Regional Hydrological Impacts of Climatic Change—Hydroclimatic Variability
(Proceedings of symposium S6 held during the Seventh IAHS Scientific Assembly at Foz do Iguaçu, Brazil, April 2005). IAHS Publ. 296, 2005.

Storage capacity and long-term water balance of the Volta Basin, West Africa

JAN FRIESEN[1,4], MARC ANDREINI[1,2], WINSTON ANDAH[3], BARNABAS AMISIGO[1,3] & NICK VAN DE GIESEN[4,1]

1 *Centre for Development Research, Bonn University, Walter-Flex-Str. 3, D-53113 Bonn, Germany*
j.friesen@uni-bonn.de

2 *International Water Management Institute, Sub-regional Office West Africa, PMB CT 112, Cantonments, Accra, Ghana*

3 *Water Research Institute, PO Box M.32, Accra, Ghana*

4 *TU Delft, Water Resources Section, PO Box 5048, 2600 GA Delft, The Netherlands*

Abstract Rainfall in West Africa is often typified as being subject to large inter-annual variability. For the Volta Basin, this variability is actually not very large. The coefficient of variation for rainfall is only 0.08 (1931–1995) with an average of 400 km^3 year^{-1}. Yet, a much higher coefficient of variation of 0.38 (1931–1995) is found for runoff with an average of 43 km^3 year^{-1}. The basin shows a nonlinear response that amplifies small changes in rainfall into large changes in runoff. A simple runoff model for the Volta Basin was formulated with a Nash-Sutcliffe efficiency of 72%. This model implies that once rainfall exceeds a threshold of 342 km^3 year^{-1}, more than 50% of the exceedence runs off. This threshold behaviour makes the water resources of the Volta Basin highly sensitive to both climatic variability and anthropogenic impacts. First, the impact of climate variability is quantified. Subsequently, development of the storage capacity of the Basin is evaluated on the basis of the water balance over the period 1966–1995 with an adapted Thornthwaite-Mather model. Results show that there is no change in hydrological behaviour of the basin that could be attributed to human impact. This lack of a clear anthropogenic signal can partially be explained by two contrary developments, increase in surface water storage in reservoirs and decrease in soil moisture storage due to soil and vegetation decline.

Key words anthropogenic impact; basin-wide storage capacity; climate impact; Volta; water balance; West Africa

INTRODUCTION

Climate and anthropogenic change can be detected in West Africa at both the point and regional levels. Climate change is apparent when looking at rainfall time series, whereas increasing population figures and changes in land use and cover indicate anthropogenic changes. This work investigates to what extent changes are detectable at the level of the Volta Basin, which has an area of 400 000 km^2 (Fig. 1). Previous work for the Nakambe basin (White Volta), a sub-basin of the Volta Basin in northern Burkina Faso, showed that both climate and anthropogenic change had impact on the river flow (Mahé *et al*., 2002). In this study, we examine whether long-term changes in the runoff regime can be observed at the level of the whole Volta Basin. On the basis of a storage capacity and water balance analysis, it will be shown that climatic changes

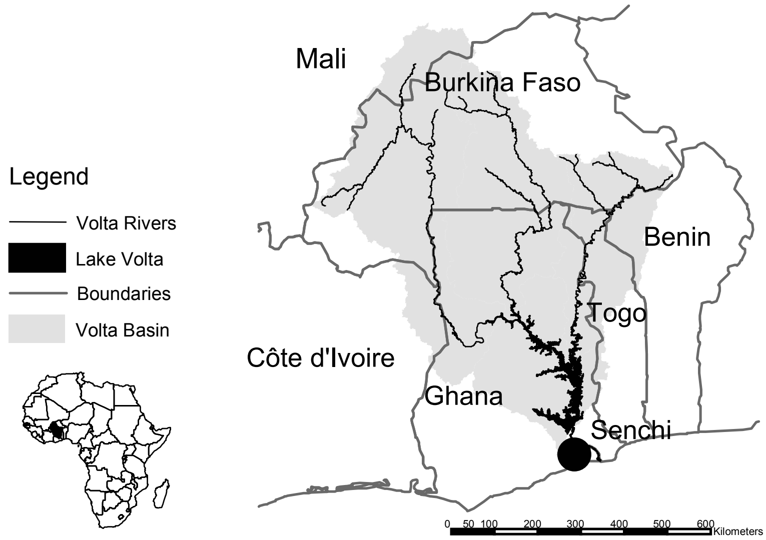

Fig. 1 Map of the Volta Basin, West Africa.

do result in changes in runoff behavior. In the Nakambe Basin, anthropogenic changes could be linked to long-term changes in runoff. Here, at the level of the whole Volta Basin, no such change can be detected.

