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Volta Basin Water Balance

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Acknowledgements

This paper is a preliminary exploration of some of the Volta River Basin hydrologic data gathered in support of the GLOWA Project proposal: Nachhaltiger Umgang mit der Ressource Wasser: Intensivierte Landnutzung, Niederschlagsvariabilität und Wasserbedarf im Voltabecken (Sustainable Use of Water Resources: Intensified Land Use, Rainfall Variability and Water Demands in the Volta Basin) under the Globaler Wandel des Wasserkreislaufes (GLOWA), Global Change in the Hydrologic Cycle, of the Ministry of Education, Science, and Technology (BMBF). The generous financial, technical, and administrative support extended by the Zentrum für Entwicklungsforschung (ZEF) is acknowledged. The contribution of Prof. Dr. Daniel Hillel whose thoughtful comments did much to improve this article is also gratefully acknowledged. Special thanks go to Prof. Dr. Paul Vlek and the gracious staff of ZEFc. Special thanks also go to Jan Friesen and Michaela Weber whose enthusiastic and unwavering support is greatly appreciated.

Abstract

Water balances pertaining to the flux of water through the Volta River Basin and a black box model of the rainfall/runoff relationship for estimating the river flows into the Akosombo Reservoir are presented. As the water demand has approached supply, the tradeoffs between competing water uses are likely to intensify. It is also apparent from the balances that land use and land cover changes in the uplands of the basin are destined to play a pivotal role in determining the future of the basin.

Kurzfassung

Im folgenden werden die sich auf den Abfluss beziehenden Wasserbilanzen des Volta Beckens, sowie ein Black Box Modell der Niederschlags-/Abflussrelation, um die Zuflüsse in den Akosombo Damm zu berechnen, vorgestellt. Mit der zunehmenden Angleichung des Wasserangebots an die Nachfrage ist es wahrscheinlich, dass sich der Austausch konkurrierender Wassernutzungen intensivieren wird. Aus den Wasserbilanzen wird offensichtlich, dass Landnutzungs- und Landbedeckungsänderungen in den höher gelegenen Gebieten des Beckens eine zentrale Rolle bei der zukünftigen Planung des Volta Beckens spielen werden.

1 Introduction

When Ghana gained its independence in 1957, it was a largely agrarian society with very little modern infrastructure. Ghana's leaders saw industrialization as essential to the development of the country and electric power from the Volta River Project (VRP) as central to that industrialization (Government of Ghana, 1961). The shear size of the Volta River and the important role the VRP plays in the development of the country require that particular attention be drawn to the hydrological management of the Volta Basin. With the intensification of land use within the basin, the increasing demand for VRP power, and the competing demands for Ghana's water resources, there is an ever more pressing imperative to develop sustainable water management strategies.

The GLOWA proposal, "Sustainable Use of Water Resources: Intensified Land Use, Rainfall Variability, and Water Demands in the Volta Basin", has been submitted for scientific evaluation and funding approval. The stated goal of this project is to develop a scientifically sound decision-support system for the assessment, development and sustainable use of water resources in the Volta Basin by means of an integrated model of the basin. Developing such a model is an ambitious goal. Although the need for such integrated approaches has often been espoused, examples of genuinely interdisciplinary, integrated programs are rare. Meteorological, land use change, and economic optimization models developed in combination with a hydraulic model will provide powerful tools for integrated water resource management within the basin. Once the content of each module output is agreed, the individual modules will be developed to supply outputs that are in harmony with the requirements of the other modules. From the outset, coordination amongst the modelers and model components is essential if the individual parts of the decision support system are to be woven into a cohesive integrated whole.

As a first step towards the goal of an integrated model, a water balance will be made using the available long term data. As water moves through the environment, it is partitioned in various ways. A fraction of the rain falling on the Volta Basin returns to the atmosphere as evapotranspiration, a fraction percolates through the root zone to become groundwater, and another fraction runs across the surface to rivers winding their way to the sea. A water balance accounts for the entire movement of the water passing through the basin. We are able to make crude, but reasonable, assumptions about the various fluxes of water through the system. By marrying the measured data with our tentative assumptions about the system and analyzing what may be happening in light of the resulting construct, we can begin to define the system. From these simple models we will draw inferences and comment on the sensitivity of the system to various influences. As we shall see, the manner in which the water is partitioned is of vital importance to the people of Ghana.

2 Setting

On the coast of West Africa, Ghana is a country of 238,539 km² and a population of over 17 million. There are two major vegetation types: equatorial forest and wooded savanna. A variety of agricultural products is grown and Ghana is the world's third largest exporter of cocoa. It has mineral resources of great economic value; it exports diamonds, gold and manganese. There are substantial deposits of high-grade bauxite and iron ore.

Three quarters of the country is drained by the mighty Volta River, which enters the country's northern regions and flows to the sea. The main channel of the Volta River flows more than 1400 km before reaching the Gulf of Guinea near the town of Ada. The river's mean annual discharge before construction of the dam was approximately 35 km³. Generally, river basins are categorized as large if they cover more than 10,000 km² (Liebscher, 1993). The Volta River basin covers 400,000 km². In addition to three quarters of Ghana, it also drains approximately two thirds of Burkina Faso, a large part of Togo and small slices of Côte d'Ivoire, Benin, and Mali. The basin can be subdivided into smaller basins belonging to its three major tributaries, the Black Volta, the White Volta, the Oti, and the Lower Volta, referring to the river downstream of the confluence of the Black Volta and White Volta. The Black Volta flows from Burkina Faso, along the border of Ghana and Côte d'Ivoire, through the Bui Gorge into the Voltaian Basin. To the east, the White Volta also flows south from Burkina Faso. When it encounters the Gambaga escarpment it turns in a westerly direction traversing the foot of the escarpment until it reaches the end where it continues southward into the Voltaian basin. Further east, the Oti River flows below the western slopes of the Buem Ranges before joining the Volta. The river flows through the Voltaian sandstone basin occupying an area of 112,768 km² in the heart of the north-central region of Ghana. In this basin are Paleozoic formations of sandstone, shale and mudstone and pebbly conglomerate beds (Windmeijer and Andriesse, 1993). These materials are easily eroded and gently dipping or flat bedded (Dickson, and Benneh, 1970). The basin is bounded on the south by the Southern Voltaian Plateau and in the northeast by the Gambaga escarpment. The river exits the basin through a narrow gorge at Akosombo, offering the opportunity to dam the river with a relatively small structure.

Water management in this great catchment is not easy and in the upland areas of the basin problems of rainfall variability are of grave concern. In Ghana, the 1975-1977 drought raised awareness of the problem of reliable water supply in the uplands and served as a catalyst for increased research (Ofori-Sarpong, 1985). People in rural areas and farmers in particular who live without adequate infrastructure are extremely vulnerable to shortages. Irregular rainfall results in reduced production, wasted seed and inputs, and complicates the farmer's planning process. Drought results in crop failure, livestock losses, malnutrition, and increased health risks. Ofori-Sarpong (1985) examined rainfall records and water budgets in the Upper East

Region of Ghana. They indicated that cereal production, while possible during wet years, is generally problematic without irrigation because of the wide annual and seasonal rainfall fluctuations so often experienced there. This problem is not unique to this area. In addition, researchers have begun to characterize within-season rainfall variability, estimating average dry-spell durations, and developing simulation models. For instance, Adiku et al. (1997) found that the average rainy season dry spell in Tamale was about three days, while in Accra the dry-spell duration fluctuated from seven days in March, to two days in June and five days in July. The more regular pattern in Tamale suggests that dryland farming may be more successful near Tamale than near Accra.

