

Hydrological Modeling of Large Drainage Basins Using a GIS-Based Hybrid Atmospheric and Terrestrial Water Balance (HATWAB) Model

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ABSTRACT

A Hydrological model is proposed to study the spatial and temporal variability of the water budget components of large drainage basin systems from atmospheric and terrestrial water balances. In order to understand the water balances that include, surface runoff, actual evapotranspiration and soil moisture, a GIS-based simple water balance model which is referred as Hydrological Model from Hybrid Atmospheric and Terrestrial Water Balances with acronym HATWAB is presented. The spatio-temporal climatology database was created from a network of climate stations from CLIMWAT data base to reconstruct the monthly primary inputs to HATWAB model, rainfall and potential evapotranspiration. The modeling principles and HATWAB model are demonstrated using the Limpopo and Congo basins in Africa. The model was used to simulate water balance components by taking rainfall-runoff processes in the basin including soil-texture controlled moisture in the terrestrial system, and the vertical integrated moisture convergence that accounts for the net water vapor flux from the basins in order to close the hydrologic water budget.

Keywords: HATWAB; Water Budget; Large Drainage Basin; Soil Moisture; Vertical Integrated Moisture Convergence; Water Flux; GIS

1. Introduction

Hydrological modeling of large drainage basins is used to understand the complex hydrological processes that control the distribution and availability of hydrologic components and water resources availability in terms of atmospheric and terrestrial water balances. It is principally undertaken through precipitation partitioning into surface and groundwater flows, soil moisture and evapotranspiration. Spatial and temporal variations of regional water and energy balances over long and short time scales play an important role in changes in the stream flow of a basin. Precipitation being rainfall, evapotranspiration, runoff, percolation and soil moisture are the main components of the hydrologic cycle within semi arid regions. Their overall role to the hydrologic cycle are influenced by their interaction with soil, vegetation, topography and climate of the given area and to some extent by human interaction on the dry-land being crops, pastures and forestry.

Complex hydrologic systems have always been simplified in order to understand water balances within a catchment. To understand the spatial water balance components hydrological models have been employed for precipitation-runoff modeling based on GIS [1-3]. Among

the most earlier catchment water balancing approach undertaken based on long term monthly climatic conditions was the one by [4], which then led to many researches on water balance models for similar conditions on a catchment, a region or a continental scale. Typical examples are 1) the USGS micro-computer Thornthwaite Water Balance model [5]; 2) a grid-based model for Latin America [6-8]; 3) a GIS-based water balance model at southern Africa scale [9]; 4) the Rhine flow model [10]; and 5) the large-scale water balance model for the upper Blue Nile in Ethiopia [11]. In South Africa, the Department of Water affairs and Forestry (DWAF) has developed a Water Balance Situation Assessment Model (WSAM) [12]. WSAM is widely used model in southern Africa to simulate streamflow, which allows calibration based on parameters for partitioning of precipitation into surface and subsurface components. The Famine Early Warning System Network (FEWS NET) hydrological model for the Limpopo basin [13], which is still under development, is one standard rainfall-runoff model that is expected to provide a continuous daily simulation of stream flow mainly developed for flood forecasting.

Increasing computer technology including use of GIS technique and physical (or quasi-physical) based hydro-

logic modeling has become important in contemporary hydrology research for assessing the impact of human and/or possible climatic change on basin hydrology and water resources. This approach is widely used in the hydrologic research community compared to the systems-type black box models. Another advantage of physical or quasi-physical hydrological modeling is also its usefulness for investigating large-scale hydrological modeling thereby helping with planning, allocation and management of water resources.