To analyse the long-term behaviour of the Volta Basin, a simple rainfall–runoff model based on the Thornthwaite-Mather (TM) model was developed. The output from the TM model was compared with the results of a mass balance calculated for Lake Volta. Modifications to the original TM procedure had to be made to adapt it to the West African hydrology. These adjustments were mainly necessary due to the specific rainfall regime, which is dominated by wet and dry seasons, to the unique vegetation and land cover patterns, and to the high losses through evapotranspiration.

MODELS

Data

The data used consist of global datasets of rainfall and potential evapotranspiration (*ETp*) with a 0.5° spatial resolution and a monthly temporal resolution. Time series data from 1931 to 1995 from the Climate Research Unit (CRU) were used (New *et al.*, 1999, 2000). Basin boundaries were taken from the GTOPO30 HYDRO 1k data set to determine rainfall and *ETp* over the basin area; *ETp* was calculated on the basis of Penman.

For model calibration, measured runoff at Senchi near the mouth of the river (Fig. 1) was used for the years 1937–1963. These data were provided by the Office de Recherche Scientifique & Technologique Outre Mer (ORSTOM) and the Water Research Institute, Ghana. Lake levels, discharge data, and storage-area-level curves for Lake Volta were provided by the Volta River Authority, Ghana.

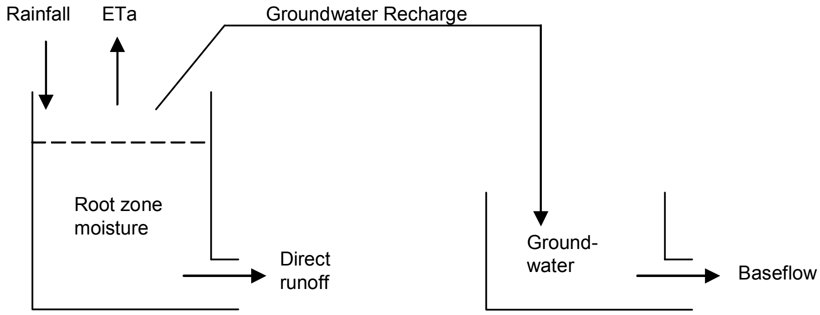

Fig. 2 Rainfall–runoff model scheme. Total river flow is the sum of direct runoff and baseflow.

Rainfall–runoff model

The rainfall–runoff model is based on a Thornthwaite-Mather (TM) storage model. The algorithm is a modified version (Fig. 2) of the model presented by Steenhuis & van der Molen (Steenhuis & van der Molen, 1986; Thornthwaite & Mather, 1955, 1957). The original TM procedure calculates groundwater recharge from the root zone water balance on a monthly time step. To adapt the procedure to the West African hydrology, the following modifications were made. Runoff was considered to be composed of two components, baseflow and direct runoff (Fig. 2). Baseflow is here defined as runoff from the groundwater reservoirs or aquifers, which in turn are filled by groundwater recharge from the root zone. Direct runoff is the sum of saturation excess flow (Dunn flow) and runoff caused by infiltration capacity excess (Horton flow). The importance of direct runoff in West Africa has been presented in detail by several authors (Windmeijer & Andriesse, 1993; van de Giesen *et al.*, 2000; Masiyandima *et al.*, 2003). It seems that at the level of the Volta Basin, most direct runoff is generated as Dunn flow from the saturated flood plainss that have relatively fixed areas.