Efforts at better weather prediction have also begun. A correlation between east equatorial Atlantic sea surface temperature (SST) and rainfall in Ghana has been noted. There are time lags between the SSTs and their correlated rainfall amounts. These lags offer the possibility of forecasts being made two months in advance of the events (Opoku-Ankomah and Cordery, 1994). Adiku and Stone (1995) found that although direct correlation between Southern Oscillation Index (SOI) and rainfall did not yield a strong relationship, the use of lagged relationships and the SOI-phase system appears promising as a means of developing useful predictors. There is also interest in longer term variation. Is rainfall increasing or decreasing due to global climate change or regional land use changes? There is a body of opinion that Africa has been drier the last few decades and Nicholson, (1998) presents evidence to support this belief. After evaluating the last 40 years of Southwestern Ghana's rainfall and runoff records, Opoku-Ankomah and Amisigo (1998) concluded that there has been a statistically significant reduction in rainfall and runoff in the region, which they assert is "linked to the influence of climate change". Clearly, there is Ghanaian expertise and interest in the issues of rainfall variability and water management. Any scientifically sound decision support system will have to build on these strengths and incorporate this local knowledge into its models.

The fate of the uplands and the Volta River are intimately linked, a fact that perhaps was not fully understood when the thought of damming the river was first conceived. The idea was initially proposed as long ago as the 1920's by Sir Albert Kitson, Director of the Gold Coast Geological Survey (Hart, 1980), but the subject did not enter public discourse in Ghana until it was introduced as a plank of the Convention Peoples Party platform during the first general elections of February 1951. From 1951, the Gold Coast Government and subsequently the Government of Ghana pursued negotiations with the British and United States governments, aluminum producers and financiers, and the World Bank, among others, to arrange for the construction of what would ultimately become known as the Volta River Project. During this protracted process Prime Minister Kwame Nkrumah remained "convinced that the project was the most important way of bringing Ghana forward to a more balanced economy" (Government of Ghana, 1961).

In December 1959, a letter of intent was signed by the Government of Ghana and the Volta Aluminum Company (Valco), a consortium of aluminum producers lead by Kaiser Aluminum and Chemical Company. This document, known as the “Principles of Agreement”, set out the principles that would guide the detailed negotiations for the establishment of a major aluminum smelter in Ghana. Among the provisions was one stipulating that Valco would agree to purchase power at a fixed rate from the Volta River Authority. Valco agreed to buy a specified amount of power or, in lieu of buying the power, to pay for the specified amount. The financing of the project was dependent on this “take or pay” arrangement, and with it in place the financiers agreed to loan the Volta River Authority the money for the construction of the dam (Government of Ghana, 1962).

As inducement to Valco, the Government of Ghana agreed to provide, among other things, the ancillary infrastructure necessary for running the smelter, generous tax relief, and guarantees against government expropriation of Valco’s long term loan capital. Today, most of Valco’s production is shipped to Europe with ten percent supplied to Ghanaian customers. What did the Government expect in exchange? It expected to get the capital to build the Volta River Project, whose purpose was to supply “electric power from the Volta River for industry and for lighting up our towns and villages” (Government of Ghana, 1961). Electrical demand from the mining sector was 36 MW more than supplied and mines operated private power stations. The mining companies would not buy Volta power unless assured that it would be totally reliable and could be supplied at a price below their own costs of 1.5 to 2 cents/kWh (King, 1967). It was anticipated that the aluminum smelter would consume approximately 300 MW, leaving 200 MW for distribution throughout the rest of the country. The project was seen as part of the process of nation building. Without the leverage provided by Valco’s electricity supply contract, it would not have been possible to build the dam.

The Akosombo Dam is an impressive engineering feat. It was built by Impregilo for a contract price of 16 million British Pounds (Mackintosh, 1965b). Begun in 1961, the dam was closed in 1964. It was built in three and three quarters years instead of the estimated four and a half. It is a rockfill dam with an impervious core. The embankment is 119 m high and 640 m long. The total embankment volume is 7,962,000 m^3. On the left hand side of the river there is a small sloping core, rockfill, saddle dam with a total embankment volume of 555,400 m^3 (Mackintosh, 1965a). The concrete structures comprise a diversion tunnel, intake structure, spillway, and power plant. The initial generating capacity at Akosombo was 512 MW. As of 1982, with completion of the Kpong Dam downstream of Akosombo, the combined generating capacity of the two plants is 1,060 MW.

Construction of the Akosombo Dam created a reservoir with a storage capacity of 148 km^3, called the Akosombo Reservoir or, more commonly, Volta Lake. The reservoir has a dendritic shape and a generally north-south orientation. It has a surface area at Full Supply Level (FSL) of approximately 8500 km^2. Its average width is 25 km and the back waters of the longest arm of the lake reach approximately 400 km from the dam northward below the bridge at the Tamale Port at Yapei.

Flooding this immense area was the single most abrupt and dramatic land use change in the history of post-colonial Ghana. Filling the lake disrupted traditional trading routes. However, by 1986 half the cargo traffic formerly carried overland was now carried on the lake (Dickson and Benneh, 1995). Of more immediate concern was the relocation of tens of thousands of people occasioned by the filling of the lake. During the project's planning phase, resettlement was given serious consideration. The government proposed "happily resettling approximately 67,000 persons now living in the area which will be flooded." It intended to provide assistance for new home construction and farm clearing. There would be new roads, public buildings, schools and churches, and improved services: water supplies, police, postal and telephone systems (Government of Ghana, 1961). Among the stated goals were the following: no one should be worse off as a result of their enforced move than they were beforehand, new dwellings should be built by the settlers in a spirit of self help and incentives, and compensation should precede resettlement (Chambers, 1970). By 1955 the Preparatory Commission had laid the groundwork for the planned resettlement and there was optimism that it would proceed smoothly. However, because of the delay in implementation of the project from 1955 until 1961 the momentum of coordinated planning was lost (Jackson, 1970).

The resettlement resulted in the relocation of 80,000 people and the transformation of 700 villages into 52 rural townships (Mills-Tettey, 1989). The resettlement was done hastily often in ad hoc fashion. The flooded area had 51,200 ha in productive use and by 1966, two years after dam closure, only 6000 ha of the planned 21,600 ha had been cleared (Graham, 1986). Modern farming methods were to be employed with equipment held by cooperative ventures, and cash crops were to be introduced. Very few farmers were able to make the transition smoothly. In 1968, a new program was initiated to allocate 1.2 ha per farmer that would be cultivated by hand. The success of resettlement schemes often hangs on the success of the settlers' farms. E.K. Afriye (1973) concluded that the VRP management was operating without the statistical information it required to formulate appropriate agricultural policies. By 1970, only 25,000 of the original settlers remained in the settlements (DAP Butcher and EK Afriye, unpublished data, 1970, in Taylor, 1973). Although the situation faced by the farmers was disappointing, the growth of the Lake Volta fishery was more rapid and extensive than anticipated. There were approximately 1200 men fishing along the submerged Volta and its tributaries, with an annual catch valued at US$ 125,000 (P Westway , unpublished data, 1970; in Butcher, 1973). As of 1970, there were 12,500 fishermen living in 1000 villages whose annual catch of 60,000 metric tons was valued at US$ 8,000,000 (G.Bazigos, unpublished data, 1970; also in Butcher, 1973).

