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WEST AFRICA: VOLTA DISCHARGE DATA QUALITY ASSESSMENT AND USE[1]

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ABSTRACT: Water resource management in West Africa is often a complicated process due to inadequate resources, climatic extremes, and insufficient hydrological information. Insufficient data hinder sustainable watershed management practices, one of the top priorities in the Volta River Basin. This research properly fills in missing data by modeling the hydrological distribution in the Volta River Basin. On average, discharge gages across the basin are missing 20 percent of their monthly data over 20 years. Two methods were used to supplement missing data: a statistically linear model and a conceptual hydrological model. A linear equation, developed from the regression of precipitation and runoff, was used to evaluate the quality of existing data. The hydrological model separates the system into root and groundwater zones. Measured values were used to calibrate the hydrological model and to validate the statistical model. The quality of existing data was analyzed and organized for usability. Accuracy of the hydrological model was also evaluated for its effectiveness using R^2 and standard error. It was found that the hydrological model was an improvement from the linear model on a monthly basis; R^2 values improved by as much as 0.5 and monthly error decreased. Monthly predictions of the hydrological model were used to fill gaps of measured data sets.

(KEY TERMS: water balance; modeling, hydrology, statistics, Volta River Basin, West Africa.)

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INTRODUCTION

Environmental sustainability is of top priority of watershed management in the Volta River Basin (Andreini *et al.,* 2000). Hindrances to watershed management in the Volta River Basin include high population densities, population growth rate, poverty, watershed size, the size and number of dams within the basin, the dynamics of the climate and environment insufficient information, and inadequate communication between countries (Andreini *et al.,* 2000; UNEP, 2001). The countries in the watershed, Ghana, Burkina Faso, Cote d'Ivoire, Togo, Benin, and Mali, are largely interdependent, as upstream/downstream actions and effects are greatly connected. Therefore, discourse between the countries aided by the use of a hydrological model is imperative. A model that represents the entire watershed and is accepted by the international community can improve communication between each country, and support efforts towards environmental sustainability. At present, no comprehensive hydrological model for the Volta River Basin exists (Andreini *et al.,* 2000), which makes objective communication about water issues nearly impossible. To develop such a model requires quality, long term data sets of river discharge, precipitation, and evaporation, none of which are complete and available from any country in the watershed. Various methods have been developed to fill in for missing data within a set. Here a model has been developed to test and refine the quality of the data to describe river discharge.

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Many models can be used to estimate river discharge; model choice depends on such factors as hydrological regime and data availability. To classify models according to hydrological regime, the distinction between base flow versus direct overland flow is important. Another way models are categorized is by data requirements. Generally, a distinction is made between lumped and distributed models; lumped models can predict stream discharge at the outlet of a watershed relatively well with a few lumped parameters. However, these models cannot address the water content of individual fields or slopes within the watershed. Semidistributed models, such as TOPMODEL (Beven *et al.,* 1995), and distributed models, such as Soil Moisture Routing (SMR) (Kuo *et al.,* 1999), predict the spatial location of the runoff areas as well as the watershed discharge. For distributed models, spatial input data on topography, soils, and plant cover are needed. In addition to rules for calculating surface runoff, each of these models maintains a water balance that calculates evaporation as a function of potential evaporation and moisture status of the soil. For lumped models the water balance usually holds for the entire watershed contributing to the streamflow where distributed models calculate moisture content for individual grid cells in the watershed.

Data requirements vary between models. For a model to be useful, its data requirements must be readily obtainable. For example, infiltration excess models require detailed information on soil type, moisture status, and vegetation characteristics. Often, and in the case of the Volta watershed, these data are extremely difficult to obtain. Lumped models have less stringent data requirements. With just precipitation (P) and potential evapotranspiration (ETp) data, discharge can be calculated with the lumped Thornthwaite-Mather (TM) procedure for relatively large watersheds using generalized soil and aquifer characteristics (Thornthwaite and Mather, 1955). The TM procedure was developed in the early 1940s and has successfully been applied in basins throughout the world such as Mount Kilimanjaro in Kenya (Dunne and Leopold, 1978), Luancheng County in Northern China (Kendy *et al.,* 2003), Singkarark-Ombilin in Indonesia (Peranginangin *et al.,* 2004), and northeastern Mexico (Mendoza *et al.,* 2003). For this project, the TM procedure was used on a monthly time step because of its proven ability to successfully predict monthly stream discharge for larger watershed where only P and ETp data are available.

Comparative assessments of models are necessary to highlight strengths and weaknesses. To test the performance of the TM procedure, we compared it to a simple precipitation runoff linear model. This linear model was chosen over others because it involves the least parameters. It has been demonstrated that simpler models are of preference because they are less affected by parameter uncertainty (Perrin *et al.,* 2001). In the past this model has performed better than models that involve more parameters that are subject to overparameterization and low performance levels (Perrin *et al.,* 2001).

THE VOLTA DESCRIBED

The Volta watershed (see Figure 1) drains approximately 400,000 km^2 of the six riparian countries, and is the ninth largest river/basin in SubSaharan Africa (UNEP, 2001). The percentage of the watershed in each country varies: 42 percent in Burkina Faso, 40.2 percent in Ghana, 6.35 percent in Togo, 4.57 percent in Mali, 3.62 percent in Benin, and 3.24 percent in Cote d'Ivoire (Green Cross International, 2001). The landscape is predominantly flat with elevations not exceeding 1,000 m. Climatic extremes that characterize this region are recurring drought, harmattan (hot, dry, usually dusty wind that blows from the northeast or east in the southern Sahara mainly in winter), and sometimes torrential flooding. Highest precipitation levels occur in the south and can reach an annual measurement of 2,000 mm, where levels in the driest regions in the north can be as low as 200 mm annually.

Throughout the region, the terrain includes rain forest, beaches, lagoons, plateaus, wetlands, desert, and savanna. The length of the watershed is approximately 1,600 km long and has three major tributaries, the Black Volta (Mouhoun), the White Volta (Nakanbe), and the Oti (Pendjari). Both the Black and the White Volta rivers flow south from Burkina Faso, and the Oti flows south from Togo. The Oti, the smaller tributary, is 940 km long. The Black Volta extends 1,360 km and the White Volta flows for 1,140 km before merging into the River Volta. Lake Volta, formed by the Akosombo dam, submerges most of the River Volta and has an area of 8,500 km^2 with a storage capacity 153,000 million m^3. This dam produces over 90 percent of the electric energy in Ghana. Environmental problems of top priority in the watershed are loss of biodiversity, waterborne diseases, diminishing water resources, insufficient irrigation, inadequate/lack of information, and poor institution/legal framework (UNEP, 2001).