In this manuscript results of a simplified water balance model, named Hydrological Model from Atmospheric and Terrestrial Water Balance (HATWAB) model [14], is presented and demonstrated for two basins, 1) the Limpopo river basin based on previously reported original data for the basin [15]; and 2) the Congo basin, based on previously presented data [16]. The model is capable of estimating monthly soil moisture, actual evapotranspiration, runoff and the vertical integrated moisture convergence. Such a model may be used for planning and decision support system in the region. HATWAB model was developed based on the approach proposed in [9], but was upgraded to cater for seasonal variation of vertically integrated moisture convergence (C) as well as correcting the imbalances in the closure of the water budget which are catered for precisely to address a common challenge in water budget modelling at a basin scale. Perhaps this aspect remains one important contribution and attribute of this paper.

The major objective of this study was to understand the hydrological budget and processes in large drainage basins using HATWAB. The specific benefits of HATWAB and the objectives presented in this manuscript include: 1) determining the available spatial and temporal hydro-climatic information and data gaps to undertake water budget study, which is based on available sparse data; 2) mapping the spatial and temporal variability of rainfall, effective rainfall and potential evapotranspiration a basin scale; 3) assessing the spatial and temporal variability basin water budget in terms of soil moisture, actual evapotranspiration, runoff, and vertically integrated moisture convergence.

By doing so a number applications of HATWAB can be sought that include mainly: 1) Assessment of water availability and distribution in a drainage basin; and 2) Assessment of climate change and large scale human-induced changes.

2. Approach and Methodology

Selecting a Template

The modeling approach followed was based on parameterizations to compute temporal and spatial variability of water budgets at geo-referenced grid cells covering a

drainage basin. The model computes the integrated moisture convergence (C) and soil moisture in solving the water budgets in the atmospheric and terrestrial components, respectively. Uncertainties on atmospheric water balance estimates and imbalances are also investigated.

The atmospheric component of the water balance is expressed as follows [14]:

$$dW/dt = -P + E + C \quad (1)$$

where dW/dt is the storage change (LT-1). C is the vertical integrated moisture convergence (LT-1) and was expressed as a function of a variable Q which is the water vapour flux (LT-1), as follows:

$$C = -\nabla \times Q \quad (2)$$

The storage change, dW/dt is usually ignored because changes in precipitable water are quite small in averages over time scales of a month or more [8]. Then Equation (1) reduces to

$$P - E = C \quad (3)$$

The terrestrial water balance model on a monthly time scale can be written as

$$dS/dt = P - E - R \quad (4)$$

where S is soil moisture storage (L); P is precipitation (LT-1); E is actual evapotranspiration (LT-1); and R is the observed runoff (LT-1). The monthly E can be calculated once the soil moisture is determined. Then by combining Equations (3) and (4), it follows that the vertical integrated moisture convergence, C is computed as:

$$C = dS/dt + R \quad (5)$$

In a steady state $P - E = R$. Changes in storage could however lead to $P - E$ being different from R . These could also be due to certain errors in representing rainfall within a basin under consideration. These lead to the expression of an imbalance equation

$$I_{mb} = \frac{C - (dS/dt + R)}{R} = \frac{C}{R} - \frac{dS/dt}{R} + 1 \quad (6)$$

Contrary to the formulation adopted in this study based on Equation (6), [8] assumed that dS/dt is negligible for monthly time scales and applied it to the Amazon basin, which reported unaccounted residuals in water budgets. Whereas in the proposed model in this study, the soil moisture variation dS/dt is varying from season to season as a function of the prevailing Ep and P at a given location according to Equation (4), in which the imbalance should also cater for this variability according to Equation (6). One of the contributions of this study is that, once the imbalance (Equation (6)) is kept to a minimum in the water balance computation at each grid, then the simulated variables and water balances, P , E , R , R/P , $E - P$, E/Ep , S and C can then be used to investigate

the seasonal and temporal variability of a basin’s water budget.

The amount of precipitation and potential evapotranspiration determine soil moisture availability, which in turn is controlled by the water holding capacity of the soils. Solution of the mass balance equation was solved for E, R and S based on procedures given in [6,9,17].