Wise management of the Volta Basin is of great importance. Many Ghanaians make their livelihood using the land within the basin, and the VRP generates 1060 MW of the 1160 MW national capacity, thereby contributing indirectly to the welfare of many more people. A great deal of time has been devoted to critiques of the VRP and its impact on the basin. There have been discussions of who benefited financially and speculation about the environmental impacts of the project. The resettlement scheme was particularly closely scrutinized. These discussions were more useful when the construction of similar projects was being considered, but now, for Ghana with a dam three decades old, the real issue is what should be done henceforth. In this discussion, as land use changes in the upland are pivotal; we shall consider the basin as a whole.

3 Data

The data used in this analysis come from several sources. This discussion requires estimates of rainfall in the basin, runoff (i.e. river flows), evaporation from the lake, rainfall on the lake and the volume of water stored in the lake. Runoff, reported as flow rates, rainfall and evaporation reported as depths, and reservoir storage reported as lake levels were all converted to volumes. The cubic kilometer, km^3, was chosen as the appropriate unit because of the large quantities of water flowing through a system as vast as the Volta Basin.

The data are from the following sources: (1) The runoff data are from the Global Runoff Data Center, Federal Institute of Hydrology, Koblenz, Germany. (2) Reservoir levels and Akosombo outflows are provided by the Water Resources Institute of the Council for Scientific and Industrial Research, Accra, Ghana. (3) Level vs. volume and level vs. area tables for the Akosombo Reservoir are from the Volta River Authority, Accra, Ghana. (4) Rainfall data are from the Global Gridded Climatology presented at a new high resolution (0.5° latitude/longitude) distributed by the Climate Impacts LINK Project, Climatic Research Unit, University of East Anglia, Norwich, UK (New et al., 1999a and 1999b).

Evaporation from the lake was estimated by assuming that evaporation is equal to mean annual potential evapotranspiration values from 1961 through 1990, reported in Ghana's Water Resources (WARM, 1998). This is justified because in this region, potential evapotranspiration and open water evaporation are approximately the same over periods of a year (Walker, 1962, referred to in Hayward and Oguntoyinbo, 1987).

Changes in reservoir's storage and surface area were estimated using the level vs. storage and level vs. surface area tables with the monthly water level records.

Rainfall estimates for a particular area were made by overlaying a map of the area with a pixel grid. Each rainfall pixel was weighted by that pixel's contribution to the total area. Then the mean monthly rainfall estimate was computed by summing the weighted pixels in the total area. As the lake rises and falls there is significant variation in the surface area of the lake. In the case of rain falling directly onto the lake and evaporation from the lake, estimates of the volumes entering or leaving the lake at FSL were reduced proportionally to reflect the actual size of the lake.

4 Water Balances

The flux through the Volta Basin may be viewed from two, of many, perspectives: first from that of a water balance without reference to the reservoir and second from that of a water balance focusing on the reservoir. In this section our exploration of the hydrology of the Volta Basin proceeds as follows (1) the first water balance (without reference to reservoir) is presented, (2) a black-box model to predict runoff is introduced, (3) measurements for the Volta's major tributaries are used to comment on spatial variation within the basin, (4) the second water balance (focusing on the reservoir) is presented, and (5) the second water balance is used to estimate runoff . We conclude with a discussion of rainfall and runoff in the basin.

The first water balance is described by Equation 1. Our focus is on rainfall and runoff, that is surface water yield, as a function of rainfall. Approximately nine percent of the rainfall exits the catchment as runoff. It is reasonable to assume that the change in groundwater storage over longer periods is negligible. Therefore, actual evapotranspiration is approximately 91% of the total rainfall. Because evapotranspiration takes mainly place in the uplands, land use and land cover in the uplands are very important in determining the quantity of runoff in the basin. Figure 1 shows the Volta Basin rainfall and runoff records for the period 1936 through 1998. It should be noted that the Akosombo Dam was closed in 1964; outflows from that year forward were no longer free, but regulated by the Volta River Authority (with the exception of 1968 when the reservoir was filled to capacity and its spillway flowed freely).

$$\text{Rainfall} = \text{Runoff} + \text{Evapotranspiration} + \text{Groundwater Recharge} \quad \text{(Eq. 1)}$$

There is low variability in the rainfall at the basin scale (see Table 1). These data show that the input to the system on an annual basis is not extremely variable. The rainfall volume for the period after construction of the dam has decreased approximately five percent. Although this division of the record at the time of the dam's construction is arbitrary, the creation of a reservoir within the watershed with a surface area of 8500 km^2 at FSL (two percent of the catchment) is in all likelihood the most dramatic and sudden land use change ever visited upon this area.

Figure 1: Water Balance

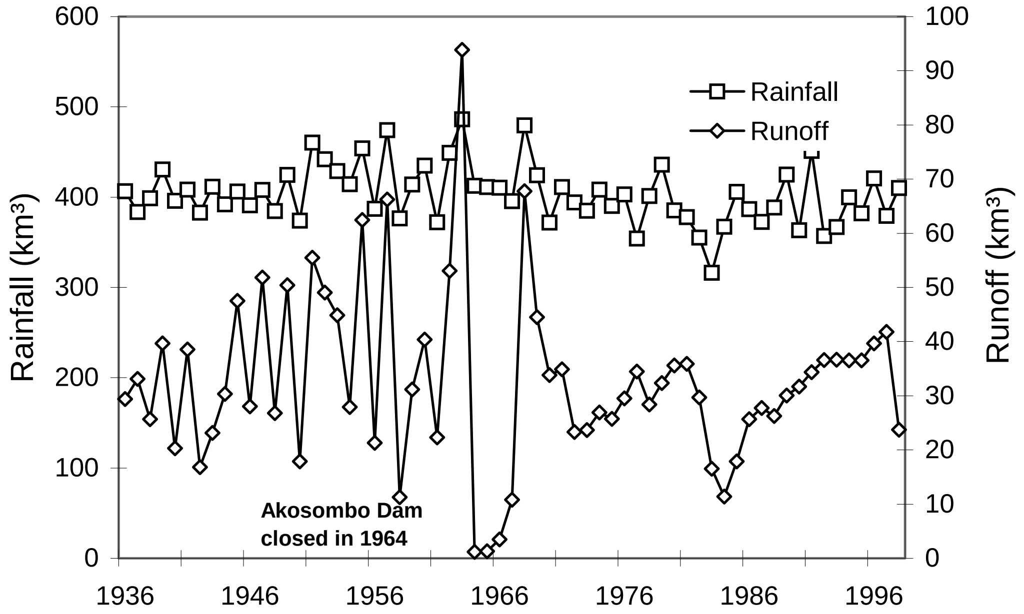


Table 1: Rainfall and Runoff, Volta River Watershed

	Before the Construction of the Akosombo Dam (1936-1963)	After the Construction of the Akosombo Dam (1967-1998)
Mean Annual Rainfall (km³)	414	393
Coefficient of Variation	0.07	0.04
Mean Annual Runoff (km³)	35	31
Coefficient of Variation	0.57	0.33

The watershed level runoff data presents a different picture. As is to be expected runoff is much more variable than rainfall (see Table 1). Variation in runoff, before the dam was built, is an order of magnitude greater than that for rainfall. The much greater degree of variation seen in the runoff record is to be expected and is indicative of the nonlinearity of the processes and the spatial (and temporal) variability characteristic of a watershed of this size. The muted variation seen in the flows after the dam was built is a direct reflection of VRA's management of the reservoir.