For most of the basin precipitation variability is problematic, forcing the region to suffer consequences of both droughts and floods. Droughts between 1982 and 1984 caused catastrophic energy decreases in Benin, Ghana, and Togo, and accounted for several hundred thousand deaths throughout the basin, which promoted awareness of problems with reliable

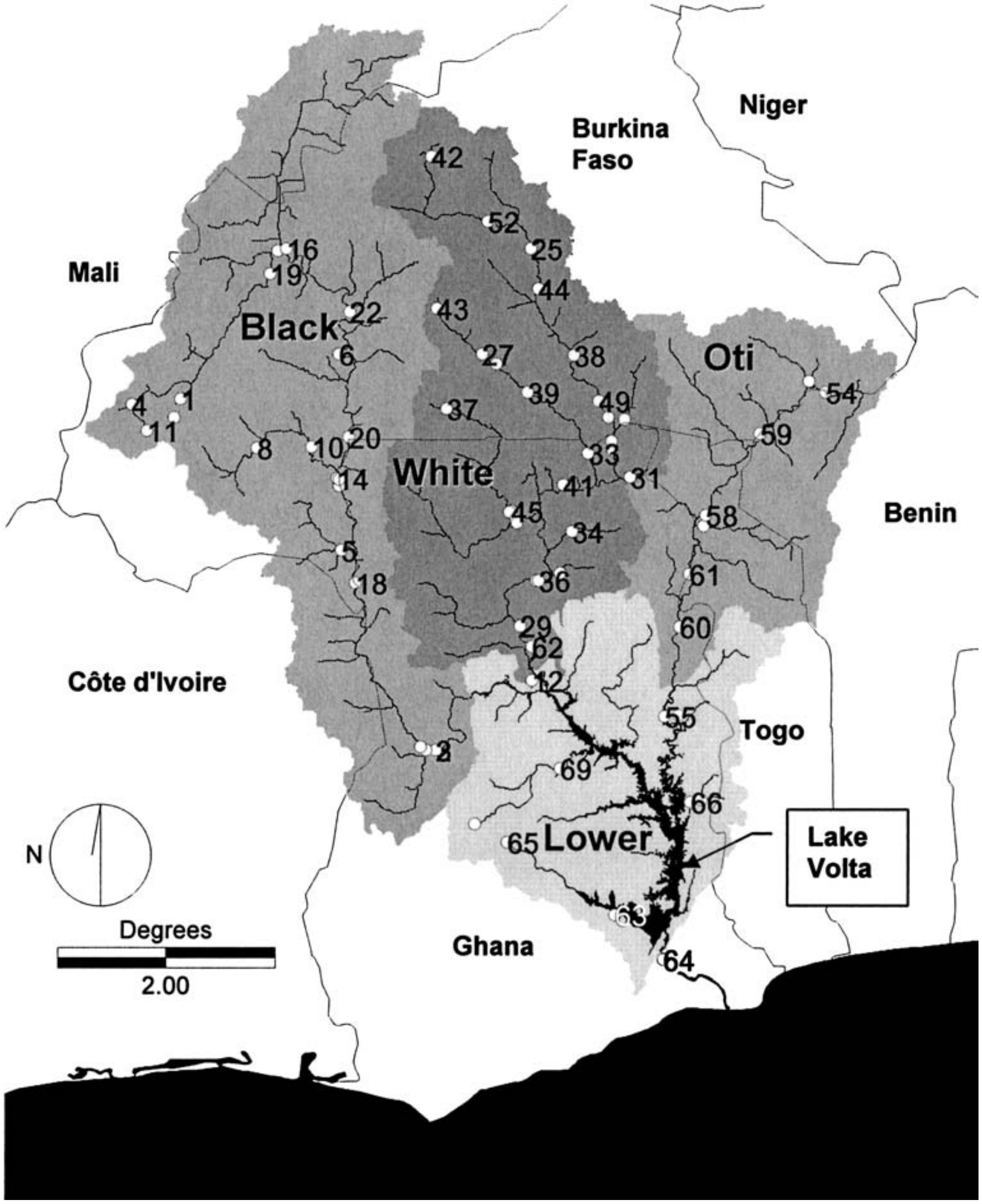

Figure 1. Map Showing Tributaries, Dams, Stream Networks, Gaging Stations, and Drainage Areas of the Volta River Basin. Labels refer to gaging station ID numbers in Table 1. Overlapping labels have been omitted.

water supply, and initiated increases in research (Ofori-Sarpong, 1985). Floods during 1995 and 1999 were responsible for several more deaths and the displacement of more than 300,000 people (Akuffo, 1998). Since then research has attempted to characterize within season precipitation variability (Ofori-Sarpong, 1985), estimate average dry spell duration (Adiku *et al.,* 1997), enhance weather prediction (Opuku-Ankomah and Cordery, 1994), and develop a correlation between global climate change and regional land use changes (Opoku-Ankoham and Amisigo, 1998). However, a complete and thorough water balance study of the entire basin, the first step to watershed management, has not been carried out. This project models the entire watershed as one system by dividing the watershed into its major subbasins, and by dividing sub-basins into smaller sections. Modeling the entire basin as smaller sections provides detailed information on the effects of each country to the basin as a whole.

THE HYDROLOGICAL MODEL

This paper uses P, ETp, and soil physical parameters to administer the TM procedure for modeling stream discharge. The soil physical parameter of interest is available water capacity (AWC) of the root zone and is defined as the volume of water that is available to the roots of the plant after soil has been wetted to above field capacity

$$AWC = D_{rz}*(FC-WP) \tag{1}$$

where field capacity (FC) and wilting point (WP) are water contents by volume and D_{rz} represents the depth of the root zone. Any moisture above the field capacity can no longer be held by capillary forces and therefore will drain out of the soil. Additionally, plants cannot withdraw moisture below the WP. The WP was estimated as one third of the field capacity (Dunne and Leopold, 1978). Also we define the parameter soil moisture (SM), which is the depth (volume/unit area) of water held above WP in the root zone.

In the TM procedure, the calculation of evaporation and soil moisture depends on the distinction between wet and dry months. For wet months, the P is greater that the ETp and for dry months, the P is smaller than the ETp. In the procedure, the value of AWC of the last month of a dry season is taken as the initial soil moisture of the first wet month. For subsequent wet months, the amount of plant available moisture in the root zone is calculated as

$$SM_t = SM_{t-1} + P - ETp \tag{2}$$

where SM_t is the soil moisture storage of the current month and SM_{t-1} is the soil moisture of the previous month. Note that SM is the soil moisture available to plants and thus at SM = 0 the moisture content in the soil is at the WP. In Equation (2), values of P and ETp are monthly values. Since surplus water above field capacity, $SM_{surplus}$, cannot be held by the soil, during the months where the calculated SM_t is greater than the AWC, SM_t is set to AWC and the surplus becomes recharge to the ground water.

For the dry months, the soil moisture is calculated as

$$SM_t = SM_{t-1} * \exp\left(\frac{P - ETp}{AWC}\right) \tag{3}$$

Moisture surplus, $SM_{surplus}$, is zero when the calculated SM_t is less than the AWC.

The ground water recharge only takes place in the seasonal wet valleys. Consequently, only a portion of the ground water in the watershed contributes to the streamflow. Then, the average volume of recharge, R_t, per unit area in the watershed can be calculated as

$$R_t = \beta * SM_{surplus} \tag{4}$$

where β is the fraction of the watershed that recharges the ground water.

The stream discharge itself is a function of the ground water storage, S_G. The ground water storage is depleted by the base flow in the stream and supplemented by the recharge. We follow here the original TM procedure (Thornthwaite and Mather, 1955) which assumes that a constant fraction (1-α) of the ground water storage each month becomes streamflow. The parameter a, is that fraction of the ground water storage at the beginning of the month that remains as storage at the end of the month. Based on this, S_G can be written as

$$S_{G(t)} = (1 - \alpha) * (S_{G(t-1)} + R_t) \tag{5}$$

where $S_{G(t-1)}$ is the ground water storage in the previous month, $S_{G(t)}$ is the current ground water storage, and R_t is the ground water recharge during the past month. The fraction of water that leaves the basin as runoff varies with the physics of the basin. Thornthwaite and Mather (1955) suggest that for large catchments in the southeastern United States, approximately 50 percent (i.e., $\alpha = 0.5$) of the total available runoff actually becomes river flow each month. The rest of the surplus is retained in the subsoil, small lakes, and channels and is available for run-off in the following month. Values for AWC, α, and β are estimated by calibration as discussed later in this paper.

