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THE ROLE OF BASIN PHYSICAL PROPERTY DATA IN ASSESSING WATER STRESS IN WATER RESOURCES STUDIES: THE APPLICATION OF THE PITMAN RAINFALL-RUNOFF MODEL IN NIGERIA

A. O. Ayeni[1] and E. Kapangaziwiri[2]
[1]*Department of Geography, University of Lagos, Lagos – Nigeria*
[2]*HydroSciences Research Group, Natural Resources & Environment, CSIR Pretoria, South-Africa*
aayeni@unilag.edu.ng, ayeniao2000@yahoo.com

ABSTRACT

This paper examines the role played by basin physical attributes in determining river runoff. The approach uses soil and other available hydro-meteorological and geophysical information to directly estimate the parameters of the Pitman rainfall-runoff model to generate time series of historical and future hydrology of the basin. This study discusses the physical property information required, which includes basin soil texture types, depths, soil hydraulic and drainage properties, topographic slope and sub-surface geological conditions. FAO and available Nigeria soil maps provided a baseline of the requisite general soil information and other soil attributes information was inferred from literature. Owena, Asa and Ogun basins were used as case studies to evaluate the parameter estimation routines and the Pitman rainfall-runoff monthly model in Nigeria. Owena basin has some historical data, and based on the experience of using the model gained in this basin the approaches were then transferred to the ungauged basins of Asa and Ogun. While relative success was achieved in generating the hydrology of the test basins, it is suggested that the uncertainty related to the parameter estimation and the rainfall input be investigated and incorporated into the estimation process to provide a range of probable basin hydrology.

Keywords: basin management, water stress, modeling, prediction in ungauged basins, and parameter estimation

INTRODUCTION

In data scarce regions of the world, hydrological simulations still face various challenges which include, inadequate understanding of hydrological processes and mechanisms coupled with limited historical observations at appropriate model application spatio-temporal scales, and high capacity computers (Shun and Duffy, 1998; Kumar and Duffy, 2009). The Fourth Assessment Report of the IPCC predicts an intensification of the global hydrological cycle due to climate change which will affect both the ground and surface water supply. The report concluded that the negative impacts of climate change on freshwater systems may significantly outweigh its benefits with runoff declining in most streams and rivers (IPCC, 2007). River basins may be in the severe water stress category for different reasons. In low-flow periods, relatively high water consumption may result in absolute threat of water shortages, and consequently increase the pressure on both water quality and quantity in water stressed river basins (Falkenmark, 1989; Amber and Matlock, 2011). In 2002, the IPCC assessment revealed that projected climate change could further decrease stream flow and groundwater recharge in many water stressed countries (IPCC, 2002).

LITERATURE REVIEW

In hydro-climatic patterns modeling, long-term rainfall and temperature play important roles; for instance the amount of runoff considerably depends on spatio-temporal variability of rainfall (Cayan *et al.*, 1998; Webb *et al.*, 2004; Kumar and Duffy, 2009). Coupled with climatic factors, the basin's anthropogenic and physiographic (including edaphic) factors are also very important in generating and explaining river flow patterns (Potter *et al.*, 2004; Dettinger and Diaz, 2000; Mulholland *et al.*, 2008; Kumar and Duffy, 2009; Peel, 2009, Potter *et al.*, 2010; Davidson *et al.*, 2012). As a component of the ecosystem, soil functions include collection, storage, and control of water within soil profile. These functions are fundamental for suitable environmental conditions particularly river catchment conservation. Physical and chemical characteristics of soil influence the type and how much water runoff the surface (Moushumi, 2011). These are influenced basically by amount, intensity and duration of rainfall, slope, vegetation, and soil (Pinchamuthu, 1967; Moushumi *et al.,* 2011). The soil type and surface geological formation (transmissivity, existence of fissures, interstices, cracks, etc.) of a basin influence the infiltration capacity and ground water recharge of such basin. In addition, soil water movement and storage are controlled by the structure of surface soil horizons (Duley 1939; Morin *et al*. 1989). As a result, soil is an important component for analyzing water infiltration, erosion, recharge rates, and river runoff. Water scarcity and stress could be attributed to the basin physical characteristics/properties (Moushumi et al., 2011). Therefore, understanding the basin characteristics particularly soil information are necessary for capturing basin's river flow regime and erosion characteristics in addressing water stress and scarcity (Ramasastri, 2002; Moushumi *et al.,* 2011). Soil surface physical characteristics regulate water distribution in the hydrological cycle; for instance, high soil infiltration capacity increases the soil moisture storage which is used for the sustenance of plant life and also for the recharge of aquifers, consequently leading to a decrease of surface runoff and soil erosion. In this way, soil water has a dynamic behaviour whose understanding achieves a key importance, particularly in areas with serious water stress as currently observed in Sub-Sahara Africa.