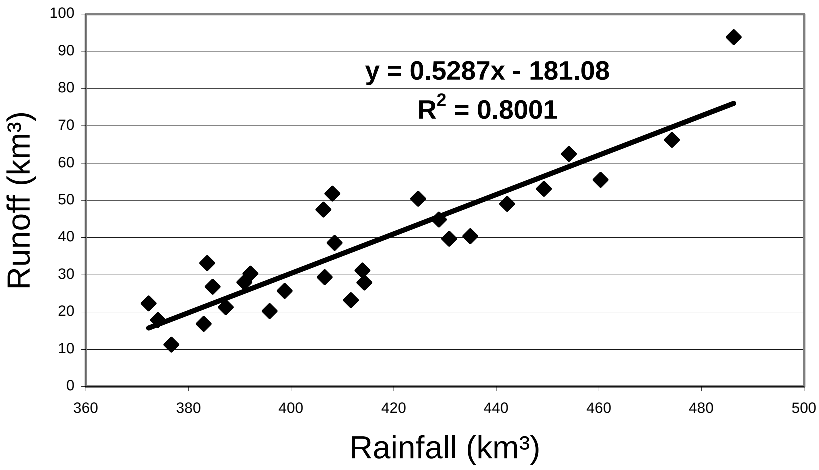
Regressing annual runoff volume versus annual rainfall volume (see Figure 2) results in a simple model of runoff:

Runoff = 0.5287 x Rainfall – 181.08, with an r^2 value of 0.80 (Eq. 2)

The nonlinearity of the system is reflected in this model. It suggests that approximately 340 km³ of rain falls on the catchment before a significant amount of runoff occurs. Furthermore, after this threshold is reached, the regression suggests that about half of the additional rainfall becomes runoff. Therefore, small changes in total rainfall can result in large changes in total runoff. This model does not take into account the spatial variability within a 400,000 km² watershed and its use of annual data leaves ample room for temporal refinements. Nonetheless, it appears to predict river flow reasonably well.

The gauging data in our possession, measuring flows from the rivers and streams into the reservoir, are replete with gaps both temporal and spatial. The runoff these data represent, even if complete, is only a fraction of the water flowing into the reservoir. When considering the reservoir balance, we find that the simple model is not sufficiently exact. Therefore, to estimate runoff into the lake after the construction of the dam, we need an improved runoff model.

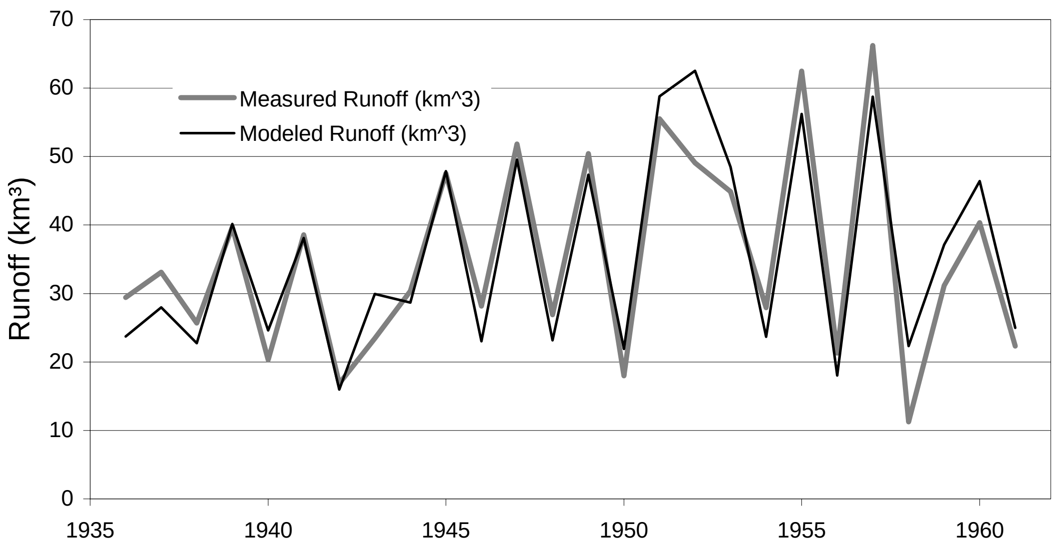
Figure 2: Runoff as a Function of Rainfall (1936-1963)



A black box model of the rainfall-runoff relationship was consequently developed. Although it is a storage model based on the concepts of Thornthwaite and Mather (1955,1957), no attempt was made to assure that the parameter values physically describe as large and diverse a system as the Volta River Basin. The model functions like a bucket with precipitation falling into it, evaporation leaving it at a rate varying in proportion to the moisture content of the root zone, and runoff flowing out of it when the storage exceeds a certain maximum level. A monthly time step was used and the monthly results totaled to compute a yearly runoff estimate. The parameters were adjusted only with a view to reproducing the measured calibration data as accurately as possible without any concern for the verisimilitude of the values. The model was run for the years 1936 through 1961, the year construction began on the dam, with the exception of 1954, a year in which one half of the runoff data was missing from our records. A random sample of half of those years was used to calibrate the model and a sample consisting of the remaining years was used to validate it.

As this is a black box model and not a physical model, it should not be expected to yield usable results outside the range of flows for which it was calibrated. Figure 3 shows the measured and modeled runoff for the period from 1936 to 1961. The modeled values fit the measured outflows reasonably well. If our model is to be accepted as an improvement, there should be a tighter fit when modeled and measured runoff are correlated than there is when runoff was regressed with rainfall. There is indeed a strong correlation between the measured and black box modeled values. The r^2 value of the correlation is 0.87. This is an improvement from the simpler model's r^2 value of 0.80.

Figure 3: Measured and Modeled Runoff



To further test the assertion that the black box model is an improvement, we also compared the models using another measure of goodness-of-fit. A popular criterion for the evaluation of goodness-of-fit between observed runoff, Q, and computed runoff, Q*, is the sum of squares of deviations between Q and Q* (Guay-Boakye, 1994). The smaller the sum, the better the fit.

$$\min(f) = \sum \left(Q - Q^*\right)^2 \qquad \text{(Eq.3)}$$

Over the 1936-61 period, the sum of squares of deviations for the rainfall regression model is 1458 and for the black box model 733. This demonstrates the marked superiority of the black box model. The improvement can be attributed to the temporal refinement implicit in this new approach. The simpler model only used yearly data; the new one uses monthly time steps.

