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Flow simulation in an ungauged basin using a digital elevation model

LEKAN OYEBANDE & OLUSEGUN ADEAGA
Department of Geography, University of Lagos, Nigeria
lekan@infoweb.abs.net

Abstract A systematic drainage basin approach remains an appropriate means of investigating water resources, their distribution, monitoring and effective planning, development and management within a basin. In this study, quantitative estimation of basin system response to rainfall input was carried out using a terrain analysis, which in turn employed a digital elevation model (DEM) for the parameterization.

Key words D-8 model; system response; transfer function; ungauged basin

INTRODUCTION

The rate of water withdrawal from both surface and groundwater has increased dramatically in the last two decades. The climate change scenarios constitute an additional threat that makes the need to review water resources planning and design in the light of projected change in water requirements and resources extremely urgent. The current situation in Nigeria and Africa is that sustainable water resources development and management is being hindered by inadequate hydrological data in most drainage basins. This dearth of data has seriously affected understanding of drainage basin dynamics, including water resources variability and trends, as well as its complex ecological interactions (Oyebande *et al.*, 1982).

In this study, the response of the basin system to rainfall input was studied in the Yewa basin, a poorly gauged basin. The assessment involves the use of a hydrological terrain-based model. The transboundary basin is also viewed as a candidate basin for the application of PUB technology in the coming years.

REGIONAL SETTING

The Yewa River drains a transboundary basin, which extends from Nigeria into the Republic of Benin, with a total catchment area of about 5000 km^2 (Fig. 1). The basin is classified as belonging to the equatorial hot, wet climate, with distinct dry and wet seasons. The mean annual rainfall varies between 800 and 1150 mm, in the north to 1500 mm in the south, while the annual mean temperature is about 28ºC with a range of ±4ºC.

The basin has a predominantly rural economy with over 80% of the population engaged in agriculture. During the dry season, the main means of livelihood in the basin is recession or flood plain farming. Badagry is the most important town in the basin. The basin will most likely become more rapidly urbanized in the next decade as

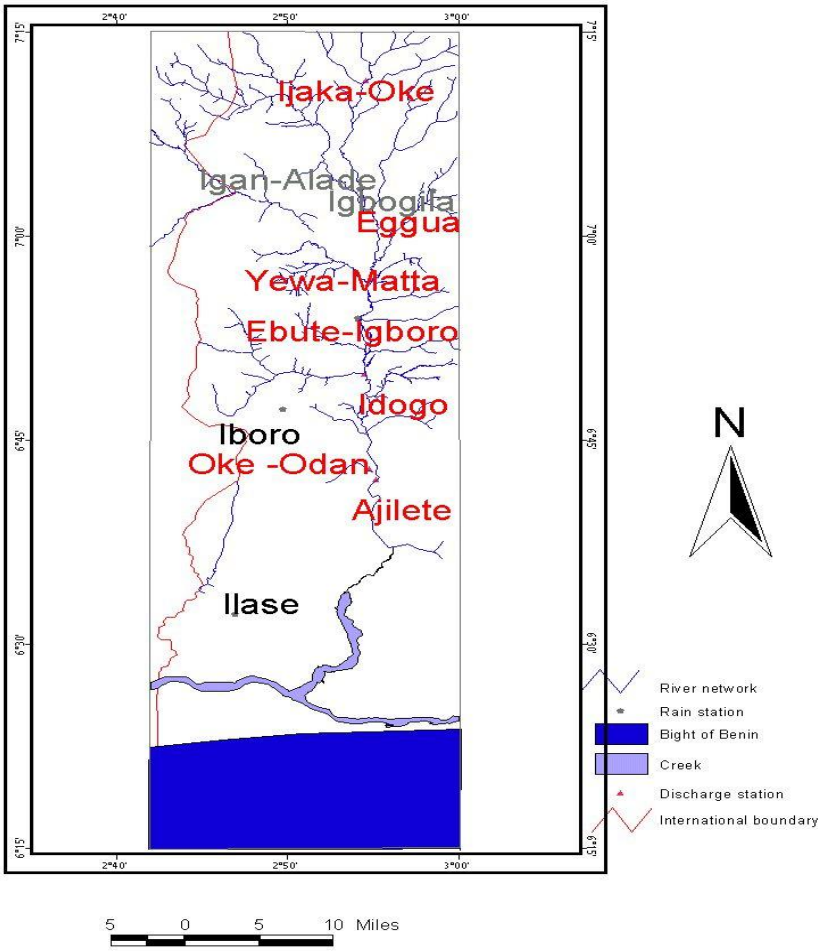


Fig. 1 The Yewa basin its river network.