DATA AVAILABLE

The model and simulation devised in this project required various types of data. The data used for the hydrological model included ETp and P as input parameters, and stream discharge for calibration and validation. Other data used includes a digital elevation map (Land Processes, 2004). This map was used in a geographic information system (GIS) based program, Idrissi 32 (Clark Labs, 2006), where watershed areas were outlined to extrapolate ETp, P, and dimension information.

Because multiple sources were available for specific data, it was necessary as a first step to select between different sources. Precipitation data were obtained from three sources: Water Resources Institute of the Council for Scientific and Industrial Research (WRI), Accra, Ghana; the Global Gridded Climatology (GGC) compiled by the Climatic Research Unit at resolution of 0.50 lat/lon, and published by New *et al.* (1999a,b); and Direction Générale de l'Inventaire des Ressources

Hydrauliques du Burkina-Faso (DGIRH). (Editor's note: The author has explained that some data sets used for this paper were obtained from organizations by very special request, and that no full citation is possible.) The records from DGIRH included monthly precipitation data from 82 gages across the watershed over an average of 40 years. The GGC compiled monthly data from nearly 90 gages over 50 years across the entire watershed area, where WRI detailed weekly data from only nine gages over an average of 60 years exclusively in Ghana. Because WRI was not comprehensive enough, these data were not considered or analyzed for its usability. To compare the precipitation data from the two data sets, the monthly precipitation within the Black Volta basin from DGIRH for gages (PDGIRH) were averaged together and then compared to monthly totals extracted from one GGS pixel grid (PGGC) representing the Black Volta sub-basin. The Black Volta subbasin was chosen because precipitation gages within the DGIRH spreadsheet were the most consistent. The R^2 was obtained and prediction error, PE was calculated as

$$PE = \sqrt{\frac{\sum_{i=1}^{n}\left[\left(P_{DGIRH}\right)_i - \left(P_{GGC}\right)_i\right]^2}{n-1}} \qquad (6)$$

where n is the number of observations. Figure 2 shows a graphical comparison between the two data sets for the gages covering the area of the Black Volta subbasin. The R^2 value of 0.97 and the error of 15.5 mm show that the two data sources for the Black Volta subbasin (Figure 2) are similar. We decide therefore to use the GGC data in all comparisons and simulations. Additionally, GGC data was more convenient as it could be used directly with GIS while the DGIRH set was provided in a spreadsheet that was not organized by gage position and would have to be reformatted and recalculated for each stream discharge gage.

Potential evaporation was available from DGIRH. The Climatic Research Unit (CRU) (New *et al.,* 1999a,b) also provided data for vapor pressure, wind speed, and temperature that was used to calculate ETp using Penman's equation. These calculations were compiled by Philip Oguntunde of the Center for Development Research at Bonn University, Germany to allow use of GIS. The data from Burkina Faso covers the region inside Burkina Faso exclusively. This source provides monthly ETp data for eight sites throughout the country from 1961-1990. Because Oguntunde's calculation was more inclusive, it was chosen as the source of ETp data. Both precipitation and precipitation estimates were made by overlaying a map of the area with a pixel grid. Each pixel, at 0.5° x 0.5° per cell (1 cell ≈ 11,700 km^2), was weighted by that pixel's contribution to the total area, and the monthly mean was computed by adding the weighted pixels in the total area (Andreini *et al.,* 2000).

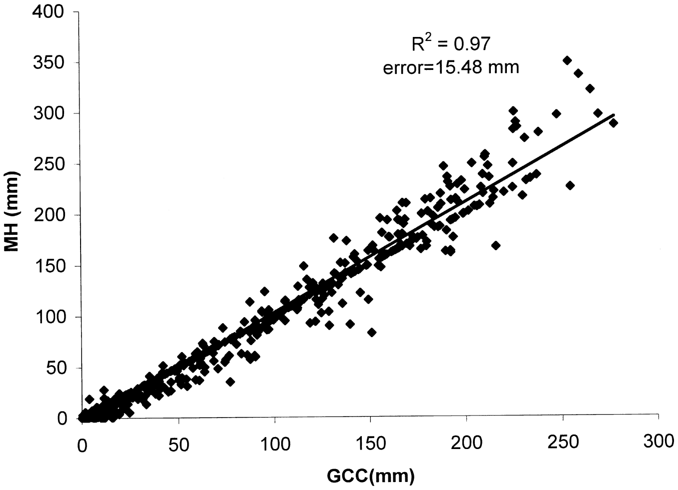

Figure 2. Linear Regression of Monthly Precipitation Data Between GGC and MH on the Black Volta River.

Two sources of stream discharge, the WRI of Ghana and L'Institut de Recherche pour le Développement (ORSTOM), proved advantageous. Figure 1 shows the location of each streamflow gage listed in Table 1. Table 1 lists the stream discharge gages for which data were available by source. Gages are categorized by subbasin and are located on the principal river unless noted. Gages located on tributaries of rivers are followed by the name of the tributary in parentheses. The second column indicates which data source provided the data. Between both sources, 20 percent of the data over the entire watershed is missing. Many of the gages are missing as much as 50 percent of their data, which indicates the necessity to fill these gaps. This high percentage of missing data (Table 1) together with the percent difference between the sources (Table 2) suggests data inaccuracy.

Often one source would have data for a gage that another would not, which allowed for filling in missing data from one source to another. To determine if this was feasible, correspondence between the two gages was investigated. For the years and stations where both sources provided data, a linear regression was performed to examine the correlation between the two sources. Figure 3 is a sample graph showing the correlation between these two sources at Bamboi on the Black Volta River. Bamboi, the gauging station that measures the entire Black Volta subbasin, was chosen as an example gage, because it has the fullest record of the gages that cover an entire subbasin.

TABLE 1. Streamflow Gage Site Details.