Therefore, this study aims to demonstrate the workability and applicability of the usefulness of Pitman monthly rainfall-runoff model in Nigeria using catchments with problem of gauging records. The demonstration based on model performance and success recorded in the countries like South Africa, Zimbabwe, Swaziland, Mozambique, Malawi, and Tanzanian catchments (Hughes, 1996; Hughes and Metzler, 1998), and China Lhasa Basin (Bharati and Gamage, 2010) to mention few. In the Southern African region, Pitman model has been widely used tool in hydrological assessment. It is the authors' conviction that it could be used to a greater extent in the future in the region and as well extends to other regions (Kapangaziwiri, 2007).

Brief description of the Pitman rainfall-runoff model: The main purpose of the modeling component is to set up the hydrological baseline river basin runoff. Given the paucity of historical observed data for model calibration in the study area, the application of the model used the physically-based parameter estimation routines described in Kapangaziwiri and Hughes (2008) and Kapangaziwiri (2011). The Pitman model includes explicit routines to simulate interception, infiltration excess surface runoff, soil moisture (or unsaturated zone) runoff, groundwater recharge and drainage to stream flow, evaporative losses from the unsaturated zone as well as the groundwater storage (in the vicinity of the river channel). The model therefore has a relatively large number of parameters and it is typically impossible to establish parameter sets that generate unique results through conventional calibration approaches. However, the potential advantage of the model is that the different contributions to stream flow can be determined and should be sensitive to changes that occur within sub-basins. These changes may involve climate, land use and land cover or different types of abstractions and water use. Table 1 contains a list of the main model parameters that influence volumes of runoff generation as well as a brief summary of the estimation approaches that are followed to quantify them.

Main calibration parameters of the Pitman model: ST (mm) represents the maximum unsaturated zone storage capacity. It is estimated from the soil depth and texture characteristics and including storage in the rock above the phreatic level based on fracture density and depth to groundwater. This is very important in hydrology as it represents the immediate store of infiltrated rainfall before it is lost to either evapotranspiration or to percolation and runoff. Fig. 1 (upper bound) shows that the default estimate of porosity is primarily based on percentage distribution of sand, clay and silt within different texture classes (Rawls *et al.,* 1982; Kapangaziwiri, 2007). Soil depth is estimated from the percentage areas of the basin occupied by three main topographic units - upper slope, mid slope and valley bottom and their associate average soil depths (Fig. 1-lower bound).

FT (mm month^{-1}) parameter represents the maximum unsaturated zone when storage = ST. Estimated from topographic slope, drainage density, soil depth and texture (translated to permeability). It includes an unsaturated zone contribution based on fracture zone transmissivity and gradient. POW is the shape of the relationship that determines reduced runoff (relative to the maximum) as the moisture contents of the soil and unsaturated zones decrease.