Although the TM procedure and its additions form a purely conceptual model, the model does fit the West African hydrology, as observed in the field and as reported in the literature. The rainfall regime is dominated by contrasting wet and dry seasons. The flood plains become saturated relatively quickly and start to produce direct runoff soon after the rains start. The uplands have very deep soils with root zones that feed *ETa*. The uplands take a long time before they become sufficiently wet for recharge to occur. This is mimicked by the TM procedure in which recharge only takes place once the storage capacity of the root zone is exceeded. The recharge from the root zone is collected in a linear groundwater reservoir, which discharges as baseflow into the rivers for a brief period after the rains have ceased. The sum of direct runoff and baseflow is the total river flow. The model was calibrated for a period from March 1936 to February 1963, using hydrological years that run from March to February. For a complete cross-validation, the data were divided into five blocks. The cross-validation was then repeated five times. Each time, one block was used as a validation set and the other blocks were put together to form the calibration set. The average Nash-Sutcliffe efficiency over the five validation blocks, or out-of-sample efficiency, is 72%.

Lake model

In 1963, the Volta was dammed at Akosombo, just north of Senchi. The resulting Lake Volta is, in terms of area, the largest manmade lake in the world. To compare runoff as predicted by the adjusted TM model with historical flows after the dam was constructed, it was necessary to derive inflows into the lake from the mass balance. The mass balance was used to calculate monthly inflow as the difference between rainfall, evaporation, turbine discharge, and change in storage. Differences in lake surface area were accounted for in the rainfall and evaporation calculations.

WATER BALANCE

Volta Basin water balance (excluding Lake Volta)

With the modified TM model, one can resolve how water moves through the basin and in which compartments it is stored over time. Here, we analyse the dynamics of water storage in these different compartments in order to see if any changes over time can be detected that might be anthropogenic.

Table 1 shows the annual statistics of the water balance. Mean annual rainfall over the basin is 401 km^3. Rain falling in the basin is partitioned over *ETa* (89%) and runoff (11%). Runoff can be divided into direct runoff and baseflow. On a long-term basis, the ratio of direct runoff to baseflow is 54:46. Coefficients of variation indicate high variability for baseflow, and low variability for direct runoff. These results confirm the low contribution from Hortonian overland flow and the relatively large contribution

Table 1 Volta Basin water balance: model parameters (1931–1995).

	P	*ETp*	*ETa*	*Q*1	*Q*2	*RO*
Mean (km^3 $year^{-1}$)	400.9	774.2	357.1	23.2	19.7	42.9
CV (%)	8.0	1.0	5.0	5.0	79.0	38.0

P: rainfall; *ETp*: potential evapotranspiration; *ETa*: actual evapotranspiration; *Q*1: direct runoff; *Q*2: baseflow; *RO*: runoff.

Table 2 Comparison of wet, dry, and average years.

		P	*ETp*	*ETa*	*Q*1	*Q*2	*RO*
Wet year (1968)	Total (km^3 $year^{-1}$)	472.6	774.1	396.5	25.4	48.5	73.9
	Mean (km^3 $month^{-1}$)	39.4	64.5	33.0	2.1	4.0	6.2
	CV (%)	86.0	17.0	38.0	58.0	148	112
Dry year (1992)	Total (km^3 $year^{-1}$)	354.0	765.9	340.1	22.3	1.4	23.7
	Mean (km^3 $month^{-1}$)	29.5	63.8	28.3	1.9	0.1	2.0
	CV (%)	94.0	18.0	42.0	61.0	172	53.0
Average year (1985)	Total (km^3 $year^{-1}$)	399.5	749.9	346.1	23.3	28.0	51.3
	Mean (km^3 $month^{-1}$)	33.1	10.0	13.3	1.3	4.2	5.1
	CV (%)	99.0	16.0	46.0	65.0	178	119

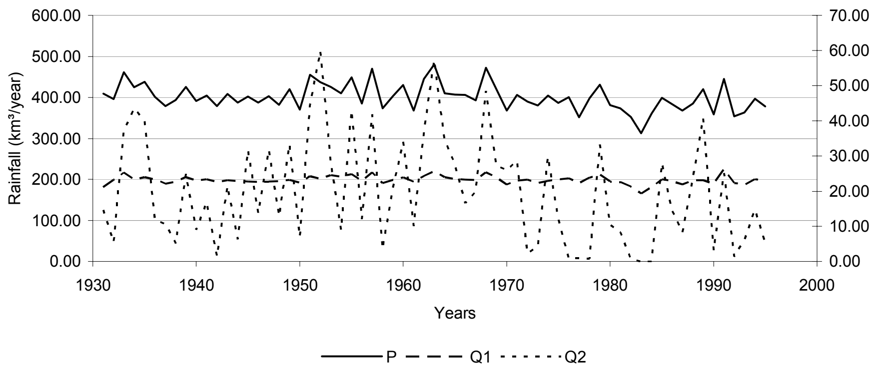

Fig. 3 Long-term dynamics of rainfall (*P*), direct runoff (*Q*1), and baseflow (*Q*2) for the Volta Basin.

from wetland areas (Masiyandima *et al*., 2003). As the wetland areas vary very little in size, their contribution to runoff shows low variability, which is reproduced well by the modelled direct runoff.