ID	Name	Source	CC	Lat. (˚)	Long. (˚)	Yi 19xx	Yf 19xx	No. Years	%miss	Area (km^2)
				Black Volta						
1	Badara (Kou)	ORSTOM	BF	11.37	-4.37	55	85	16	57.5	971
2	Bamboi-WRI	WRI	GH	8.15	-2.03	51	91	33	36	134,200
3	Bamboi	ORSTOM	GH	8.15	-2.03	51	74	24	0.7	134,200
4	Banzo	ORSTOM	BF	11.32	-4.82	56	87	32	8.62	3,024
5	Batie (Bambassou)	ORSTOM	BF	9.98	-2.90	71	85	15	2.9	6,075
6	Boromo	ORSTOM	BF	11.78	-2.92	55	91	31	0.7	48,078
7	Bui-WRI	WRI	GH	8.15	-2.12	54	93	33	4.5	111,853
8	Dan (Bougouriba)	ORSTOM	BF	10.92	-3.67	70	85	16	28.83	90,85
9	Dapola	ORSTOM	BF	10.57	-2.92	52	84	32	0.63	96,437
10	Diebougou (Bougouriba)	ORSTOM	BF	10.93	-3.17	63	86	24	9.82	15,140
11	Guena	ORSTOM	BF	11.08	-4.68	62	82	10	64.4	907
12	Kalbuipe (Sur)-WRI	WRI	GH	8.79	-1.14	63	97	16	48.2	3,044
13	Kouri	ORSTOM	BF	12.73	-3.48	55	83	21	33.63	27,156
14	Lawra-WRI	WRI	GH	10.64	-2.94	51	75	23	16.8	96,000
15	Lawra	ORSTOM	GH	10.63	-2.92	51	73	23	0	96,000
16	Manimenso	ORSTOM	BF	12.75	-3.40	56	85	29	3.4	21,124
17	Nasso (Kou)	ORSTOM	BF	11.20	-4.43	61	71	11	6.25	406
18	Noumbiel	ORSTOM	BF	9.68	-2.77	75	85	8	27.6	87,625
19	Nwokuy	ORSTOM	BF	12.52	-3.55	56	88	33	0	12094
20	Ouessa	ORSTOM	BF	11.02	-2.83	70	85	16	16.7	60283
21	Tainso (Tain)-WRI	WRI	GH	8.18	-2.17	63	92	19	29	6113
22	Tenado	ORSTOM	BF	12.17	-2.82	76	85	10	0	24086
				White Volta						
23	Bagre	ORSTOM	BF	11.20	0.43	74	90	17	6.4	36102
24	Bagre (Tcherbo)	ORSTOM	BF	11.69	1.47	78	86	8	29.5	6033
25	Bissiga (nakanbe)	ORSTOM	BF	12.75	1.15	74	83	10	5.8	18003
26	Bittou (Nouhao)	ORSTOM	BF	11.18	0.28	74	85	12	20.5	6044
27	Dakaye	ORSTOM	BF	11.78	1.60	75	86	12	1.4	6033
28	Garu-WRI	WRI	GH	10.90	0.39	66	70	5	47.2	132
29	Lankatere (Mole)-WRI	WRI	GH	9.29	1.25	71	77	6	47.4	18253
30	Nabogo(Nabogo)-WRI	WRI	GH	9.77	0.88	62	86	25	22	3040
31	Nakpanduri(Red)-WRI	WRI	GH	10.65	0.23	58	63	6	47.2	3030
32	Nangodi(Nazinon)-W	WRI	GH	10.87	0.62	63	74	10	16.2	12077
33	Nangodi (Nazinon)	ORSTOM	GH	10.87	0.62	63	73	11	0	12077
34	Nasia (Nasia)	WRI	GH	10.15	0.77	67	89	12	57.6	6070
35	Nawuni	ORSTOM	GH	9.70	1.10	53	73	21	2.8	99741
36	Nawuni	WRI	GH	9.70	1.08	53	90	36	12.8	99741
37	Nebbou (Sissili-WHT)	ORSTOM	BF	11.28	1.93	74	85	12	8.3	3030
38	Niagho (Nakanbe)	ORSTOM	BF	11.77	0.75	51	84	27	9.5	30046
39	Nobere	WRI	GH	11.43	1.18	58	75	17	13.4	9052
40	Pwalugu (WHT)	WRI	GH	10.58	0.85	52	77	25	30.6	48243
41	Pwalugu (WHT)	ORSTOM	GH	10.58	0.85	52	73	21	0	48243
42	Rambo	ORSTOM	BF	13.6	2.07	83	87	4	13.3	2995
43	Sakoinse (Red,Nazinon)	ORSTOM	BF	12.2	2.02	70	85	11	33	3001

Notes: Identification numbers correspond to gage locations in Figure 1, Map of the Volta River Basin. Gages are listed per subbasin. CC = Country Code, BF = Burkina Faso, GH = Ghana, TG = Togo, IV = Cote d'Iviore, BJ = Benin. Latitude and longitude, datum WGS84, are given in decimal degrees. Yi (year initial) and Yf (year final) indicate the start and end of the range of data. The next column gives the total number of years that have data within the range followed by %miss, which indicates the percentage of data missing throughout the full range. The watershed areas of each station are in square kilometers as extrapolated from GIS program.

TABLE 1. Streamflow Gage Site Details (cont'd).

ID	Name	Source	CC	Lat. (˚)	Long. (˚)	Yi 19xx	Yf 19xx	No. Years	%miss	Area (km^2)
				White Volta (cont'd).						
44	Wayen	ORSTOM	BF	12.38	1.08	65	87	24	27.7	21,010
45	Wiasi (Sisili)	WRI	GH	10.34	1.33	62	90	18	55.9	12,105
46	Wiasi (Sisili)	ORSTOM	GH	10.33	1.35	62	73	12	0	12,105
47	Yagaba (Kalpawn)	WRI	GH	10.26	1.29	58	79	22	15.9	9,100
48	Yagaba (Kalpawn)	ORSTOM	GH	10.23	1.28	58	73	16	2.66	9,100
49	Yakala (Nakanbe)	ORSTOM	BF	11.35	0.52	56	84	26	16.6	33,065
50	Yarugu	WRI	BF	10.98	0.40	62	77	16	8.5	39,132
51	Yarugu	ORSTOM	BF	10.98	0.40	66	73	8	0	39,132
52	Yilou (Nakanbe)	ORSTOM	BF	13.00	1.55	73	83	11	3.9	14,995
				Oti/Daka						
53	Arly-dou(Oti)	ORSTOM	TG	11.53	1.42	78	85	8	18	9,063
54	Arly-Pendjari	ORSTOM	BF	11.43	1.57	78	85	8	35.4	15,097
55	Ekumdipe (Daka)	WRI	GH	8.46	0.09	63	73	9	27.1	9,133
56	Ekumdipe (Daka)	ORSTOM	GH	8.47	0.22	63	73	11	0	9,133
57	Koumangou (Kou)	ORSTOM	TG	10.2	0.45	59	73	15	0	6,070
58	Mango	ORSTOM	TG	10.3	0.47	53	73	21	0	36,287
59	Porga	ORSTOM	BJ	11.05	0.97	52	93	35	25.4	27,197
60	Sabari	ORSTOM	GH	9.28	0.23	59	73	15	0	72,775
61	Saboba (see gage)	WRI	TG	9.76	0.32	53	90	30	43.75	48,423
62	Yendi* (Daka)	WRI	GH	9.1	-1.14	58	87	26	65.24	6,084
				Volta Prop						
63	Senchi	ORSTOM	GH	6.22	0.08	37	63	27	3.7	400,000
64	Senchi	ORSTOM	GH	6.22	0.08	51	79	29	1.7	400,000
65	Aframso (Afram)	WRI	GH	7.3	-1.37	67	95	23	36.7	4,500
66	Ahamnasu (asukawkaw)	WRI	GH	7.67	0.33	79	91	5	72	1,018
67	Asukawkaw (Volta)	WRI	GH	7.69	0.43	78	92	7	86	6,109
68	Podoe	WRI	GH	6.63	-0.37	69	81	13	8.6	3,067
69	Prang (Pru)	ORSTOM	GH	7.98	-0.88	57	67	11	3.1	6,113
70	Pruso	WRI	GH	7.47	-1.67	57	91	35	13.4	4,100

Notes: Identification numbers correspond to gage locations in Figure 1, Map of the Volta River Basin. Gages are listed per subbasin. CC = Country Code, BF = Burkina Faso, GH = Ghana, TG = Togo, IV = Cote d'Iviore, BJ = Benin. Latitude and longitude, datum WGS84, are given in decimal degrees. Yi (year initial) and Yf (year final) indicate the start and end of the range of data. The next column gives the total number of years that have data within the range followed by %miss, which indicates the percentage of data missing throughout the full range. The watershed areas of each station are in square kilometers as extrapolated from GIS program.

TABLE 2. Discharge Data Source Correlation.

Gage	Bamboi	Lawra	Yarugu	Nawuni	Wiasi	Nangodi	Yagaba	Ekumdipe
R^2	0.94	0.96	0.84	0.99	0.99	0.51	0.97	0.96
% diff_{ave}	6	6	12	4	1	28	4	9

Note: This table shows the association between data from WRI and ORSTOM. Row 1 holds the R^2 values where Row 2 shows the percent difference from ORSTOM to WRI.