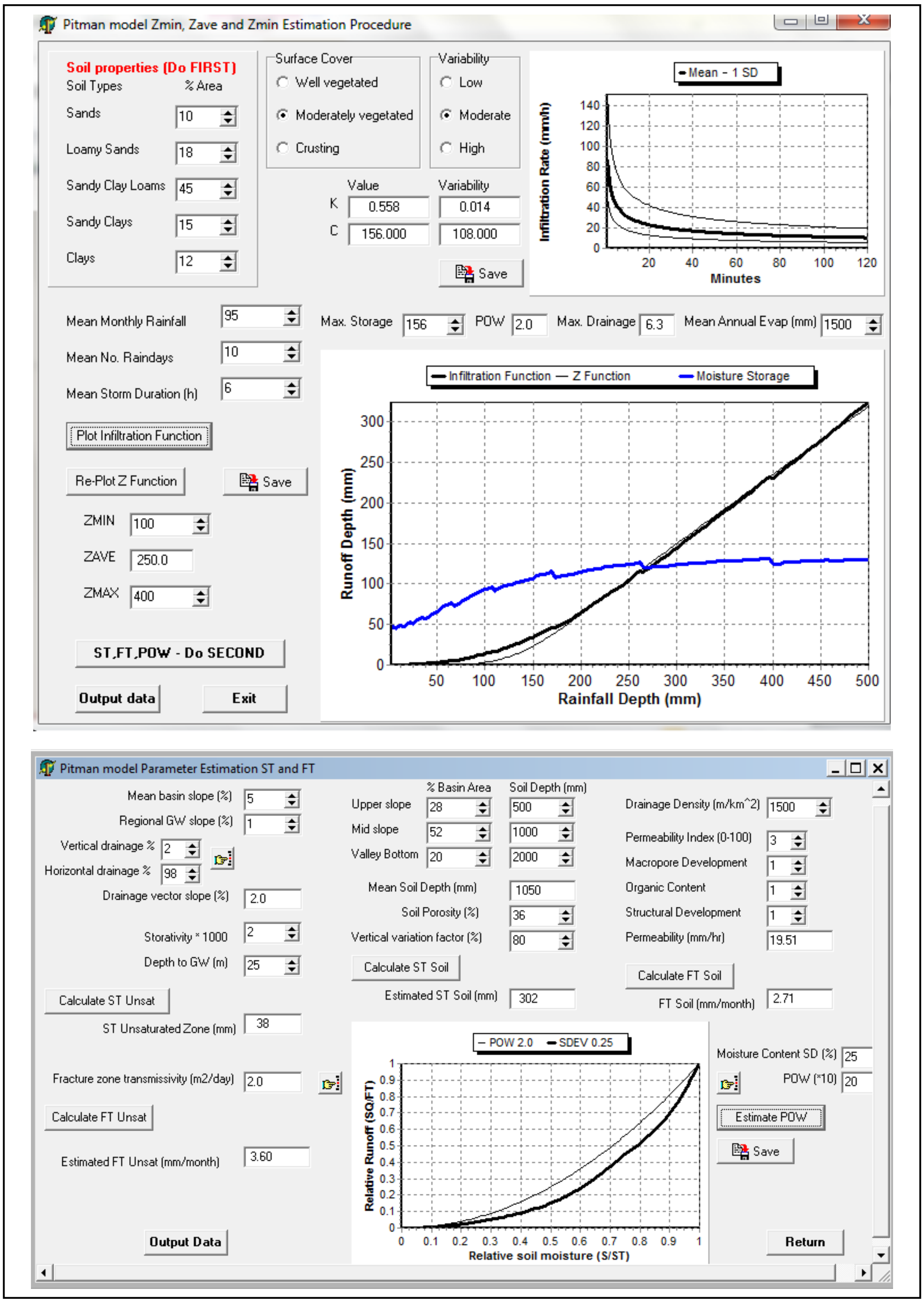
Table 1: Main parameters of the Pitman model and their estimation (Hughes *et al.*, 2010)

Parameter	Model effects
RDF, non-dimen.	Controls the time distribution of rainfall within a month
PI, mm month^{-1}	Interception capacity (two parameters are used to differentiate between two main vegetation types (typically forest and non-forest)
FF, non-dimen	Ratio of evapotranspiration demand from forest vegetation relative to non-forest vegetation
ZMIN, ZAVE, ZMAX, mm month^{-1}	Controls surface runoff generation through the catchment adsorption function. Represents the main source of runoff in semi-arid basins, but can also be important in humid areas that experience heavy rainfall or where soils are shallow (mountain areas)
ST, mm	Maximum limit of unsaturated zone or soil moisture storage. Interacts with many other parameters and its effects are very dependent on other parameter values
FT, mm month^{-1}	Maximum runoff from soil moisture storage at ST. Determines the balance between evaporation and runoff in humid basins, but generally zero for semi-arid and low slope basins
POW, non-dimen.	Power of the relationship between soil moisture storage and runoff. Controls the rate of runoff from the soil for any moisture state
R, non-dimen.	Controls the rate at which evaporation reduces as soil moisture is depleted and therefore related to vegetation cover and soil type
TL, months	Runoff routing parameter (catchment lag)
GW, mm month^{-1}	Maximum groundwater (GW) recharge depth at ST
GPOW, non-dimen.	Power of the relationship between soil moisture storage and recharge. Controls the rate of recharge from the soil for any moisture state
DDENS, km km^{-2}	Effective drainage density for GW inputs to stream flow
T, m^{2} d^{-1}	Groundwater transmissivity
S, non-dimen.	Groundwater storativity
RSF, %	Controls riparian evaporation losses from GW storage
TLGMax, mm month^{-1}	Channel loss parameter for both incremental runoff (within one sub-catchment) and runoff from upstream sub-catchments