Lagos metropolis in the southwest and the Ota industrial zone in the north encroach into the Yewa catchment. It may therefore in effect be a basin in transition from a rural one to an urbanized one.

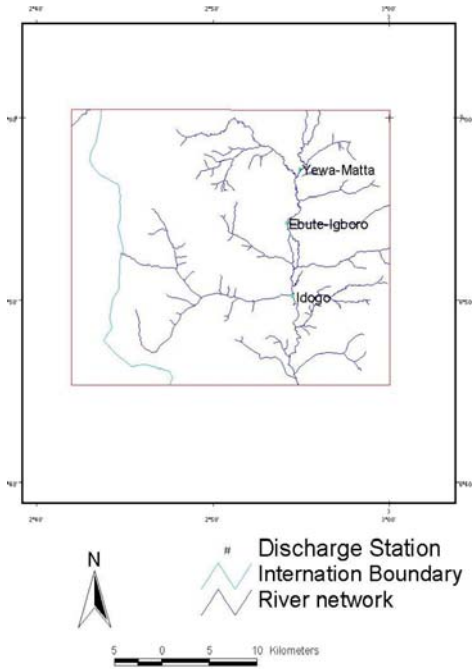
METHODOLOGY

The 1:50 000 topographical maps obtained from Federal Survey Department were used for the analysis. The eight map sheets used show a well-defined river network of part of the Yewa basin. Only one of the sub-basins (River Igbun catchment (sub-basin 1) with a total surface area of 198.27 km^2 was eventually selected for flow simulation. The sub-basin is shaded in Fig. 2.

The Demiurge Group of Digital Terrain Models (DTM) Version 3.11 (Demiurge Version 3.11, 1999) developed by Institut de Recherche pour Développement (IRD, formerly ORSTOM) was used for the analyses. Demiurge consists of five software packages: T2, OROLOG, DTM (MNT), LAMONT4, TOPASE and FTM, which currently provide the following capabilities:

(a) T2 & OROLOG—Digitization of the isoelevation lines (contours) from the topographic maps in order to generate a digital elevation model (DEM) for the

(a)



(b)

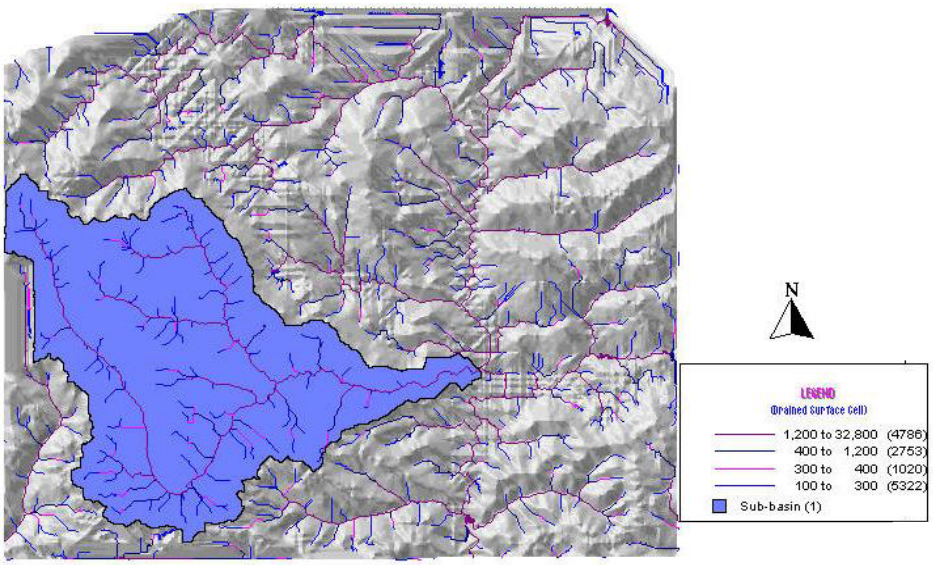


Fig. 2 (a) Digitized and (b) automatically generated river network of Sheet 278 NE and Part of NW.

basin using cubic spline interpolation, an application of elementary polynomial function;

(b) LAMONT4—Pit removal by flooding to ensure hydraulic connectivity within the watershed;

(c) LAMONT4—Computation of flow directions and slopes;

(d) LAMOMT4—Determining contributing area using single (and multiple) flow direction methods. It currently has capability for using single flow direction;

(e) LAMONT4—Multiple methods for the delineation of channel networks including

curvature based methods sensitive to spatially variable drainage density;

(f) LAMONT4—Objective methods for determination of the channel network delineation threshold based on stream drops;

(g) Stream ordering—Demiurge does not perform this treatment;

(h) LAMONT4—Delineation of watersheds and sub-watersheds draining into each stream segment and association between watershed and segment attributes for setting up hydrological models;

(i) TOPASE—Spatial integration of hydrological and geomorphological derivatives through Statistical method (topological discretization)–TOPASE, or Empirical method (morphological function)—FTM;

(j) Generation of a synthetic unit hydrograph or instantaneous geomorphological hydrograph–TOPASE and FTM.