Six of the eight locations showed R^2 values (WRI versus ORSTOM) of 0.94 and higher and errors were less than 10 percent of the mean (Table 2). The gage at Yarugu on the White Volta had an R^2 value of 0.84 and 12 percent difference, which is barely acceptable. Clearly for the Nangodi station on the White Volta one of the data sources was in error. In the next section, we address the accuracy of the data and use the calibrated TM procedure to fill in the missing records.

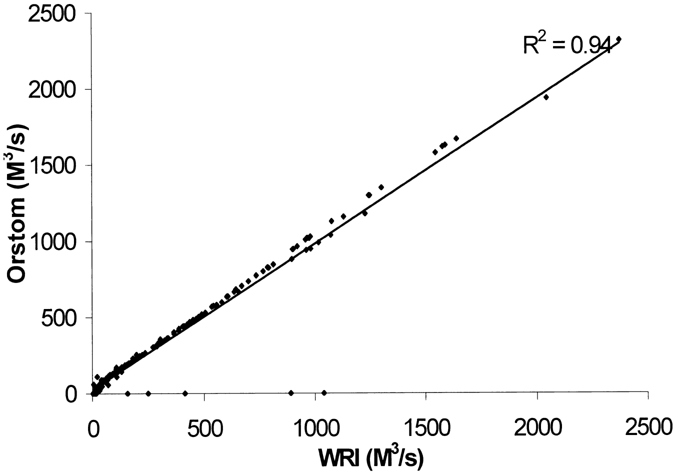

Figure 3. Comparison of Streamflow Data Sources.

DATA QUALITY AND MODEL ASSESSMENT

This section describes how streamflow data were evaluated for accuracy. First, we classify the streamflow gages according to their quality. The TM model is then analyzed for its effectiveness in predicting streamflow. Finally, parameter values for the TM model are given and trends are discussed.

The quality of the stream discharge at each gage is not known. It is important to discover which stations provide discharge data with reasonable accuracy and which do not. Since we expect that more precipitation will result in greater discharge, as a first test, annual precipitation and annual discharge were linearly regressed to predict runoff. This linear regression can also be used to predict streamflow for missing years. Although high correlation coefficients do not guarantee that stream discharge records are acceptable, poor correlations indicate that there are some problems with the discharge data. The linear regression method used was in the form of

$$\frac{Qa}{A} = c * (P - Ia) \tag{7}$$

where A is the drainage area, P is the average annual precipitation in the watershed area with annual discharge volume, Qa, and c is the runoff coefficient (dimensionless) that represents the amount of precipitation that becomes runoff after the initial annual abstraction, Ia, is met. To be more explicit, we use the simple equation for the slope of a line, y = mx + b, where the runoff of interest y = Qa/A, the slope of precipitation and runoff m = c, and the intercept b = Ia*m. Ia is the amount of annual precipitation that does not become runoff over the area that contributes to the streamflow.

Arbitrarily, an R^2 value of 0.50 for annual precipitation and runoff was chosen as the minimum value below which gages were deemed highly inaccurate and were rejected for usage in simulation. Gages that met this criterion are listed in Table 3, and rejected gages are listed in Table 4. An exception is the Rambo gages, with an R^2 value of 0.82, where the parameters calibrated to the TM procedure were too low to be physically possible. The equation for each gage is shown in Column 2 of Tables 3 and 4 (entitled linear regression method). In Tables 3 and 4, gages are categorized by subbasin and are located on the principal rivers unless noted. Gages are listed according to position from furthest south on the river followed by gages directly upstream. Of interest in Table 3 is the Senchi gaging station below the dam. The annual coefficient of determination of P versus runoff (RO) for the period, 1937 to 1963 before the dam was built is 0.82, the highest in the watershed. However, for the period after the dam was built, from 1963 to 1996, the value drops to 0.55, showing little relationship between annual runoff flowing into the dam and dam discharge and indicating, as expected, that flow below the dam is governed by the operation of the turbine over a time scale larger than the annual cycle.

Error in the prediction, PE, was calculated to show the difference between predicted values from the linear model and measured values. These values are listed in Table 3, Column 5, and were calculated using the relationship

$$PE = \sqrt{\frac{\sum_{i=1}^{n} \left[Q_i - Qm_i\right]^2}{n-1}} \tag{8}$$

where Q indicates the measured discharge, Qm indicates the model results, and n represents the number of measured values.

The linear regression of annual values in Table 3, Column 2, gives some interesting trends. In the upper part of the Black Volta (located in the Burkina Faso), the amount of annual precipitation before runoff occurs is on the order of 400 to 600 mm and is the lowest in the Volta basin. This is the driest part of the region. In the rest of the basin (i.e., Oti and White Volta basins) the initial abstraction is generally on the order of 700 to 800 mm. These higher initial abstraction values could be attributed either to the existence of more reservoirs with higher evaporation losses or the large national parks in these areas that

TABLE 3. Results of Data Quality and Model Assessment.

Gage Name	LM Equation	LM R^2 (year)	LM R^2 (month)	PE (year)	AWC (mm)	α TAR	β %CA	TM R^2 (year)	TM R^2 (month)	PE (year)
Black Volta	**0.16*(P-640)**	**0.59**	**0.23**	**15.43**	**60**	**0.35**	**35**	**0.59**	**0.60**	**18**
Bamboi-W	0.3*(P-770)	0.80	0.16	14.84	83	0.33	58	0.58	0.66	25
Bamboi -O	0.29*(P-730)	0.85	0.15	15.22	83	0.33	58	0.61	0.56	30
Tainso (Tain)	0.06*(P-950)	0.50	0.15	17.82	84	0.50	11	0.67	0.56	13
Bui	0.27*(P-718)	0.65	0.20	33.31	39	0.35	58	0.54	0.63	35
Kalbuipe (Sur)	0.13*(P-803)	0.50	0.26	21.99	83	0.41	20	0.49	0.66	22
Dapola	0.13*(P-580)	0.68	0.21	7.88	33	0.31	30	0.71	0.61	10
Lawra-W	0.12*(P-590)	0.61	0.16	7.96	52	0.28	32	0.42	0.64	13
Lawra-O	0.14*(P-590)	0.70	0.16	7.43	52	0.28	32	0.55	0.60	11
Dan (Boug)	0.15*(P-770)	0.64	0.16	11.56	90	0.42	21	0.47	0.63	15
Diebougou (B)	0.18*(P-700)	0.50	0.19	20.77	92	0.40	37	0.68	0.67	18
Ouessa	0.1*(P-580)	0.51	0.37	7.43	20	0.33	25	0.86	0.68	6
Banzo	0.25*(P-600)	0.50	0.38	35.67	74	0.44	48	0.45	0.70	40
Boromo	0.07*(P-420)	0.50	0.18	6.81	20	0.27	30	0.44	0.47	10
Tenado	0.09*(P-430)	0.50	0.33	6.79	24	0.30	41	0.52	0.55	11
Nwokuy	0.17*(P-600)	0.50	0.02	22.04	100	0.30	38	0.65	0.55	20
Manimenso	0.08*(P-513)	0.52	0.62	9.33	33	0.34	20	0.74	0.48	8
White Volta	**0.52*(P-790)**	**0.54**	**0.33**	**38.24**	**112**	**0.56**	**63**	**0.59**	**0.68**	**37**
Lankatere(Mo)	1.1*(P-915)	0.54	0.27	77.20	176	0.75	87	0.69	0.77	72
Nawuni-O	0.19*(P-526)	0.50	0.34	14.48	66	0.50	60	0.55	0.76	19
Nasia (Nasia)	0.95*(P-956)	0.67	0.30	38.70	163	0.55	64	0.80	0.82	33
Yagaba (Kalp)-O	0.52*(P-800)	0.51	0.33	62.12	109	0.61	68	0.70	0.77	58
Wiasi-O (Sisili)	0.31*(P-780)	0.50	0.39	23.09	86	0.62	43	0.37	0.72	23
Ngodi (Naz)-W	0.28*(P-700)	0.51	0.35	13.83	71	0.32	55	0.40	0.26	20
Oti	**0.45*(P-750)**	**0.59**	**0.25**	**34.51**	**143**	**0.48**	**68**	**0.63**	**0.63**	**40**
Ekumdipe (Da)	0.62*(P-880)	0.56	0.15	55.36	174	0.50	100	0.73	0.73	47
Sabari	0.54*(P-820)	0.62	0.33	34.15	167	0.40	80	0.77	0.80	31
Saboba	0.72*(P-760)	0.59	0.26	61.49	133	0.65	100	0.59	0.71	62
Koumangu (K)	0.77*(P-760)	0.71	0.44	57.83	200	0.61	100	0.58	0.86	90
Mango	0.48*(P-730)	0.62	0.23	29.53	161	0.35	94	0.56	0.68	42
Porga	0.25*(P-670)	0.50	0.20	25.21	101	0.35	47	0.60	0.70	23
Arly	0.1*(P-700)	0.59	0.23	6.80	27	0.30	16	0.55	0.53	6
Arly (Dou)	0.09*(P-670)	0.56	0.16	5.71	180	0.70	10	0.62	0.00	19
Volta Prop	**0.31(P-840)**	**0.62**	**0.14**	**58.48**	**139**	**0.48**	**52**	**0.58**	**0.55**	**65**
Senchi (37-63)	0.54*(P-850)	0.82	0.20	19.12	70	0.33	69	0.70	0.72	26
Senchi (51-80)	0.25*(P-728)	0.55	0.09	41.43	63	0.55	59	0.35	0.37	43
Aframso (Afr)	0.04*(P-850)	0.79	0.21	6.70	67	0.37	50	0.61	0.53	6
Ahamnasu (A)	0.38*(P-997)	0.68	0.14	70.45	73	0.39	38	0.31	0.64	89
Podoe	0.09*(P-790)	0.50	0.11	13.93	67	0.45	18	0.62	0.34	12
Prang (Pru)	0.84*(P-1070)	0.50	0.08	142.83	351	0.70	100	0.77	0.69	153