In the soil zone the relationship is likely to be mainly influenced by patterns of moisture redistribution following rainfall events and how these patterns affect the distribution of saturated zones (Kapangaziwiri, 2007). Geology, topography, vegetation cover, soil type, and texture will all influence patterns of moisture redistribution within a basin. However, in the absence of detailed field data, a simpler approach was adopted based on the probability distributed principle of Moore (1985) and similar to the procedures used within the VTI model (Hughes and Sami, 1994). As explained by Kapangaziwiri, 2007, the resulting relationship between mean relative basin moisture content and relative runoff is then identical to the format of the Pitman model ‘soil’ moisture runoff function (see Fig.1-lower bound).

GW represents the maximum groundwater recharge rate (mm month^{-1}) when storage = ST. Difficult to estimate directly and is typically calibrated against estimates of mean annual recharge from available literature. GPOW is the power of the relationship between groundwater recharge rate and unsaturated zone storage. GPOW will be similarly calibrated and compared against observed low flows where available. These approaches are considered to be adequate at this stage of the development of the parameter estimation procedures.

ZMIN, ZAVE, and ZMAX are the parameters of the asymmetric triangular distribution of catchment adsorption rate (mm month^{-1}) and estimated from the infiltration characteristics of the soil (Fig. 1-upper bound). These parameters are manually fitted to match the infiltration equation based estimates of runoff for different monthly rainfalls. According to Kapangaziwiri, (2007), the mean values of the parameters and their assumed spatial variability (expressed as the standard deviation of a log-normal distribution) are estimated from soil texture properties and surface cover. As explained by Kapangaziwiri, 2007, fig. 1(lower bound) illustrates the graphical representation of the infiltration equation and its variability. The details of this approach can be found in Hughes and Sami (1994).



Pitman model Zmin, Zave and Zmin Estimation Procedure

Soil properties (Do FIRST)

Soil Types	% Area
Sands	10
Loamy Sands	18
Sandy Clay Loams	45
Sandy Clays	15
Clays	12

Surface Cover: ○ Well vegetated ● Moderately vegetated ○ Crusting

Variability: ○ Low ● Moderate ○ High

	Value	Variability
K	0.558	0.014
C	156.000	108.000

Mean Monthly Rainfall: 95
Mean No. Raindays: 10
Mean Storm Duration (h): 6
Max. Storage: 156
POW: 2.0
Max. Drainage: 6.3
Mean Annual Evap (mm): 1500
ZMIN: 100
ZAVE: 250.0
ZMAX: 400

Pitman model Parameter Estimation ST and FT

Mean basin slope (%): 5
Regional GW slope (%): 1
Vertical drainage %: 2
Horizontal drainage %: 98
Drainage vector slope (%): 2.0
Storativity * 1000: 2
Depth to GW (m): 25
ST Unsaturated Zone (mm): 38
Fracture zone transmissivity (m2/day): 2.0
Estimated FT Unsat (mm/month): 3.60

	% Basin Area	Soil Depth (mm)
Upper slope	28	500
Mid slope	52	1000
Valley Bottom	20	2000

Mean Soil Depth (mm): 1050
Soil Porosity (%): 36
Vertical variation factor (%): 80
Estimated ST Soil (mm): 302
Drainage Density (m/km^2): 1500
Permeability Index (0-100): 3
Macropore Development: 1
Organic Content: 1
Structural Development: 1
Permeability (mm/hr): 19.51
FT Soil (mm/month): 2.71
Moisture Content SD (%): 25
POW (*10): 20

Fig. 1: Illustration of the initial screens of the basin property and parameter estimation.