3. The Study Area and Data

The study area considered, the Limpopo river basin and the Congo basin, are two of the major drainage systems in Africa (**Figure 1**) with huge interest for regional development among the riparian states. The Limpopo basin represents predominately arid to semi arid regions with low rainfall regimes where as Congo basin predominately represents high rainfall regimes.

In order to solve the water budget equations and cover the study area with the minimum available information and effort, gauged data from the FAO CLIMWAT database [18] within each basin was resampled and used. A total of 66 stations in Limpopo and 145 stations in the Congo basin were used in the analysis. The extracted data was based on a rectangular region in which the basins are located. The data includes long-term average monthly rainfall, effective rainfall (Pe), Ep and other climatic variable such as temperature (minimum, mean and maximum), wind speed, sunshine hours and solar radiation. The point distributed hydroclimatic data were spatially interpolated using the Inverse distance squared (IDS) method.

One of the main inputs required in the proposed water

balance model is the effective precipitation (Pe). At a monthly time scale, the effective precipitation is calculated as per the formula of the USDA soil conservation available from FAO manual [20]. The reference evapotranspiration (Eo) is computed according to the FAO’s Penman-Monteith method [20]. These soil textural classes have been extracted from agronomical soil classes of soils databases of FAO/UNESCO [21] according to the methodology proposed in [9]. The soils data were originally available at 10 minutes spatial resolution, which was further regrided using pixel thinning algorithm [22]. From textural reclassification of soils and vegetation cover data (based on the NDVI imagery data of 1987), soil-water retention parameters such as field capacity (FC), wilting point (WP) and available moisture content (AMC) values were extracted at each grid cell within the basin according to soil-water relations [9,23]. All the spatial data were compiled in a GIS raster grid format at a spatial resolution of 5’ by 5’ (9.2 km by 9.2 km) representing the study basins.

4. Analysis of Results and Discussions

For a single geographically referenced grid cell, the model is run independently for the simulation period of 30-years to derive a basin-wide map of water balances. The water balances were conducted for a period of 30 years assuming that the mean does not change during this normal period. This was important as 30 years is the mean record length of the data obtained from CLIMWAT database [18], which represents the rainfall and other climatic variables. In each simulation year, the model