Notes: For stations with acceptable quality of data ($R^2 > 0.5$ for the linear model), bold values are averages; LM = linear model equation described in the model assessment; LM R^2 = the R^2 values of the LM versus measured values; PE = Prediction Error (year); AWC = Available Water Capacity; α = portion of total available runoff (TAR); β = percent of catchment area contributing to runoff; and TM R^2 = the R^2 values of TM versus measured values.

TABLE 4. Gages That Were Discarded Because LM Values Did Not Meet the Set Criteria.

Gage Name	LM Equation	LM R^2 (year)	LM R^2 (month)	PE (year)	AWC (mm)	α TAR	β %CA	TM R^2 (year)	TM R^2 (month)	PE (year)
Black Volta		**0.17**	**0.28**	**76**	**97**	**0.44**	**44**	**0.30**	**0.47**	**105**
Guena	1.3*(P-800)	0.14	0.02	213	173	0.20	20	0.62	0.4	244
Batie (Bamb)	0.19*(P-670)	0.30	0.33	31	36	0.57	57	0.50	0.73	28
Noumbiel	0.11*(P-580)	0.39	0.35	10	131	0.20	20	0.46	0.27	14
Badara (Kou)	0.07*(P+900)	0.03	0.45	73	84	0.60	60	0.06	0.72	81
Kouri	0.04*(P-3)	0.10	0.00	14	93	0.30	30	0.15	0.19	14
Nasso (Kou)	0.24*(P+120)	0.06	0.54	115	67	0.76	76	0.03	0.50	250
White Volta		**0.18**	**0.37**	**100**	**44**	**0.56**	**56**	**0.37**	**0.45**	**72**
Bissiga (Naka)		0.00	0.35	5	7	0.44	44	0.23	0.00	34
Bagre (Tcher)		0.0051	0.4	2	27	0.40	40	0.04	0.64	25
Bagre (Nak)	0.09*(P-370)	0.16	0.55	15	1	0.62	62	0.63	0.72	22
Bittou (Nouhao)	0.1*(P-430)	0.06	0.54	30	33	0.70	70	0.8	0.7	21
Garu	0.04*(P-500)	0.012	0.13	22	1	0.50	50	0.2	0.07	437
Nakpan(Red)	0.02*(P-2500)	0.03	0.36	102	1	0.60	60	0.04	0.42	379
Nabogo (Nab)	0.43*(P-780)	0.35	0.30	68	179	0.68	68	0.71	0.65	53
Sakoins(Red)	0.02*(P-400)	0.29	0.35	57	21	0.70	70	0.84	0.72	3
Yarugu-W	0.3*(P-600)	0.29	0.42	33	111	0.90	90	0.35	0.16	53
Yarugu-O	0.03*(P-1440)	0.007	0.53	78	111	0.90	90	0.48	0.45	48
Nawuni -W	0.25*(P-650)	0.38	0.33	25	66	0.50	50	0.46	0.75	23
Nobere	1.13*(P+690)	0.38	0.44	1700	3	0.43	43	0.6	0.6	92
Pwalugu-W	0.09*(P-200)	0.05	0.44	27	5	0.49	49	0.22	0.65	32
Pwalugu-O	0.14*(P-320)	0.1	0.41	28	5	0.49	49	0.42	0.63	24
Rambo	0.1*(P-270)	0.82	0.61	4	1	0.70	70	0.02	0.01	88
Nangodi (Naz)-O	0.25*(P-690)	0.31	0.44	23	71	0.32	32	0.74	0.56	15
Nebbou (Sis)	-0.04(P-1258)	0.15	0.26	10	61	0.92	92	0.08	0.27	29
Niagho (Nak)	0.24*(P-223)	0.15	0.35	46	1	0.30	30	0.10	0.31	118
Wiasi-W (Sisili)	0.13*(P-640)	0.114	0.35	29	104	0.62	62	0.02	0.75	39
Yakala (Nak)	0.08*(P-380)	0.28	0.53	12	27	0.48	48	0.53	0.32	14
Yilou (Nak)	0.02*(P-30)	0.06	0.00	7	109	0.17	17	0.30	0.13	12
Yagaba (Kalp)-W	0.5*(P-850)	0.35	0.28	75	109	0.61	61	0.68	0.73	104
Dakaye	-0.01*(P-1956)	0.03	0.42	5	2	0.62	62	0.13	0.49	41
Wayen	0.01*(P+4)		0.07	8	3	0.30	30	0.17	0.19	17
Oti		**0.23**	**0.23**	**286**	**155**	**0.54**	**54**	**0.12**	**0.61**	**105**
Ekumdipe-W (Da)	-3*(P-1830)	0.02	0.13	541	174	0.50	50	0.14	0.66	119
Yendi (Daka)	0.16*(P-890)	0.23	0.33	31	135	0.57	57	0.10	0.56	91
Proper		**0.35**	**0.05**	**46**	**289**	**0.38**	**38**	**0.39**	**0.49**	**48**
Asukaw (Vo)	0.21*(P-1095)	0.37	0.01	62	518	0.43	43	0.38	0.61	83
Pruso	0.06*(P-900)	0.32	0.09	30	61	0.32	32	0.40	0.37	13

Note: This table shows the results of gages where LM values did not meet the set criteria. For a description of terms refer to Table 3.

are home to a diversity of plants, little erosion, and a greater retention of rainwater. The highest initial abstraction is 1,070 mm for the Prang station in the Volta proper subbasin, which is below all three subbasins but upstream of the Akosombo Dam. Since the R^2 value is rather low, the high initial abstraction is likely a consequence of the fitting of the data rather than significant geographic features. The runoff coefficients, defined as a portion of the precipitation above the initial abstraction that becomes streamflow, also follow trends. In the Black Volta subbasin values do not exceed 0.3 and are 0.16 on average. In both downstream ends of the White Volta and Oti basins, the runoff coefficients are higher than that for the Black

Volta subbasin. Upstream in the White Volta and Oti, runoff coefficients are lower and similar to the values in the Black Volta.