System memory, the effect of the short term history of a catchment, often influences the runoff response. This more refined model may also capture this memory effect.

Spatial variation within the basin is ignored by both of these models. It is reasonable to assume that over a watershed the size of the Volta Basin there would be significant spatial variations. There are records of river flows at Bui on the Black Volta, Nawuni on the White Volta, and Sabari on the Oti River. These three sub-watersheds, along with the Lower Volta, comprise the Volta basin (see Figure 4). Figure 5 shows the rainfall in each of the three sub-watersheds and the runoff from each of them. Comparison of the two graphs demonstrates the pronounced variability among these sub-watersheds. Table 2 summarizes the differences seen in this figure. The coefficients of variation indicate that runoff from the sub-watersheds is much more variable than rainfall, as it was at the larger scale. Runoff from the Black Volta is much more variable than that from the other two rivers. The Oti River receives less rainfall, but produces more outflow than either of the other two rivers; accounting for 44 percent of the total contribution from these tributary rivers. Even at this large scale there is demonstrable spatial variation within the basin.

Figure 4: Volta Basin

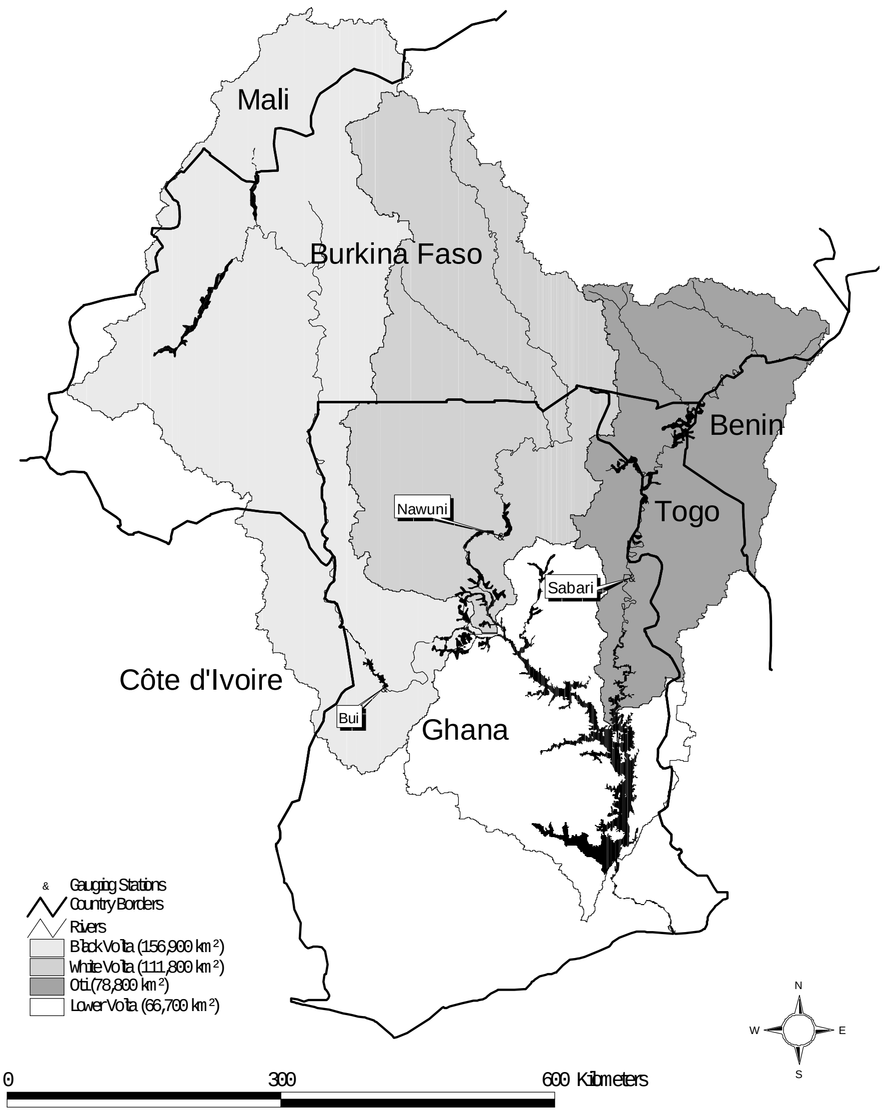


Figure 5: Tributaries, Rainfall and Runoff

Table 2: Rainfall and Runoff of the Black, White and Oti Sub-Watersheds

Sub watershed	Black Volta	White Volta	Oti	Total
Period of Measurement	1955-1975	1954-1980	1960-1973	---
Mean Annual Rainfall (km³)	140	101	84	325
Coefficient of Variation, Rainfall	0.09	0.07	0.07	---
Mean Annual Runoff (km³)	7	7	11	25
Coefficient of Variation, Runoff	0.52	0.33	0.38	---
Runoff as % of rainfall in each sub-watershed	5	7	13	8
Runoff as % of total measured from all three rivers	28	28	44	100
Runoff as % of total modeled runoff into the lake	23	23	37	83

The second water balance focusing on the reservoir is described by Equation 4. To express the magnitude of the water balance's components, we present the mean values for the period from 1969 through 1991 (see Table 3). For comparison the Akosombo reservoir holds 148 km³ and the usable storage represents about 2½ years of average runoff. This period was chosen because in 1969 and 1991 the lake levels were equal, so that the change in storage was zero and the mean values over this span are representative of the true magnitudes of the terms of the balance. The sum of the terms on the right hand side equals 0.1 km³ which is close to zero. Mass is conserved. Over this period the balance is very good.

[Change in Reservoir Storage] = [Runoff into Reservoir] + [Rainfall on Reservoir] –
[Outflow through Dam] – [Evaporation from Reservoir] (Eq.4)

Table 3: Mean Water Balance Volumes, 1969 - 1991

	Change in Storage	Modeled Runoff	Estimated Rainfall on the Reservoir	Measured Outflow	Estimated Evaporation
Volume (km³)	0.1	30.8	7.9	-28.4	-10.2
Coefficient of Variation	---	0.52	0.19	0.26	0.13

We can remove the black box or modeled runoff from the balance and rearrange the terms of Equation 4 to solve for the runoff. When the black-box model runoff is compared with the annual runoff estimated with the water balance, it is found that they are correlated as shown in Figure 6. If both methods yielded sufficiently accurate results all of the points would be expected to lie on a line with a slope of unity. Forcing the y-intercept to be zero, the slope of the line is 0.9173, which is close to one, and the r^2 value is 0.6722. Figure 7, a plot of balance and black-box runoff from 1965 to 1998, shows that the water balance and black-box model produce similar annual estimates of Volta River flows. The most significant discrepancies between the two come at the extremes, beyond the black box model's range of accuracy. During the period from 1994 to 1998, however, the correlation between the two estimates breaks down. There are multiple possible causes for this breakdown from changes in the data collection system to critical changes in upstream land use but clearly these data should be examined in more detail.