MATERIALS AND METHODS

The parameter estimation routines used in this study are based on conceptual hydrology interpretations of the model parameters at the model application scale (typically 50 – 10000 km^2) and use basin physical property data. The information required includes soil depths, soil texture (which is then translated into soil hydraulic properties), topographic slope and sub-surface geological conditions of the basins being modelled. The FAO maps (FAO, 2003) were valuable in providing a baseline indication of the general soil types of any given area and were thus used as a general guide and in conjunction with the available national soil maps e.g. dominant soils map of Nigeria. However, the information on critical soil attributes such as soil depth and texture are not available on these maps and were inferred from literature (Adegbola, 1979; Oyenuga, 1967; Sobulo, 1985; Sonneveld, 1996; Iloeje, 2001; Aregheore, 2009). The monthly rainfall records of 28 years (1981 – 2008) for Asa, Owena, and Ogun basin were available for the study. As a result of challenges in accessing historical observed river flow data in the area, only limited monthly data of 9 water years (1990 – 1999) for Owena were available for comparisons of flow duration curves. The data on estimates of potential evapotranspiration demand used as input into the model were obtained from the International Water Management Institute (IWMI) database at www.lk.iwmi.org/WAtlas /Atlas Query.htm.

The model domain – SPATSIM Software: The SPATSIM - Spatial and Time Series Information Modeling software was used in this study (Fig. 2).

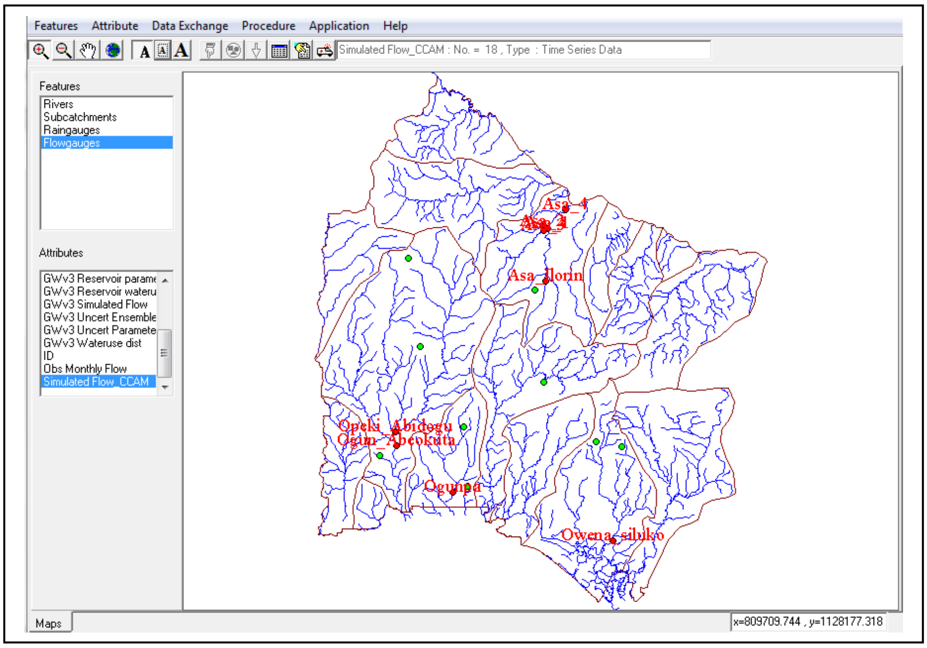


Fig. 2: The model domain

SPATSIM was developed at the Institute for Water Research (IWR) at Rhodes University, South Africa (IWR 2005). SPATISM is an integrated data management and modeling platform. It includes several external models and data analysis tools e.g. the Pitman Model.

RESULTS AND DISCUSSIONS

Application of the Pitman model and case study in Nigeria

The model parameters derived from the estimation process and all other available relevant information on water use were input into the model to generate the hydrology of selected gauged and ungauged basins in Nigeria.

***Owena – partially gauged basin*:** Parameters were estimated using the estimation methods described in the preceding sections. The available gauge data, though inadequate interms of quantity and quality, were used to roughly guide the modeling process. The modeling exercise was premised on the assumption that if the simulated time series was similar to the observed time series in terms of seasonality and water balance, then the modeling would be assumed a success and the parameters would be assumed adequate.

However, the period covered by the flow records and the quality of the data made them highly uncertain. Another factor considered was that the water use in the basins is poorly quantified, which makes the representativeness of the available flow records of the natural hydrology of the basins quite dubious. Hence, these data were only used to guide the calibration of the modeling exercises. In spite of these limitations in the available data, the simulations were deemed acceptable based on comparisons of flow duration curves of Owena River runoff (Fig. 3).