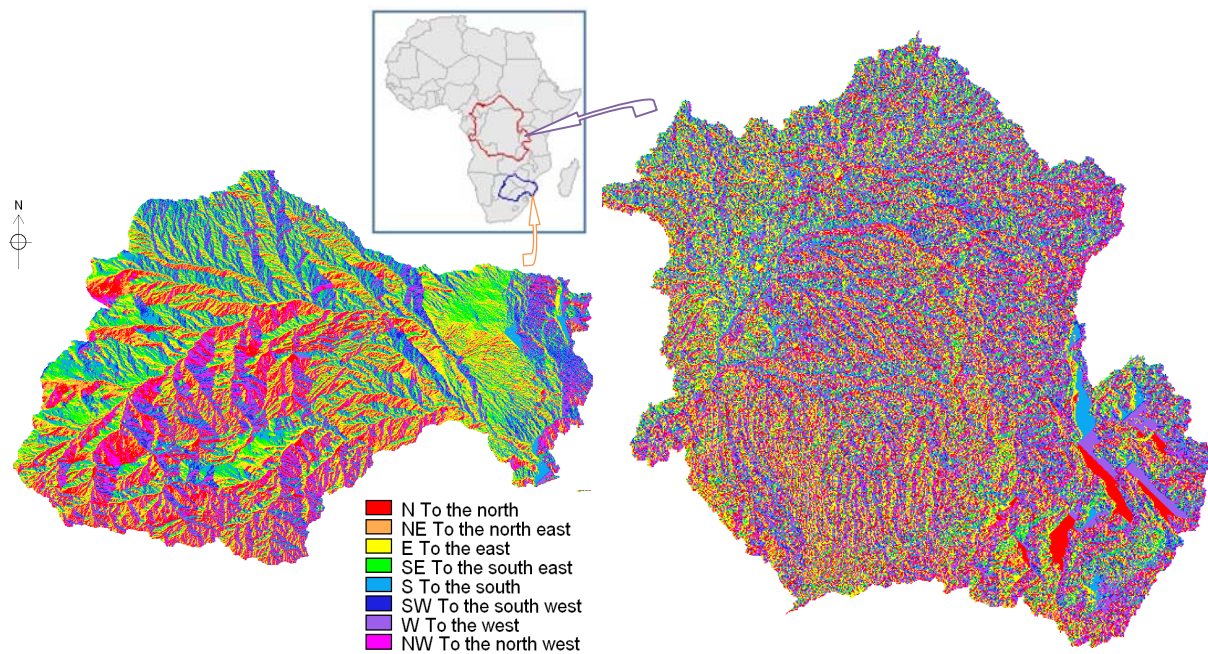


Figure 1. Location map of the Limpopo and Congo basins and flow direction grid maps (own Figures: [16,19], modified).

in the soil moisture zone is run for a time loop of 12 months, by applying the P and Ep . If a dynamic state is not achieved in soil moisture storage term (S), actual evapotranspiration (E) and runoff (R) between subsequent simulations, the simulation proceeds until a dynamic steady state is achieved within 0.01% error in all of these variables. When the steady state situation is arrived, the outputs S , E and R are maintained, and the spatial control module is invoked and computation for another grid cell continues.

The model is then applied for all grids that represent the basin under consideration according to the spatial identifier of such grids.

Computation of monthly water balances throughout all the identified grids with each basin has been undertaken, and results for geo-referenced grids in the each basin have been stored in the results database. The actual evaporation which was computed from the mass-balance equations, whose value as a ratio to its potential value, Ep is assumed to change linearly with the soil moisture storage for the given month that satisfies Equation (4). For each grid, the soil moisture was computed on a monthly basis in such a way that closure of the water budget is achieved as stipulated by mass balance equations (Equation (4)) until close of the hydrological budget is achieved.

Typical variations of temporal/seasonal water balances at selected grids is shown in **Figure 2(a)** and **Figure 2(b)** for grid cells centered on 29.03°E/19.93°S and 29.12°E/26.33°S, respectively. A common feature of all the seasonal portrayals of these water balances components is that the actual E values are less than the Ep values for any given month, which is as expected. The same applies between the rainfall and generated runoff.

The reference evapotranspiration (Ep) computed based on the FAO Penman-Monteith method [20] at 66 climate stations in the Limpopo basin and 145 climate stations in the Congo basin, which were further resampled at the corresponding pixels in the same format as the other spatial information. For Limpopo basin, the annual Ep values reach above 1100 mm with almost 50% of the basin having higher values ranging from 600 to 900 mm. Soil moisture is found to range between 50 and 450 mm with most of the area dominated with higher moisture ranges.

The actual evapotranspiration computed for the Limpopo Basin using the developed water balance model is shown in **Figure 3**. The actual evapotranspiration is found to be varying within the entire basin. The E varies from 400 to 1100 mm per year with most of the basin, accounting about 60% of the basin area having the highest E .

For the Congo basin, the simulated annual total runoff in relation to precipitation is shown in **Figure 4**. The mean annual Runoff for the Congo basin varies between