Figure 6: Runoff, Balanced vs. Modeled

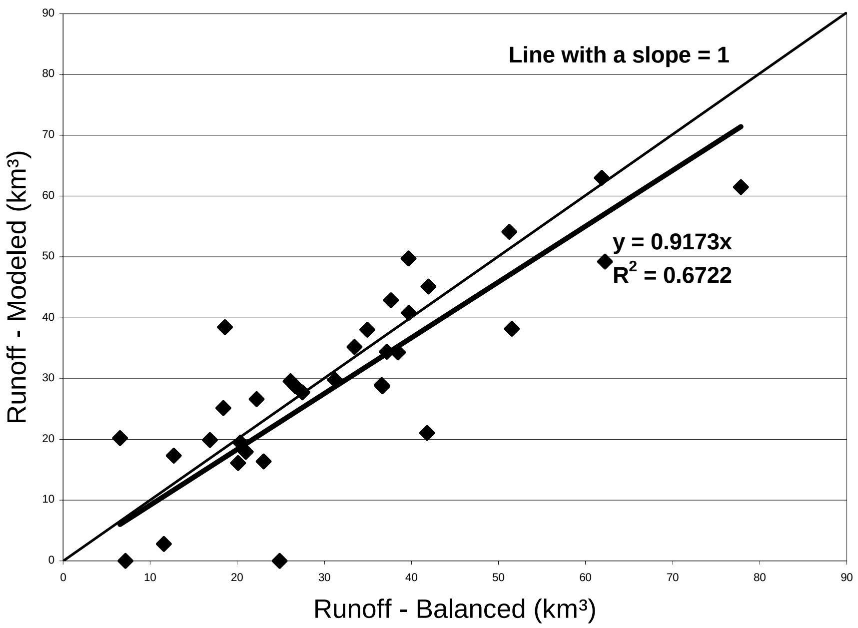
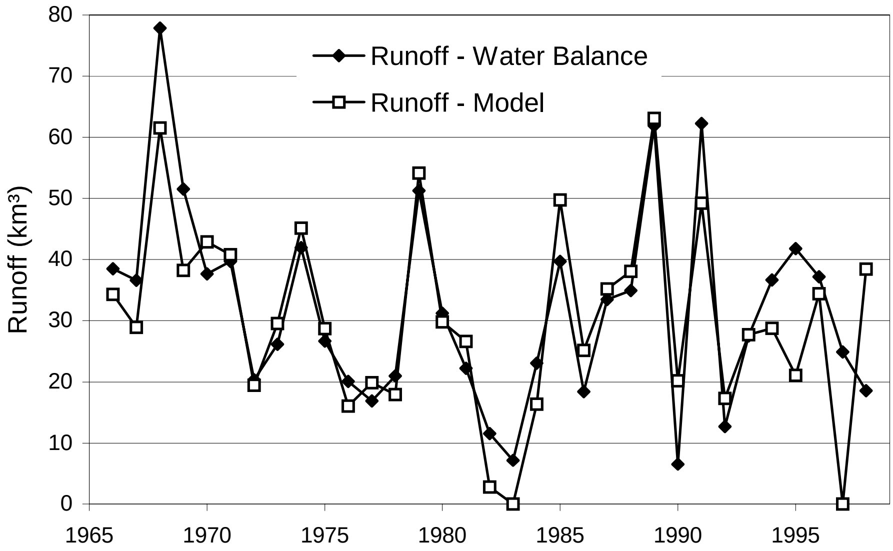


Figure 7: Runoff into Akosombo Reservoir



We now return to consideration of the basin as a whole (see Table 4). The comparison of the modeled and measured runoff for the period before the dam was built, 1936-1961, shows that they are approximately equal. This demonstrates only that the model replicates the measured flows reasonably well. Comparison of the three figures for the period after the dam was built shows that the mean runoff volumes are all approximately equal. The estimated volumes from the black box model are generated without reference to the presence or absence of the dam, but the presence of the dam is reflected in the magnitude of both the volumes estimated from the reservoir balance and the measured volumes. Therefore, it can be inferred from the near equality of the three volumes that the presence of the reservoir does not have a dramatic effect on the outflow.

Table 4: Runoff Estimates

Runoff	**Time**	**Mean Annual Volume (km³)**
Measured at Senchi	1936-1961	35.1
Modeled	1936-1961	35.5
Measured below the Dam	1967-1998	31
From Water Balance	1965-1998	32
Modeled	1965-1998	30

The mean annual rainfall decreased by approximately five percent during the period 1936 to 1998 (see Table 1). Dividing that period into two sub-periods, namely 1936-61 and 1965-98, we find that there is a decrease of about 3 km^3 to 5 km^3 or approximately 8% to 14% in the mean runoff from the first sub-period to the second. This larger decrease in runoff is reflected in all three figures for the latter period. The non-linearity suggested by Equation 2, the regression of Rainfall vs. Runoff, is evident in these figures. It is important to note that a small, five percent, change in rainfall produced a larger, 8 to 14% change in runoff.

5 Discussion

5.1 The Water Balance

Having constructed the black box model, we were able to look at the water balance from different perspectives. Five points emerge concerning the water balances themselves: (1) Small changes in the rainfall can result in larger changes in runoff. (2) The role of land use and land cover in the uplands is critical in partitioning of water within the basin. (3) More refined treatment of time may reveal temporal effects that remain obscure with these simple models. (4) There is a need to describe the spatial variation within the basin. (5) Accurate measurements of evaporation and rainfall on the reservoir are desired to increase our confidence in the balance.

The contrast between the smaller variation in the rainfall record and the much larger variation in the runoff records immediately suggests that the Volta Basin exhibits the non-linearity anticipated in the response of a watershed of this size. The runoff model exhibits an amplified response. Comparison of the mean annual runoff volumes during the wetter period from the 1930's to the 1960's with the mean runoff volumes from the drier period from the 1960's to the 1990's demonstrates that small decreases in the rainfall may result in larger decreases in the runoff.

The water balance does demonstrate that only nine percent of the rain falling in the basin appears in Lake Volta as runoff. Therefore, shifts in land use that have relatively small impacts on the flux through the upland areas (e.g. a change in evapotranspiration of a few percent), may result in a large change in the percentage of runoff flowing into the lake. It should be noted that, as much of the Volta basin lies in Burkina Faso (43%) as lies in Ghana (42%). Therefore, intensified land use in Burkina Faso may have as profound an impact as intensified land use in Ghana.

The main economic activity in the upland areas of the Volta Basin is rainfed agriculture. Rainfall is partitioned between evapotranspiration and percolation which recharges aquifers and contributes to river flows. Increasing population pressures will lead to land use changes. What precise impact this intensification will have is moot. Cropping systems displacing savanna may lead to increased baseflow in the dry season and reduced flow in the wet season because trees tend to transpire less than a vigorously growing crop, but evergreen trees transpire the year round. Despite this reasoning, there is anecdotal evidence suggesting that deforestation increases peak runoff, thus, reducing dry season base-flows. Whether or not intensification of land use will dampen the system's runoff response or increase the variation in seasonal runoff cannot be addressed by these simple water balances. Nor can we deduce whether intensification of land use will necessarily increase or decrease runoff. The conclusion we can draw from our water balances is that land use and land cover changes in the uplands are likely to have a significant impact on runoff in the watershed and therefore they deserve close attention.