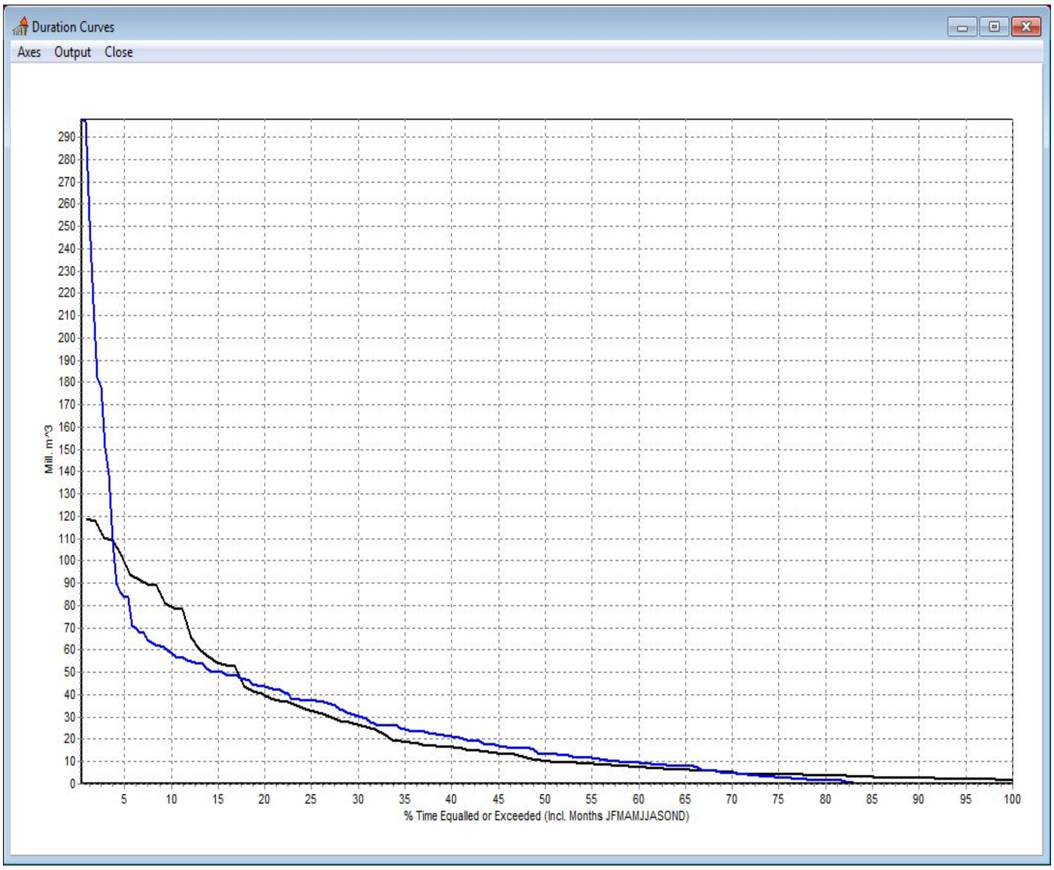


Fig. 3: A screen shot of the duration curves of the simulation results of the Owena sub-basin (Note: The blue graph is the simulated flow and the black graph is the observed flow).

The low to medium flows were quite well represented though the high flows are not so well captured. This could be a result of poor rainfall representation as there were a limited number of gauges used to estimate catchment average rainfall and they were all far from the flow gauging station and could not represent the local conditions properly. However, the success of the simulations in this (poorly) gauged provided the confidence to apply parameter estimation approach in the ungauged parts of the basins for this study.

Assumption used for simulation: If the parameter estimation methods could work for the partially gauged basin of Owena, then the same principles can be used in the ungauged basins of Asa and Ogun to generate estimate time series of the hydrology of these basins. The parameters derived from the estimation process of the model for the 3 basin are listed in the Table 2:

Table 2: Parameter assumption and abstractions used

	Basins/Catchments		
Parameters	Asa	Ogun	Owena
Rain Distribution Factor (RDF)	0.8	0.8	0.8
PI1/PI2	0.401/2.813	0.401/2.813	0.401/2.813

Annual Pan Evaporation (mm) PEVAP	*1700*	*1800*	*1800*
Min. abs. rate (mm/mth) ZMINs	50	200	250
Mean abs. rate (mm/mth) ZAVE	300	1000	400
Max. abs. rate (mm/mth) ZMAX	550	2000	550
Maximum storage capacity ST	299	2200	1500
Power : storage-runoff curve POW	2	6.5	1.5
Runoff rate at ST (mm/mth) FT	5.5	5.5	131.1
Max. Recharge rate (mm/month) GW	0.5	10.5	2.5