In this study the filled DEM D-8 flow direction model was used to generate stream networks and watershed delineation. Also, flow accumulation analysis was accomplished through assessment of cells flowing in and out of the flow direction model. The D-8 drainage model depicts the directions of drainage between the central cell and one of its eight neighbours. The direction is given in accordance to the principle of the maximum or steepest descent. Automatic channel network extraction and processing is based on the link-based approach using the steepest descent (monodirectional) algorithm. This approach provides detailed overland flow pattern along the path of steepest descent across the land surface. An ascending hierarchical classification (after Bocquillon) is then applied to the network and associated sub-basins.

FLOW SIMULATION

Two flow simulation methods were used for the analysis of the basin system response to input rainfall within a part of Yewa basin—the topographical discretization process (Moniod, 1983) and conceptualization of a morphological transfer function. The topographical discretization method involves statistical analysis of the hydrographical network and distribution of the river slope from a D-8 model. Emphasis is placed on the specific role of slope and network structure as the major controls of the hydrographical response of a basin. The principle of hydrographical network extraction is based on the assumption of cells meeting a specified threshold in order to support flow concentration of the observable thalweg (flow occurrence) and a favourable flow concentration (concave) topographic structure. Flow simulation indices include basin roughness and cross sectional shape in the generation of a triangular unit hydrograph in accordance with stated hydrodynamic parameters (Serrat & Depraetere *et al*., 1997).

In the topographical discretization method the relationship between horizontal convexity (Ch) and the drained surface (Sd) can be mathematically expressed as:

$$Ch = a \log (Sd) + b \tag{1}$$

The slope of the drainage basin at a particular point along the hydrographic network, can be expressed as:

$$\log I = -2b \log Sd + \log a^2 \tag{2}$$

where I = slope, a and b are constants derived from the relationship between slope and surface drainage. The three types of classifications obtainable from the horizontal convexity (Ch) and the drained surface (Sd) relationship using the drainage model are (i) $Sd < Chmin$ indicating cell "slopes", (ii) $Chmin \leq Sd < Chmax \Rightarrow$ an unclassified cell, and (iii) $Sd \geq Chmax \Rightarrow$ Thalweg or flow occurrence.

The velocity of water transfer from one cell towards another in relation to slope and accumulated cells volume can be expressed empirically as:

$$V = k(Sd^{c}).i^{1/2} \tag{3}$$

where k and c are two other parameters related to the roughness and the cross-sectional area of the basin, respectively.

Also the transfer time to the discharge system in the basin is expressed as:

$$T = (1000/K.a).\ (a½ + b - cT^{*}) \tag{4}$$

where T^{*} is pseudo-time of transfer independent of the catchment's surface area.

The modal value of this distribution (T^{*}) is obtained as

$$T^{*} = D = ((m - 1) / (k.m))^{1/m} \tag{5}$$

where m = the number of cells, and k is as defined above.

The statistical distribution of flow, the time of rise, time at peak discharge and peak output (Q^{*}) expressed as specific discharge, $m^3\ s^{-1}\ km^{-2}$, were all derived. However, empirical formulas were used to estimate channel width as a function of basin size and local channel slope. The process involves calculation of appropriate morphological or hydrological indices corresponding to the assumed hydrographic network dimensional fractal, while generating an instantaneous geomorphologic hydrograph (IGH) (Tarboton *et al,* 1993).

The morphological transfer function can be mathematically expressed as:

$$Q = \lambda VH \tag{6}$$

Also, V (flow velocity), ms^{-1} is quantitatively expressed as:

$$V = 4.Sd^{0.144}.\ I^{0.} \tag{7}$$

and H, basin depth is:

$$H = Q/\lambda V = Sd^{\ 0.75 - 0.45 - 0.12}.\ I^{\ 0.25 - 0.4}.k^{\ -0.6} \tag{8}$$

where Q is discharge, λ is basin width, V is flow velocity, K is the Strickler coefficient; I is slope.