Storage is divided into root zone soil moisture and groundwater storage. By extracting a dry, a wet, and an average year the sensitivities of the two storage components towards climate change and variability can be illustrated. The wet and dry years chosen are typical examples and not the absolute extremes in the available time series.

Figure 3 and Table 2 present the differences for the two runoff types. Both show that, whereas the partitioning is different, contributions from direct runoff remain almost constant in wet and dry years, and on a long-term scale. Baseflow, on the other side, shows a much higher sensitivity in its response to climate variability. In Fig. 3, this sensitivity is illustrated when comparing wet (1931–1969) and dry (1970–1995) periods, as reflected in the baseflow line.

Table 2 shows an even more extreme picture by looking at specific wet and dry years. On average the ratio between direct runoff and baseflow is 54% to 46%. Wet years show a shift towards more baseflow (66%) and dry years an almost complete decline of baseflow to only 6%.

As shown in Fig. 3, the decline of baseflow is even more extreme when short dry spells of 2–4 years of constantly low rain occur. In these cases baseflow persistently drops to almost zero after the first year and runoff is only generated directly. In general, most of the variability in runoff can be attributed to variability in groundwater recharge or baseflow. Baseflow in the Volta Basin shows strong threshold behavior, which translates in a strong non-linear response (Andreini *et al*., 2000). In principle, this behaviour would make the basin also vulnerable to human activities that would affect the storage capacity of the soils and the landscape. To see if such anthropogenic effects can be detected, the output of the TM model will now be compared to inflows as determined indirectly from the lake model.

Lake Volta mass balance

The lake mass balance was used to calculate inflows into Lake Volta from 1966 to 1995. Average results of the lake water balance are presented in Table 3. Mean annual inflow from the basin is 33.5 km^3, of which the bulk (87%) is released through the

Table 3 Lake Volta model (1966–1995).

	Releases (km^3)	*ETp* (km^3)	*P* (km^3)	*Vol_change* (km^3)	*Qin* (km^3)
Mean (km^3/year)	29.3	9.5	7.8	1.1	33.5
CV (%)	38.0	14.0	21.0	1446	49.0

Releases: turbine releases from dam; *ETp*: potential evapotranspiration over lake surface; *P*: rainfall over lake surface; *Vol_change*: difference in lake volume; *Qin*: inflow from Volta Basin.

turbines. Losses from the lake through evaporation are 1.7 km^3 $year^{-1}$ on average, and show a high variability with a coefficient of variation of 66%. Evaporative losses presented here are based on the assumption that these losses are equal to *ETp*. This leads to a conservative estimate and these losses should be regarded as minimum losses. Below, we show that the real evaporative losses are probably 1.4–1.7 times *ETp*.

What has to be considered in this context is the fact that without the lake, 89% of the rainfall now falling on the lake surface area would have been lost to evapotranspiration and only 11% would have runoff. The lake captures 100% of the rainfall that falls on its surface area. This illustrates that although there are significant evaporative losses from the lake, these are partially offset by the fact that the lake captures rainfall directly (Table 3).

CLIMATE VARIABILITY AND ANTHROPOGENIC IMPACTS

The existence of climate change or variability is best illustrated by comparing the period 1931–1969 with the period 1970–1995. The mean annual rainfall in the first period is 28 km^3 higher than in second period. On the basis of Student's *t* test, one may conclude that this difference in the mean rainfall is significant, with a confidence level of 99.9%. Given the threshold behaviour of runoff in the basin, one would expect that this change in rainfall input is transformed into important changes in runoff. This is indeed the case, as the baseflow in the period is significantly higher than the runoff in the second period. This difference is significant with a confidence level of 99.6%. The effects of changes in rainfall are captured well by the model and can be seen most prominently in the baseflow generated through groundwater recharge.