The superiority of the black-box model, using monthly time steps over the original model using yearly time steps suggests that further refinements with regard to time may be made to improve the precision of our models. The use of more detailed rainfall records coupled with more exact characterization of the basin will be attempted in our future work.

Our examination of the three large sub-watersheds suggests that there is room for improvement in the spatial domain as well. The data show that there are dramatic differences in the responses of the Black Volta, White Volta, and the Oti tributary rivers. The geometry of these sub-watersheds differs markedly. The Oti River is shorter and twice as steep as either of the other two rivers. There is existing infrastructure on the White Volta in Burkina Faso. These facts alone explain some of the differences seen. In addition, the differences in topography suggest that it is reasonable to assume that the land use and land cover also differs across these basins. We can expect differences in the landscape, land use, and land cover to express themselves as differences in the partitioning of water. Improved models will require scientifically based characterizations of the landscape and land cover.

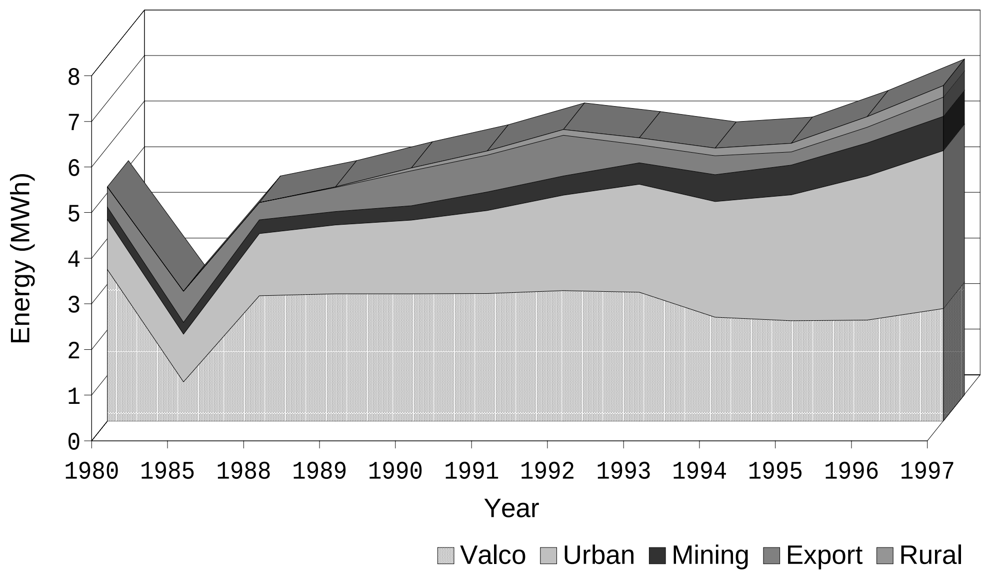
Large reservoirs are often faulted for large evaporative losses seen as “waste” and there are significant losses from a lake of this size and relatively shallow depth (mean depth, 18.8m). There are also significant gains from precipitation falling directly onto the reservoir. One hundred percent of the rain falling onto the lake reaches storage while only nine percent of the water falling on the uplands runs into the lake. Table 3 shows that both evaporation and lake rainfall are approximately one third of runoff and likewise about a third of the outflow. In our balance, rainfall on the lake largely compensates for the evaporation; the mean annual difference between evaporation and rainfall over the lake is 2.3 km^3. Evaporation is estimated using average annual evapotranspiration values. The fact that mass is conserved reassures us that these estimates are fairly realistic. Nonetheless, doubt remains as to the accuracy of these estimates. For example, Lake Victoria mysteriously rose two and a half meters between 1959 and 1964, then fell, and rose again in 1978 and 1979. The failure of existing water balances to explain this enigma is attributed to inaccuracies of over-the-lake rainfall estimates (Kite,1981). Published estimates of evaporation from Lake Victoria range form 1130 to 1600 mm/yr and rainfall from 1145 to 1850 mm/yr (Nicholson and Yin, 1998) suggesting that both rain and evaporation estimates may be questionable. As Table 4 demonstrates, there are discrepancies among the outflow estimates. Ambiguities in the analysis on the order of two to three km^3 may seem insignificant until they are compared with the planned storage capacity of the five dams in Burkina Faso, namely 1.49 km^3. It would be desirable to eliminate as many ambiguities as is practical. Perhaps reliable measurements of these quantities are already being made; if they are not they should be.

5.2 Concerns

The water balances also reveal three important concerns emerging from the recent history of the Volta Basin. First, demand for water to generate power has approached the supply stored in the reservoir. Second, as water becomes increasingly scarce, water management will increasingly require international or transboundary cooperation. Third, the modulated outflow from the dam has already caused negative consequences for the downstream water users.

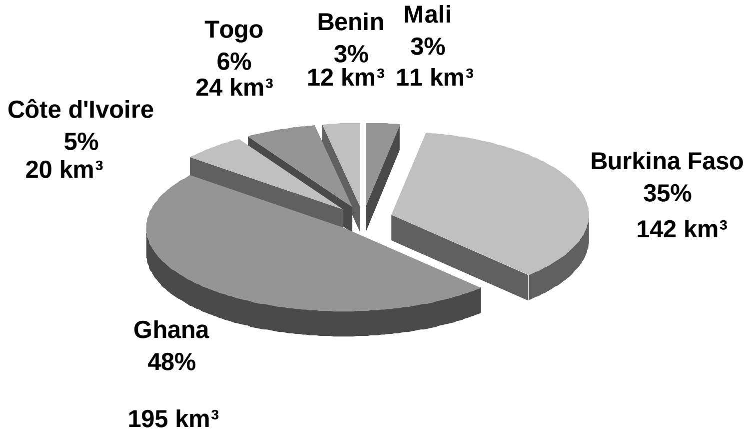
Water flowing through the Akosombo Dam increased from of 28 km³/yr to 35 km³/yr in the 1990's. This is an increase of 25%. As demand for electricity increases, there is a temptation to generate power at higher rates despite drought or storage deficits. The water balance shows that the mean volume stored in the reservoir in the 1970's was 132 km³. In the 1980's and 1990's the mean volume was 102 km³, a reduction of 20 %. This decrease in storage is of intense interest to the citizens of Ghana for a number of reasons, among them is the fact that water flowing through Akosombo's and Kpong's turbines produces 95% of the power consumed in the country. Figure 8 shows the increasing electric power consumption in Ghana. The increase in urban consumption is particularly noteworthy. Recently, severe shortages have caused disruption to local industries and aggravated consumers.

Figure 8: Electric Power Consumption



The Volta Basin is an international catchment shared by six riparian countries: Ghana, Burkina Faso, Togo, Mali, Côte d'Ivoire, and Benin (see Figure 4) . Figure 9 shows the volumes and percentages of rain falling within the basin in each country. The Black, White and Red Voltas flow from Burkina Faso into Ghana. Together they represent 56 % of the water approaching the Akosombo Reservoir from the north. Forty-four percent comes from the Oti River (see Table 2). Water use and land use choices made within these countries and their effects on trans-boundary river flows are already an issue between the two major stakeholders Ghana and Burkina Faso. In view of the size of the Oti's contribution to the lake, changes in Togo's use of the Oti River's water may also divide Togo and Ghana.