We also regressed linearly the monthly precipitation and discharge data similar to Equation (7). As expected, the annual R^2 values are generally higher than those for the monthly data (Table 3, Column 4).

Tables 3 and 4 also list the three parameters used for the TM procedure: Available Water capacity (AWC, Column 6), the fraction of ground water that does not become stream flow each month (α, Column 7), and the fraction of drainage area contributing recharge to the ground water, (β, Column 8). These parameters were calibrated toward minimum annual PE listed in Column 11 by using the solver solution function in Microsoft Excel.

A linear regression (similar to Equation 8) of the TM modeled monthly and annual discharge values against measured discharge data was done to compare with R^2 values of the linear model. The annual R^2 values are listed in Column 9 and monthly values are in Column 10 in Table 3 for the gage with a record of acceptable accuracy, and in Table 4 for which the record was questionable. Graphically, as an example, the results of the linear regression model and the TM procedure are given in Figures 4 and 5 for the Bamboi gage for the ORSTOM and WRI data.

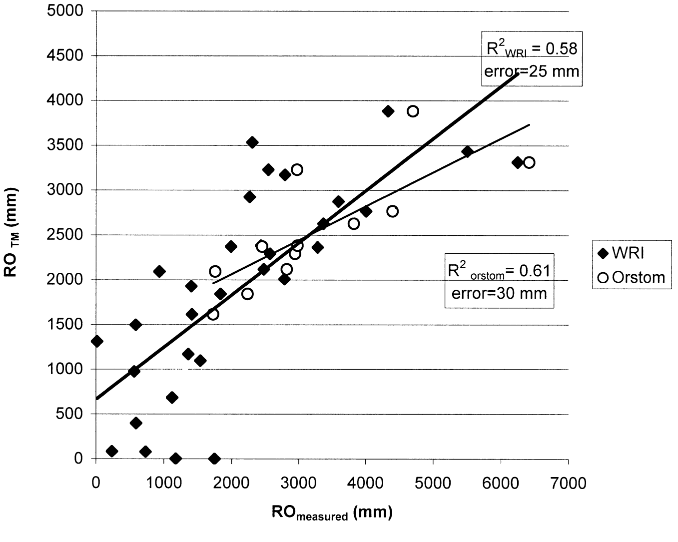

Figure 4. Results of TM Model for Annual Runoff Predictions Regressed With Measured Data From WRI and ORSTROM at Bamboi Station on the Black Volta River.

In Table 3, the annual R^2 values for the TM method and the linear regression method are generally in the same range. For some gages the R^2 values for the annual linear regression method were significantly better than annual TM method values (i.e., Bamboi), indicating that for these gages the annual TM model was not an improvement from the annual linear model. In some other cases such as the four farthest downstream stations of the White Volta in Table 3, the TM method outperformed the linear regression method using annual data. In Table 4, the R^2 values of the TM method are generally low but almost always better then the linear regression method. In some cases, the annual R^2 values were above 0.5 such as the Sakoins gage on a tributary of the White Volta. Thus, in general, if we are concerned with annual values the TM method and the linear regression method give similar results. This is not the case for the monthly values, as we will see below.

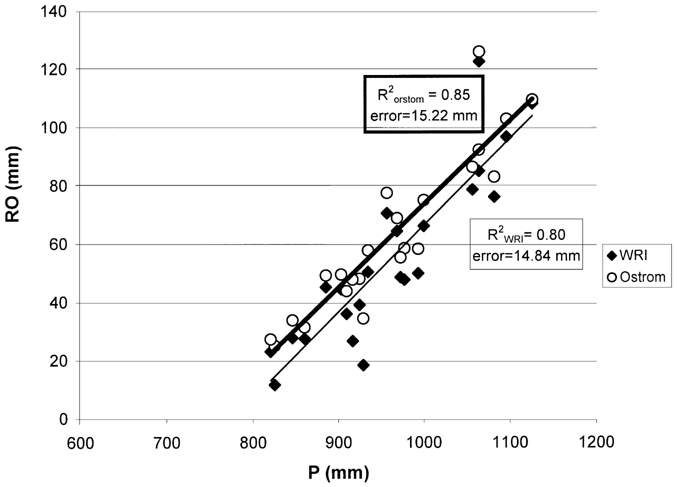

Figure 5. A Regression of Measured Annual Precipitation and Runoff (RO) Values at Bamboi. This serves as a simple model to predict runoff.

Comparing the monthly R^2 values of the TM method (Table 3, Column 10) with the R^2 values of the linearly regression method (Table 3, Column 4) we see that the TM model performs much better. This is despite the fact that the annual values were used for calibrating both methods. The better performance of the TM method is illustrated in Figures 6 and 7. In Figure 6, the results of the TM model are shown with R^2 values of 0.66 for WRI data and 0.56 for ORSTOM data, whereas Figure 7 shows the results of the linear regression method with R^2 values of nearly 0.2 for both data sources.

In Table 3, the parameter values for the TM method are all within reasonable values. The available water content for the Black Volta Basin is 60 mm on average with a standard deviation of 29 mm. For the White Volta and the Oti, available water contents are 112 mm and 143 mm, respectively, both with a standard deviation of 50 mm. The average available water content for the Volta proper is 70 mm with the exception of Prang (the uppermost, wetter subcatchment), which has an available water content of 350 mm. These values are consistent with the parameters found in Dunne and Leopold (1978) for moderately deep rooted crops (between 75 and 200 mm) and for clay in mature forest (above 350 mm).

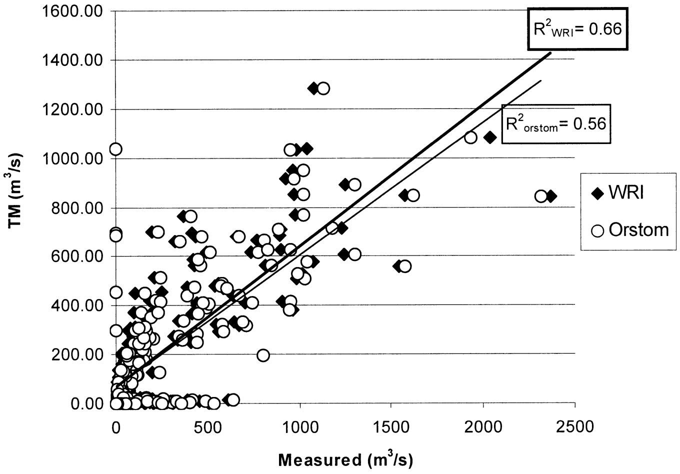

Figure 6. Results of Monthly TM Model With Measured Flows From WRI and ORSTROM Over a 50-Year Range at Bamboi Station. R^2 values of 0.66 and 0.56 show acceptable performance of the model.