The length of channel flow (L) is quantitatively expressed as:

$$L = \#^{\ 8(D-1)/(D+3)}.\ (\#^{4D}(10^{10.8}.\ \#^{-7.\ 6}.\ \Delta H.\ -^{-1.8}\ )^{D-1})^{1/(D+3)} \tag{9}$$

where # is DEM resolution, D is dimensional fractal of the layout of the basin's banks.

Estimation of the catchment system response was restricted to two topographical sheets 278 NE and Part of NW which cover areas lying within latitudes 6.75ºN and 7.00ºN and longitudes 2.70ºE and 3.00ºE with total area of 936.29 km^2 (Fig. 2). The choice facilitates achievement of a dense DEM with adaptive sampling schemes, data structures and an accurate surface interpolation method at a crude reference resolution of 60 m.

Topographic discretization analysis generated a triangular unit hydrograph (Fig. 3). The analysis involves selective use of a maximum surface drained threshold value of 0.14 km^2 from the graphical relationships between horizontal convexity and drained surface. The value represents the acceptable limit of thalweg (flow) appearance within the hydrological network. Relationship between slope tangent network (P) and drained surface (S) in the basin is given as:

$$P = 0.099+0.103(s) \tag{10}$$

The relationship between physical characteristics of catchment area slope (cells) (T) and pseudo-time of transfer (M) is quantitatively defined as:

$$T = 0.297 + 2.229\ (x) \tag{11}$$

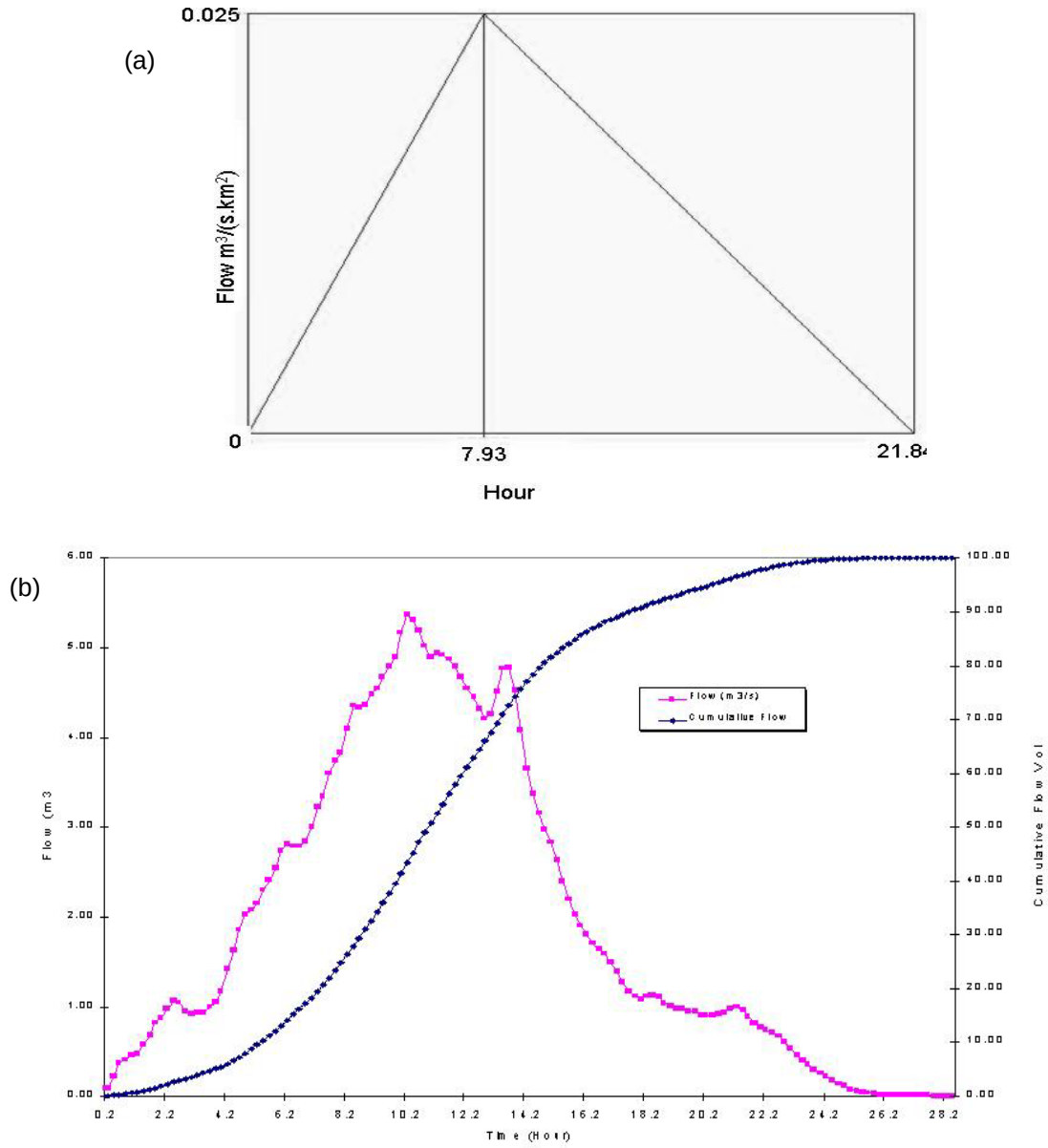


Fig. 3 Flow simulation in Iyun Basin by: (a) topographical discretization method and (b) morphological transfer function method.

Hydrodynamic parameters used to calculate the unit hydrograph include the number of profiles (392) within the basin, the (default) values of drainage basin roughness (4.00), and drainage basin shape (0.20).

Obtaining the morphological transfer function of the River Igbun catchment involves the use of the channel width and basin area as well as local slope indices and the hydrographic network at basin dimensional fractal value of 1.1.

RESULTS

The digitized river network (Fig. 2(a)) and generated network (Fig. 2(b)) at a cell accumulation threshold value of 100 cells for thwaleg (flow) occurrence can be easily compared. The preliminary results obtained, appear satisfactory, and a total of eight (8) sub-basins were extracted from the larger basin.

The instantaneous geomorphological hydrograph (IGH) obtained is shown in Fig. 3. It is premised on an application of 1 mm of effective rainfall and the basic assumptions of the unit hydrograph theory. The results of the hydrodynamic simulation using topographical disrectization and morphological transfer function analysis for the River Igbun basin are also given in Table 1. A comparison of peak discharges shows a 7.63% increase in the magnitude for the morphological transfer function (5.37 $m^3 s^{-1}$) over that of the topographical disrectization analysis (4.9 $m^3 s^{-1}$). This increase seems acceptable: it is due to the introduction of basin dimensional fractal and transfer time function indices as simulation moderators in the morphological transfer function analysis.

Table 1 Hydrodynamic simulation characteristics of River Igbun.

Hydrological parameter	Simulation technique	
	Topographical discretization	Morphological transfer function
Time to Peak (*Tr*) (hours)	7.78	8.99
Peak specific discharge, $Q_{(max)}$ ($m^3 s^{-1} km^{-2}$)	0.025	0.027
Base time (hours)	21.97	28.4

CONCLUSION

Problems of data acquisition and management problems in ungauged and poorly gauged basins further compounded the uncertainties of water resources planning and development in Nigeria and many other parts of Africa. In the absence of well-designed and functional conventional hydrological monitoring networks, acquiring such information involves hydrological modelling and the employment of adaptable investigative tools like remote sensing and geographical information systems. Although such tools are not substitutes for systematic monitoring of hydrological phenomena and processes, they provide new approaches aimed at resolving water resources problems and updating our knowledge base through research. The present study is a preliminary investigation in the Yewa basin.

REFERENCES

Demiurge Version 3.1 (1999) Production et Traitement De MNT appliques a I'Hydrologie (Logiciels Sur.Cdrom pour PC). Institut de Rechemenche pour le Developpement, Paris, France.

Depraetere, C. & Moniod F. (1995) Caractérisation du relief et du réseau hydrographique: aspect méthodologique. Rapport d'avancement des travaux, décembre 1995, ORSTOM, Montpellier, décembre 1995.

Moniod, F. (1983) Deux paramètres pour caractériser le réseau hydrographique. *Cahier ORSTOM série Hydrologie* **XX**(3–4), 191–203.

Oyebande, L. & Ayoade, J. O. (1986) The watershed as a unit for planning land development. In: *Land Clearing and Development* (ed. by R. Lal, R. A. Sanchez & R. W. Cummings, Jr.), 37–52. A.A. Balkama, Rotterdam, The Netherlands.

Serrat, P. & Depraetere, C. (1997) Incidences de facteurs géomorphologiques dans le fonctionnement d'un bassin : exemple de l'Agly (Pyrénées Orientales). *Géomorphologie: relief, processus, environnement* **1**, 63–88.

Tarboton, D. G. (1997) A new method for the determination of flow directions and contributing areas in grid digital elevation models. *Water Resour. Res.* **33**(2), 309–319.