Based on the result of duration curve for Owena sub-basin in fig. 3, the model was simulated for three sub-basins (Asa, Ogun, and Owena) dependently on parameter assumption and abstractions in the table 2. The three basins demonstrated spatial-temporal variability in their simulated mean annual runoff (MAR). Between 1981 and 2008, the MAR for Asa, Ogun, and Owena basins was 135.5 Mil.m^3 (±13.0), 440.6 Mil.m^3 (±44.9), and 169.8 Mil.m^3 (±21.6) respectively (Table 3). On average, Asa, Ogun, and Owena basins had runoff coefficient of 15.6%, 20.3%, & and 11.6% respectively for the same period (Table 3 and Fig. 4).

Table 3: Hydro-climatic and physical details for the three basins

	1981 - 1990		
	Asa	Ogun	Owena
Mean flow (Mil.m^3)	135.2	440.6	169.9
Area of sub-basin (km^2)	9600	22000	11000
Mean monthly Runoff (mm)	14.4	20	15.5
Mean monthly rainfall (mm)	90.4	99.6	132.9
Runoff coefficient (%)	15.6	20.3	11.6

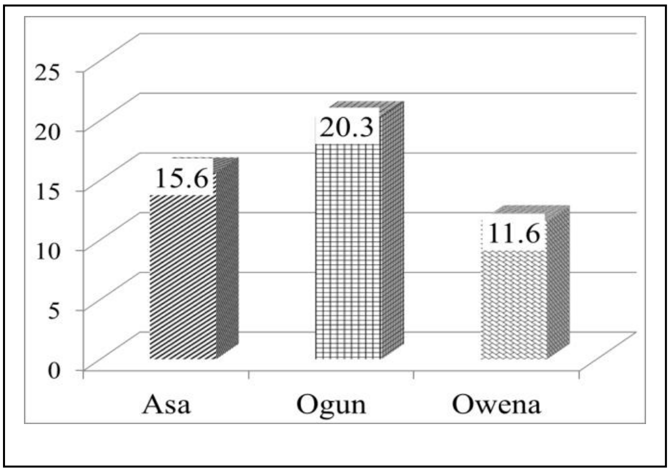


Fig. 4: The simulated Runoff coefficients (in %) of the three basins

The results revealed that 20.3% of Ogun basin annual rainfall is lost through runoff while Asa and Owena basins accounted for annual runoff of 15.6% and 11.6% in respectively. These findings indicated that the selected basins' runoff coefficient are not only a function of basin rainfall but also ceded to the basin's physical parameters including interception, infiltration excess, surface runoff, soil moisture, groundwater recharge and stream flow, evaporative losses from the unsaturated zone as well as the groundwater storage. All these depend on nature, texture, structure, types of soil among others. There are some uncertainties in the generated flows for the basins as validation with measured flow data was not possible for Asa and Ogun, the results are still useful in estimating total water availability for the basins. For instance, Ogun basin with 20.3% runoff coefficient is likely to experience water stress if runoff coefficient continues to increase in the subsequent years.

CONCLUSIONS

The flow regime is recognized as a key factor in determining the catchments/rivers' biological and physical processes and characteristics. All other factors being equal, the model was simpler to calibrate and performed well over the selected Asa, Ogun, and Owena catchments in the Southwestern Nigeria. However, the relative unavailability of some basin property data suggests that prediction uncertainty may be high. Nevertheless, this uncertainty is expected to be substantially reduced and the model will perform better in Nigerian catchments, if more reliable datasets can be made available through collaborative efforts between the soil scientists, geologists, environmental scientists, hydrologists, and meteorologists. In conclusion, the model estimate is very valuable for further studies that depend on information about the total water availability in the catchment. The results of monthly flow volumes generated can be used for water accounting and management by comparing total water availability simulated from the model to water use/demand from the different water use sectors in the basin. In addition, the simulated monthly discharge curves can be used to understand and evaluate catchment rainfall-runoff in water year planning. Based on the model parameters and the estimation methods described in this study, the modeling results can be improved if soil and rainfall data are adequately available in the future for the input parameters needed for the model. These simulations can be applied to other studies in un-gauged river basins and data stressed basin in the country as well as a basis for analyzing water resources in the basins for both the present and the future scenarios.

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