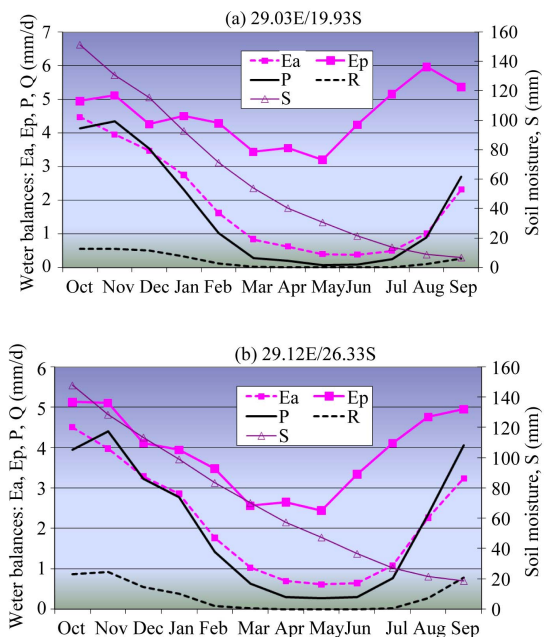


Figure 2. Temporal variation of water balance components computed in the Limpopo basin at a grid cell centered on (a) 29.03°E/19.93°S and (b) 29.12°E/26.33°S (own figure, modified from [15]).

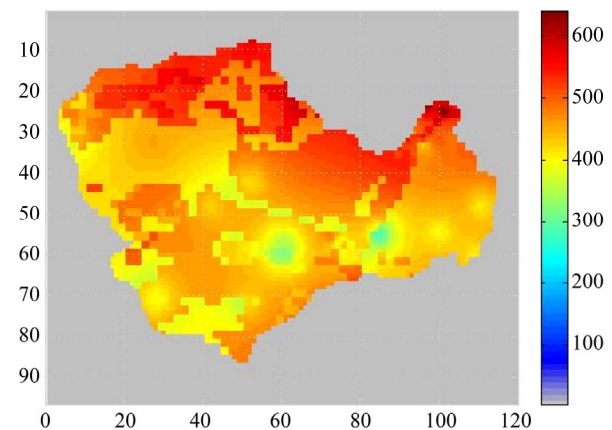


Figure 3. Annual actual evapotranspiration variation in the Limpopo basin (mm).

1 and 1945 mm with a mean annual runoff of 342 mm. The annual simulated runoff show a general trend strongly influenced by the distribution pattern of precipitation. The highest values are concentrated in the heart of the equatorial forest along the Middle Congo river branch. This area records higher rainfalls in the whole basin. The lowest value is simulated in the southern hemisphere around the grid of coordinate 31°E and 6.73°S (western part of Tanzania). A part the lakes, the highest values of runoff are simulated in the heart of the equatorial forest across the equator, and decrease progressively towards the tropics. This trend is relatively disturbed with the soil

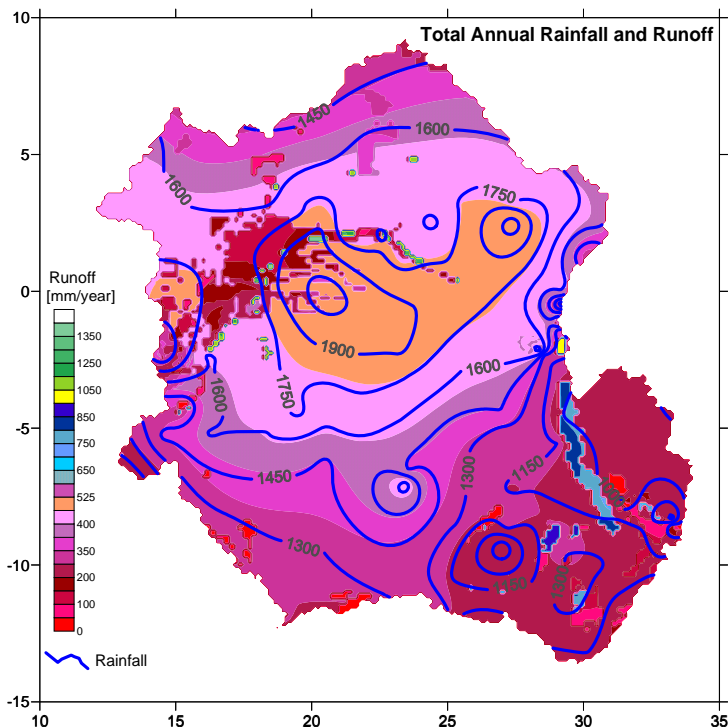


Figure 4. The simulated runoff and areal precipitation in the Congo river basin.