Figure 9: Volta Basin Rainfall



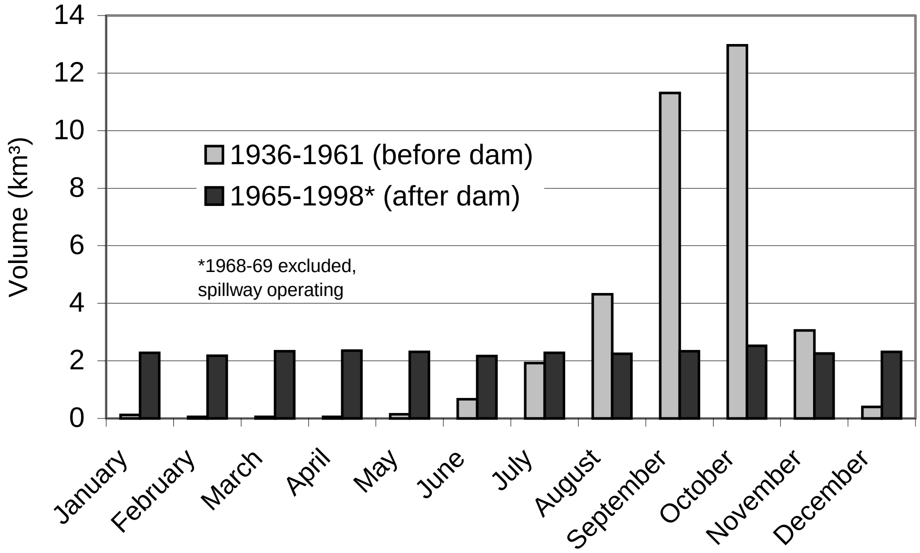
Rapid increases in demand for water in the domestic, agricultural, mining, and industrial sectors, particularly for hydropower are leading to conflicts over water use on the international level. To help reduce these tensions, Ghana intended to sell hydropower to Burkina Faso, but, according to official comments, these efforts were "stopped at the border". Ghana claimed that it would be much cheaper for Burkina Faso to buy hydropower from Ghana than to build its own hydropower plants (Ghana World Wide News, 1998). The Energy and Mines Minister from Burkina Faso argued that it would be cheaper to generate power from thermal plants than to buy power from Ghana. Ghana intends to charge 9 cents per unit, but Burkina Faso is ready to pay only 6 cents per unit (Africa News, 1998). An explanation for Burkina Faso's refusal to buy power from Ghana might be seen not only in the high costs, but in Burkina Faso's unwillingness for political and security reasons to become dependent on Ghana's power resources

No International Treaty exists for the Volta River Basin and no institutions have been established to deal with transboundary issues. In 1999, Burkina Faso announced plans to build three dams on one of the Volta's tributaries: Two for hydro-electric generation and one to supply water to Ouagadougou. There are already two dams. With the completion of these three the total storage of Volta River water in Burkina Faso would be 1.49 km^3. The Ghanaian government opposes these plans, concerned that the flow of the Volta River could be reduced and consequently, hydropower production in Ghana might decrease. The recent drought having already occasioned power cuts in recent years, heightens this concern. The two hydropower stations at Akosombo Dam are supplying Ghana with the bulk of its domestic electricity. Hydropower is the country's fourth biggest source of export earnings (World River Review, 1995), as 48% of the hydropower is sold to VALCO industry and 7% is exported to Benin, Togo, and Côte d`Ivoire. These riparian countries, buying a portion of Ghana's hydropower production are also interested in maintaining an unreduced flow of the Volta River. The installation of additional upstream generating capacity and withdrawals for urban water supply, in Burkina Faso, could have a negative impact and are of immediate concern to the Ghanaians.

People living downstream of Akosombo have an interest not only in the quantity of runoff, but as importantly in the manner of its arrival. Before the construction of the dam, flow in the Volta River varied with the season. In October, mean peak flows were approximately 240 times the mean of the driest month, March. This phenomenon was obvious to everyone. Although storage and controlled release of the Volta's water were the intended purposes of the dam, the implications of this altered flow regime for downstream residents was not fully appreciated. Although concern for the claming industry was voiced before construction was complete (Lawson, 1963), the attention of the government was focused almost exclusively on the impacts the dam would have on the people displaced by the rising waters of the Akosombo Reservoir.

Figure 10 shows that after the dam was built, monthly flows averaged 2.3 km^3/month with very little seasonal variation. Damping fluctuations in the river's flow had profound effects on the economic life of the downstream residents. Nearly 60 percent of Ghana's inland fisheries were located in the stretch of the river below Akosombo. After the dam was built, the salt/fresh water interface during the dry season was displaced 20 to 25 km seaward. Before construction, from November to March, salt water penetrated approximately 35 km inland. After the river flow was increased during this season, the salinity boundary was held at 10 to 15 km from the sea (People and Rogoyska, 1969). Consequently, the oyster and other fisheries collapsed. During the high flows alluvium was deposited on the banks of the Volta. The fertile soils left by the river were planted in maize, cassava and vegetables. Mineral fertilizers were neither used nor required. Now that the annual floods are prevented by the dam, the soils are not replenished and the old production system is lost. Searching for alternative means of income generation, people began to produce quicklime by baking oyster shells with fuel wood. The demand for fuel wood had become so great that groves of trees were completely consumed, even the tree roots were dug up giving the trees no chance to re-sprout.

Figure 10: Mean Monthly River Flows at Senchi



As a result of the changes in their economic lives, many people of the Tongu have been displaced, seeking better opportunities elsewhere. There have been significant land use changes, and diminution of the area's biodiversity, especially the disappearance of Hippopotami, crocodiles, manatees and many bird species. While there is no way to restore the river's flow regime, sustainable alternatives to the old fishing and farming systems should be sought.

6 Conclusion

Nostalgia for the better times long ago is a common sentiment. We are frequently reminded that in the past rivers flowed deeper, fields were greener, livestock fatter, and wild game more abundant. In the case of the Volta Basin we are fortunate to have long hydrological records to aid us in our attempt to unravel whether recollections are or are not merely nostalgia for the "good old days".

The water balances developed from the records allow us a first look at the hydrology of the system and to draw the following conclusions. The quantities of water are large; total rainfall is approximately 400 km^3 and runoff is of the order of 30 to 35 km^3. The watershed exhibits non-linear behavior; small changes in rainfall cause larger changes in runoff. About nine percent of the water falling on the catchment runs off to be stored in the reservoir. Changes in the land use and land cover in the uplands are of major importance to the system.

Facing power shortages, the Ghanaians are concerned about the Volta River and particularly about the fate of the Akosombo Reservoir. Demand for water has approached supply and the tradeoffs between various water uses will be more and more carefully scrutinized by the riparians involved. The Volta Basin spans six countries. Large percentages of the uplands are found in Burkina Faso, Ghana and Togo. Conflict over issues such as the construction of dams is already beginning and should be resolved amicably. As demands of the riparian countries increase so does the need for international cooperation.

A sophisticated model will be capable of evaluating the hydrological tradeoffs among the water use sectors: dryland farming, irrigation, water supply, and hydropower. It is hoped that a decision support system for sustainable water resource management will be devised to make the land and water use choices necessary to meet the needs of all the people of the Volta River countries.

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