Anthropogenic change within the basin is determined by using the lake water balance as a runoff gauge. In first instance, evaporative losses from the lake were estimated by assuming they are equal to *ETp*. Based on this assumption, an inflow is calculated that shows the same pattern as the inflow as modelled by the TM model. There is a bias, however, between modelled inflow and inflow based on the lake water balance. To remove this bias, a factor was introduced with which *ETp* was multiplied in order to obtain real evaporative losses. When this factor was set to 1.54, the bias disappeared. The factor accounts for the oasis effect caused by Lake Volta as a large shallow inland water body. Similar *ET* losses from isolated open water bodies are well known (Brutsaert, 1982). The inflow into the lake as derived from the water balance was now predicted by the TM model with a Nash-Sutcliffe efficiency of 72%.

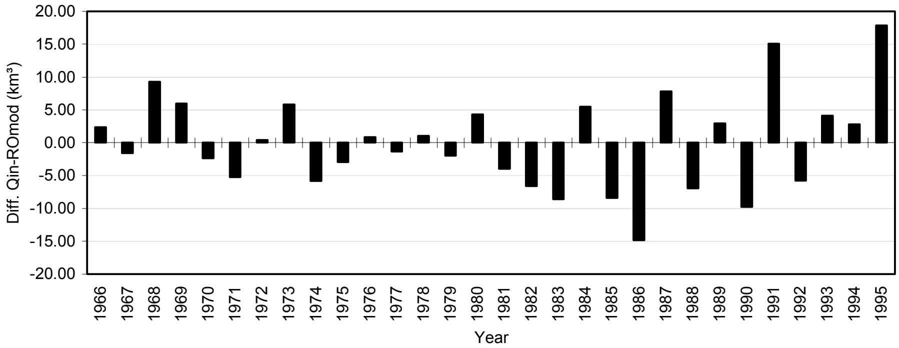

Fig. 4 Difference between Lake Volta inflow (*Qin*) and modelled runoff from the Volta Basin (*ROmod*).

To assess if an anthropogenic impact can be found at the level of the Volta Basin, the difference between the TM model output and the lake inflow based on the water balance is examined for trends. Figure 4 shows a plot of the difference between annual lake inflow and TM-based basin runoff. No clear trend can be found, which indicates that there is no major change in runoff regime or hydrological behaviour of the whole Volta Basin. According to the Student's *t* test, the null hypothesis that the mean river flows in the first (1966–1980) and second (1981–1995) periods are the same cannot be rejected (significance level 33%).

There is apparently no clear anthropogenic impact on river flow even though the basin has seen an intensified use of its land and water resources. A partial reason for this absence might be that there are two counteracting sets of human interventions that may neutralize each other. On one hand, there is the increase in small reservoirs throughout the northern part of the basin, that enhances water storage capacity and infiltration (Liebe, 2002; Mahé *et al*., 2002). On the other hand, land degradation through deforestation and intensified land use may cause higher runoff (Mahé *et al*., 2002). When focusing on sub-basins within the Volta Basin with high population pressure and land-use changes, anthropogenic impacts on runoff regimes can be detected as shown by Mahé *et al*. (2002) for the Wayen basin in northern Burkina Faso.

Although the basin upstream from the lake does not show any significant human-induced changes in hydrological behaviour, Lake Volta itself does have a significant impact. The evaporative losses are about 1.5 times *ETp* or 14.6 km^3 year^{-1}. Of the rain falling on the lake (7.8 km^3 year^{-1}), 89% or 6.9 km^3 year^{-1} would have returned to the atmosphere as *ETa*, if there had not been a lake. Still, the net evaporative losses of 7.7 km^3 year^{-1} are a significant human impact on the river flow downstream from the dam. Where average river flow at Senchi before dam construction was 42.9 km^3 year^{-1} (Table 1), this is now reduced to 29.3 km^3 year^{-1}. Most of this reduction can be attributed to losses from the lake and only a smaller part to changes in inflow due to reduced rainfall in the basin.