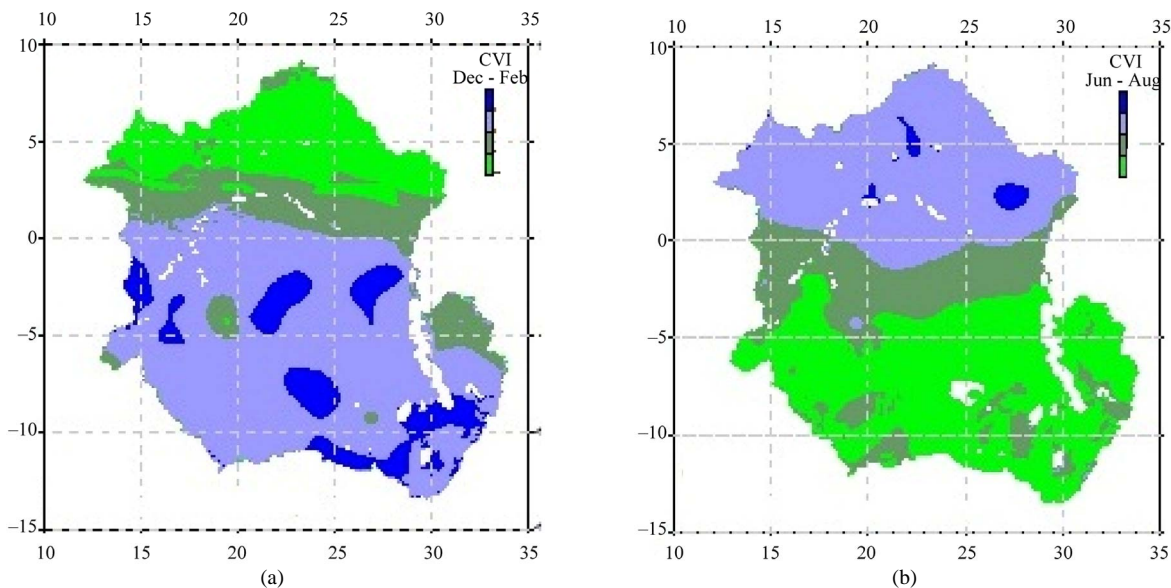


Figure 5. The simulated vertically integrated moisture convergence C in the Congo river basin (a) Dec to Feb (left); (b) Jun to Aug (right) (Source: Own data, [16]).

types especially in the south-eastern, the extreme north region and along the main Congo River.

The corresponding grid-based vertical integrated the moisture convergence (C) computed during water balance calculations for the Congo basin are shown in **Figure 5**. The moisture convergence corresponds to the negative values whereas the positive values correspond to the moisture divergence. This clearly is displayed in the

see-saw fluctuation of C between the above and below equator during the different quarters, winter and summer occurring in the two climatic regimes of the basin.

5. Summary

HATWAB, though simple in form and easy to implement with Fortran, it can be used to solve and answer basin

water resources planning questions of determining water resources availability and distribution at a basin level with localized various spatial and temporal scales depending on the need.

The changes in the input climatic variables such as precipitation and potential ET can easily be incorporated in the model structure in order to simulate the effect on runoff under climate change scenarios. Effects of land cover and land use change as a result of human activity can be considered in HATWAB.

As the grid water balance computations are compatible with raster GIS platforms, the extended application of HATWAB model for hydro-morphologic parameters that control surface runoff can be explored.

However, the model, even if it is at its early stage of development, it is potentially suitable to incorporate human induced changes such as land use land cover and climate impacts in the rainfall-runoff processes of and integrated water resources management of large drainage basins. It is also possible to study transboundary interests in joint management of shared water resources especially in data scarce Africa where this gap is overcome by the approach presented in this manuscript.

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