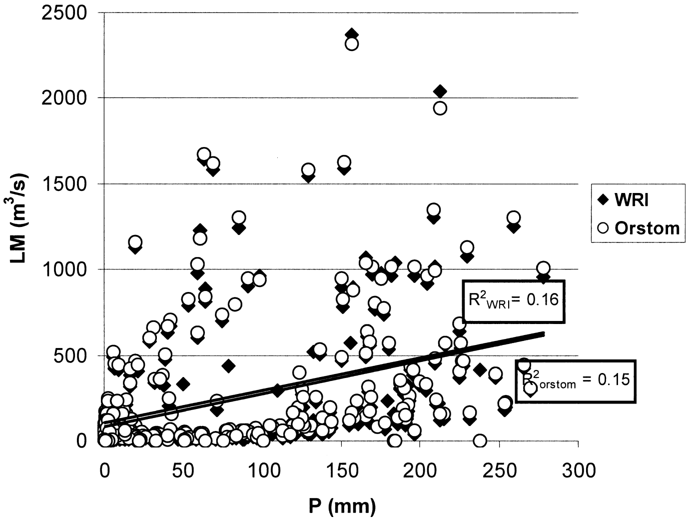

Figure 7. Results of Monthly LM Model With Measured Flows From WRI and ORSTROM Over a 50-Year Range at Bamboi Station.

The portion of available runoff that actually runs into the stream for each month on the White Volta, the Volta proper, and the Oti, 0.56, 0.48, and 0.48, respectively, is almost identical to the values used by Thornthwaite and Mather for North Carolina. Values for the Black Volta are consistently lower. The percent area of the watershed that contributes to runoff is typical for the semi-arid landscape. Average β values for the White Volta and Oti are similar and higher than the Black Volta, which also has lower available water contents on average. As expected, the wetter the basin, the higher the contributing area.

In Table 4, R^2 values for the linear model indicate low quality of streamflow data for these gages. Smalls dams located upstream that store water from one year to the next may affect values at these gages. Runoff coefficients are sometimes as low as 0.001 (i.e., Bissiga and Bagre gages), higher than 1 (i.e., Guena and Nobere gages) and even negative (i.e., Ekumdipe gage from WRI). This clearly indicates that these gages cannot be used for any model validation.

To further assess the validity of the Thornthwaite-Mather models, a cross validation analysis was done. Cross validation analysis estimates the generalization error, or average prediction error associated with the model based on resampling (Weiss and Kulikowski, 1991). Cross validation involves dividing a data set into k subsets of equal size and then using a percentage of the subsets to calibrate the model parameters. The error from this percentage will be referred to as the "in sample" error. The outcome for the remaining percentage is predicted and used to calculate the "out of sample" error. This is done repeatedly for x trials until all the data have been used to predict error. The average of the x trials of "out of sample" error produces the generalized error value from cross validation. This process was done using annual values from the gage at Senchi, which measures runoff over the entire watershed area. Since Senchi is the gage located right beneath the Akosombo, it was necessary to do a separate cross validation for before the dam was built and after. Table 5 shows the results of each trial for both the linear regression method (LM) and the TM method at these different times annually and monthly. The first row lists the error values of the "in sample" points, to which the values of AWC, β, and α, for the TM method were calibrated for minimum error. The second row gives the error values of the out of sample points.

Annually, for the years between 1937 to 1963 (before the dam was built), cross validation gives a generalized error of 19 mm for the linear model which is lower than 23 mm for the TM. It was expected that after the dam was built, both models would produce higher error values. After the dam, the general error for the annual linear model is much larger than predictions before the dam was built and only slightly lower than the TM model error. If the simulation is to be done using annual values, the linear model is clearly a better choice for filling in gaps of missing data. The goodness of fit shown by the cross validation indicates that before the dam was built, the LM is a much better model. However, after the dam was built neither model would give acceptable results.

TABLE 5. Cross Validation Analysis for Senchi.

Annual				
(1937 to 1963)	LM (mm)			
In Sample (75%)	18	19	19	**Average**
Out Sample	23	20	19	19
	TM (mm)			
In Sample (75%)	21	29	28	**Average**
Out Sample	39	15	9	**23**
(1963 to 1996)	LM (mm)			
In Sample (75%)	48	43	37	**Average**
Out Sample	13	36	31	**33**
	TM (mm)			
In Sample (75%)	43	43	39	**Average**
Out Sample	32	29	32	**36**
Monthly				
(1937 to 1963)	LM (mm)			
In Sample (75%)	75	76	75	**Average**
Out Sample	77	75	76	**76**
	TM (mm)			
In Sample (75%)	9	7	8	**Average**
Out Sample	6	10	7	**8**
(1963 to 1996)	LM (mm)			
In Sample (75%)	10	13	11	**Average**
Out Sample	15	4	14	**11**
	TM (mm)			
In Sample (75%)	11	11	11	**Average**
Out Sample	8	10	9	**10**

Monthly values give a much different outcome. Error values for the LM were much higher than for the TM procedure for the time period prior to dam construction and slightly higher than after construction. Additionally, overall monthly R^2 values for each gage within the basin are higher for the TM procedure than for than the monthly linear regression of P and RO. Since the data sets used for simulation will be for monthly values, the TM model was chosen to fill in gaps of missing data.

CONCLUSIONS

Managing a watershed for an area as large as the Volta River Basin while attempting to promote conservation and sustainable development is not a trivial task. The size of the basin alone complicates conventional watershed management practices. Socioeconomic conditions, transnational communications, environmental issues, and insufficient data add parameters that further entangle management efforts. Irrigation throughout the watershed is underdeveloped and could be used as a means to approach many of the socioeconomic and environmental shortcomings of the basin. A sound hydrological knowledge base is a prerequisite to refining management, but incomplete streamflow records hinder this.

Upon initial review of the discharge data collected and donated for this research it was noted that in general, discharge gages across the basin are missing 20 percent of their data over an average range of 20 years. Many of these gages were missing more than 50 percent of their data. This paper approached the issue of insufficient data by first evaluating the available data for its quality and then using an appropriate model to fill in the gaps. These models, the Thornthwaite-Mather and linear regression models, were also assessed for the feasibility of their use in this watershed.

The linear regression model was done as a first step to assess data quality. For gage data to be accepted as reliable, we set the requirement that the linear regressions between precipitation and runoff result in values where $R^2 > 0.5$. For the data used in this research, only half the gages met this criterion, meaning that only half of the streamflow gages matched with precipitation data and that only half of the available data could be usable for any watershed management practices. The linear regression model could be used to fill in missing gaps; however, the quality of the values produced from the linear regression model did not increase significantly. The TM model approached both the issue of low quality and insufficient data by providing basic physical information that is needed before any management can proceed. Comparing annual and monthly error values of the linear model and the TM model shows that the TM model always predicts values closer to measured values both annually and monthly. We also see higher R^2 values from resulting TM runoff results against actual precipitation values than for the linear regression model on a monthly basis. For monthly models, the TM model always results in higher R^2 values than the linear regression model. However, on an annual basis, TM gives a better correlation for only half of the gages. For this region, predicting annual values using either model could provide equivocal results, however, the TM model, which involves more detail, must be used for predicting monthly values or where management practices are concerned with hydrological processes on time increments shorter than a year.

The techniques used in this paper can be easily applied to any basin with similar data limitations. They may be particularly useful in other regions of West Africa or in other tropical climates with similar environmental and socioeconomic conditions that challenge efforts at water resource management. Data quality assessment in these environments must be the primary step to watershed management to properly approach solving such intricate problems as conservation, water allocation, and sustainable development.

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