CONCLUSIONS

A simple long-term water balance for the Volta Basin has been presented. The original TM model has been extended to model two runoff components. This modified model describes the runoff and its partitioning adequately. Analysis of the runoff dynamics shows that baseflow has a high sensitivity towards rainfall variability, whereas direct runoff shows little variation. The effects of climate change or variability are reproduced well by the model. Comparison with lake inflows as calculated from the lake water balance shows that there are no significant anthropogenic impacts at basin level. The lake itself, however, does have a large impact as the evaporative losses are found to be 1.5 times higher than ETp, which is only partially offset by rainfall on the lake.

As pointed out by the work on the Wayen basin, changes in runoff regimes can be seen on mid-level scales. As the data situation in terms of runoff data within the Volta Basin is rapidly improving, more work on climatic and anthropogenic impacts can be conducted at sub-basin level to identify hotspots of hydrological change.

The main conclusions are very relevant in the light of the international sharing of the resources of the Volta River. It has been assumed that recent low levels in Lake Volta should be attributed to over-exploitation of resources in the upper parts of the basin (Gyau-Boakye & Tumbulto, 2000). The present analysis shows that there is no scientific evidence for human impact on lake inflows.

Acknowledgements Support by Grant no. 07GWK01 (GLOWA Volta Project, http://www.glowa-volta.de) provided by the German Federal Ministry of Education and Research, and additional support from the State of North Rhine Westphalia, Germany, is gratefully acknowledged.

REFERENCES

Andreini, M., van de Giesen, N., van Edig, A., Fosu, M. & Andah, W. (2000) Volta Basin Water Balance. ZEF-Discussion Papers on Development Policy #21, Bonn, Germany.

Brutsaert, W. (1982) *Evaporation into the Atmosphere: Theory, History, and Applications*. Reidel, Boston, USA.

Gyau-Boakye, P. & Tumbulto, J. W. (2000) The Volta Lake and declining rainfall and streamflows in the Volta River basin. *Environment, Development and Sustainability* **2**, 1–10.

Liebe, J. (2002) Estimation of water storage capacity and evaporation losses of small reservoirs in the Upper East region of Ghana. Diploma Thesis, University of Bonn, Bonn, Germany.

Mahé, F.G., Dray, A., Paturel, J. E., Cres, A., Kone, F., Manga, M., Cres, F. N., Djoukam, J., Maiga, A., Ouedraogo, M., Conway, D. & Servat, E. (2002) Climatic and anthropogenic impacts on the flow regime of the Nakambe River in Burkina Faso. In: *FRIEND 2002 Regional Hydrology: Bridging the Gap between Research and Practice* (ed. by H. A. J. van Lanen & S. Demuth), 69–75. IAHS Publ. 274. IAHS Press, Wallingford, UK.

Masiyandima, M. C., van de Giesen, N., Diatta, S., Windmeijer, P. N. & Steenhuis, T. S. (2003) The hydrology of inland valleys in the sub-humid zone of West Africa: runoff processes in the M'bé experimental watershed. *Hydrol. Processes* **17**, 1213–1225.

New, M., Hulme, M. & Jones, P. (1999) Representing twentieth-century space-time climate variability. Part I: Development of a 1961–90 mean monthly terrestrial climatology. *J. Climate* **12**(3), 829–856.

New, M., Hulme, M. & Jones, P. (2000) Representing twentieth-century space-time climate variability. Part II: Development of 1901–96 monthly grids of terrestrial surface climate. *J. Climate* **13**(13), 2217–2238.

Steenhuis, T. S. & van der Molen, W. H. (1986) The Thornthwaite-Mather procedure as a simple engineering method to predict recharge. *J. Hydrol.* **84**, 221–229.

Thornthwaite, C. W. & Mather, J. R. (1955) The water balance. *Publ. Climatol.* **8**, 1–104.

Thornthwaite, C. W. & Mather, J. R. (1957) Instructions and tables for computing potential evapotranspiration and the water balance. *Publ. Climatol*. **10**, 181–311.

van de Giesen, N., Stomph, T. J. & de Ridder, N. (2000) Scale effects on Hortonian overland flow and rainfall-runoff dynamics in a West African catena landscape. *Hydrol. Processes* **14**(1), 165–175.

Windmeijer, P. N. & Andriesse, W. (1993) *Inland Valleys in West Africa: An Agro-Ecological Characterization of Rice-Growing Environments*. ILRI Publ. 52. International Institute for Land Reclamation and Improvement, Wageningen, The Netherlands.