each entail annual water requirements of over 1 billion m^3. It is difficult to estimate the extent of return flows from these projects or the reductions in flows reaching Sudan, but reduction would clearly be dramatic for the Rahad. It is currently planned to irrigate the Rahad I and II schemes in Sudan by pumping water from the Rahad when available, supplemented by water from Roseires. Ethiopian development of the Dinder and Rahad projects could likewise result in problems for nomads and the local population in Blue Nile province of Sudan. Moreover, elimination of the floodwaters in the Dinder and Rahad rivers would reduce aquifer recharge, which might disrupt yields of existing wells. Another potentially serious consequence for Sudan could be channel degradation resulting from reduced sediment loads.

In some of our previous work we have examined the possibilities for coordinated operation of the Aswan High Dam and a proposed reservoir at Lake Mobutu on the White Nile at the Sudanese–Ugandan border (Whittington and Guariso, 1983, Chapter 7). The proposed Ethiopian reservoirs discussed here are much more attractive than overyear storage on the White Nile, from the perspective of both hydropower and downstream water regulation. Storage on the White Nile is useful, but it clearly cannot directly address the major regulation problem in the Nile system: the extreme variability of the Blue Nile flows. Our results suggest that it would not be necessary to fill the Ethiopian reservoirs during a mean hydrological year, which indicates that these reservoirs could also serve a major overyear storage role as well. This would give Egypt the opportunity to operate the Aswan High Dam at substantially lower levels, thus significantly reducing the evaporation losses anticipated in the 1959 Nile Waters Agreement, and substantially increasing available water supplies in the basin. Spills from the Aswan High Dam Reservoir through the Tushka Canal might also be eliminated.

The model results also highlight the high costs of the present lack of cooperation between Sudan and Ethiopia. Despite our demonstration that Sudan does not really need an agreement with Ethiopia on the *operation* of the Ethiopian reservoirs, it is in Sudan's interest to ensure that they are eventually built. Construction of any of the four projected dams upstream of Sudan in Ethiopia would probably be preferable, for both Ethiopia and Sudan, to heightening Roseires as proposed in the Blue Nile Consultants study (1978), currently under consideration by the United States Bureau of Reclamation for the Sudanese Ministry of Irrigation. The volume-to-surface relationship for Roseires is particularly poor, and heightening the dam would increase losses with only a modest gain in storage capacity.

Conclusions

The main points of our analysis are as follows:

(1) Full development of the Blue Nile in Ethiopia would effectively end the annual Nile flood.
(2) If Ethiopia were to develop the Blue Nile basin, the amount of water available for agricultural use in Egypt and Sudan would actually increase, because the river could be more easily regulated downstream, thus reducing storage requirements in Sudan and evaporation losses from the Aswan High Dam Reservoir.
(3) There is little, if any, conflict between the riparian states on the broad policy of how such reservoirs in Ethiopia should be operated.
(4) Cooperation between Sudan and Ethiopia is important to ensure that the development of a system of reservoirs on the Ethiopian Blue Nile proceeds expeditiously. If such cooperation can be achieved in the near term, heightening Roseires dam is likely to be a poor investment.
(5) Ethiopia's development of the proposed irrigation schemes along the Dinder and Rahad rivers would heavily impact downstream users and thus clearly conflicts with Sudanese development plans.

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Water management in the Gezira Scheme

Gilbert Levine and Charles Bailey

Water management procedures and institutions have been quite effective in serving the needs of agriculture in Sudan's Gezira Scheme over the last decades. However, through changing circumstances and natural evolution of the scheme further opportunities for improvement have emerged. Realizing these opportunities will depend in part on further research and field testing of alternatives.

The Gezira Scheme has been the subject of considerable concern and attention in recent years because of the deterioration of its physical infrastructure and the presumed impact of this on the agricultural performance of the system. There is growing realization, however, that the future performance of the system will depend on more than just the restoration of the physical infrastructure to a standard that existed at some time in the past. Areas of concern include questions relating to the agricultural and water management of the scheme, the responsibilities of the Sudanese Ministry of Irrigation (MOI) and the Sudan Gezira Board (SGB), the relations between these agencies and the tenants, and larger-scale issues that affect the overall economy of Sudan.

The general issue of water distribution has been a topic of discussion for many years among all those connected with the scheme. It is of continuing importance, particularly in light of the Gezira rehabilitation and modernization programme. The primary purpose of this paper is to highlight some of the key water management issues. Following a brief introduction to the Gezira Scheme, we present a framework for this analysis and then discuss technical, behavioural and macro-level planning issues.

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The Gezira Scheme

The Gezira Scheme covers an area of about 2.1 million feddans (1 feddan = 1.038 acres) lying between the Blue and the White Niles south of Khartoum (Figure 1). Its principal features are a level and nearly uniform topography of water-retentive clay soils, centralized control of farming operations by the SGB, a narrow range of variation in farm size, and a regulated cropping pattern of cotton, groundnuts and sorghum in summer and wheat in winter. The scheme is divided into roughly equal halves: the area brought under irrigation between 1925 and 1958, and the Managil Extension developed over the course of the 1960s and early 1970s to the west and south. In the older portion of the scheme crop rotation follows a four-year pattern, including a year of fallow. In Managil the land is continuously cropped.

The arid climate necessitates irrigation of both summer and winter crops; this is effected by diversion of a portion of the flow of the Blue Nile at Sennar Dam just south of the scheme. Irrigation is primarily by gravity flow. Two parallel canals leave Sennar Dam and merge into a common pool downstream at km 57. From there one main and three subsidiary canals diverge westwards to serve Managil, and a second main canal continues northwards into the older part of the scheme. Each of these canals subdivides into branch, major and minor canals of varying sizes. Minor canals supply water to tertiary canals, called Abu Ishreens (Abu XXs), which irrigate cropping units (blocks) of

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