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Surface runoff and infiltration processes in the Volta Basin, West Africa: Observation and modeling

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Dedication

To Bishop (Dr.) David Oyeniyi Oyedepo
for showing me the path to greatness

and

to Mr. Mayowa Oyedeji (ACA)
for encouraging me against the odds

ABSTRACT

This study presents the results from field observations and subsequent development and solution of a process-based, two-dimensional numerical model capturing surface runoff processes in the Volta Basin, West Africa. The developed model summarizes the interactions between temporally varying rainfall intensity and interactive infiltration processes in soils with spatially varied soil physical and hydraulic characteristics. Varied catchment geometry, microtopographic (vegetated and soil surface) forms, slope length and angle were also examined. The model also incorporates the rainfall interception by mixed vegetation.

The interactive infiltration process is modeled with the Philip two-term equation (PTT), while ponding time is approximated with the time compression algorithm. Interception by vegetation is estimated with the modified Gash model, while the friction effect of vegetation on surface overland flow is quantified. The developed surface flow equations were solved with a second-order Leapfrog explicit finite difference scheme, with centered time and space derivatives. This scheme was modified to accommodate the peculiar nature of surface runoff on a complex microtopographical plane. The model reliably reproduces the results from experimental field data on the basis of parameterized effective soil hydraulic parameters and passed severe numerical tests for hydrodynamic equations.

The analyses of results from both field observations and numerical simulations shows that the dominant runoff generation mechanism in the study area is the infiltration excess (Hortonian) process. A consistent trend of exponential reduction runoff coefficient and runoff discharge per unit area with increasing slope length was observed. The results also showed that both temporal and spatial variability induced factors determine runoff response to rainfall events. Spatial variability in infiltration opportunities, which varies with slope length, and the distribution pattern of saturated conductivity, leading to differences in temporal dynamics of transmission losses potential during runoff routing downslope; moderated by surface roughness and vegetation (Microtopography), which determines surface depression shapes and networks, results in the consistent differences in runoff response. Temporal patterns of rainfall intensity, particularly the distribution in terms of number of pulses, the duration of pulses, total event time, length of time for recession, also affect runoff response. Initial moisture status of the soil may also significantly increase runoff volume. However, a classical demarcation of the prevalent factor at any instant could be defined.Variability in temporal factors dominates the response to high intensity events, while spatial variability in the distribution pattern of soil-related factors i.e., hydraulic properties dominate the response to low intensity events. The prevalence of temporal factors in the basin is traceable to the high intensity tropical storms, which often do not allow the spatial factors to become fully manifest.

The developed model will be useful in studying surface runoff, water erosion, and nutrient dynamics under complex microtopographic conditions, spatially varying soil hydraulic characteristics and temporally dynamic rainfall intensity occurring in many tropical catchments. It also provides practical tool for facilitating decision processes in soil management techniques aimed at managing surface runoff and soil erosion.

Oberflächenabfluss und Infiltrationsprozess im Volta-Becken: Beobachtungen und Modellierung

KURZFASSUNG

Diese Studie präsentiert die Ergebnisse aus Felduntersuchungen sowie die Entwicklung und Lösung eines prozessbasierten, zweidimensionalen numerischen Modells, das den Prozess des Oberflächenabflusses im Voltabecken, Westafrika, darstellt. Das Modell erfasst die Wechselwirkung zwischen zeitlich variierender Niederschlagsintensität und Versickerungsprozessen in Böden mit räumlich variierenden physikalischen und hydraulischen Eigenschaften. Eine unterschiedliche Oberflächengestalt des Wassereinzugsgebiets, verschiedene mikrotopographische Formen (mit und ohne Vegetationsbedeckung), Hanglängen und –neigungen wurden ebenfalls untersucht. Das Modell berücksichtigt auch die Interzeption des Niederschlags durch die Vegetation.

Der interaktive Infiltrationsprozess ist mit der ‚Philip two-term' Gleichung (PTT) gekoppelt, während die Wasserakkumulation (ponding) mit dem Algorithmus der Zeitkompression (Zeitverdichtung) ermittelt wird. Die Interzeption durch den Niederschlag wird mit dem modifizierten Gash Modell bestimmt, der Reibungseffekt der Vegetation durch einen entwickelten Vegetationsfaktor. Die Gleichung wurde mit dem bekannten Schema 2. Ordnung, Leapfrog Explizit-Finite-Unterschiede (FDM) mit zentrierten zeitlichen und räumlichen Differentialquotienten gelöst. Dieses Schema wurde modifiziert, um die besondere Natur des Oberflächenabflusses auf einer komplexen mikrotopographischen Ebene zu erfassen. Das Modell reproduziert zuverlässig die Ergebnisse der Feldversuche auf der Basis von parametisierten wirksamen bodenhydraulischen Parametern und bestand die strengen numerischen Tests für die hydrodynamischen Gleichungen.

Die Analysen sowohl der Felddaten als auch der numerischen Simulationen weisen den Prozess des Infiltrationsüberschusses als den am stärksten bestimmenden Mechanismus bei der Erzeugung von Oberflächenabfluss im Voltabecken nach. Ein durchgängiger Trend hinsichtlich der exponentiellen Reduktion des Abflusskoeffizienten und der Menge des Oberflächenabflusses wurde mit zunehmender Hanglänge beobachtet. Die Ergebnisse zeigen weiterhin, dass die sowohl durch zeitliche als auch räumliche Variabilität bedingten Faktoren die Reaktion des Abflusses auf das Niederschlagsereignis bestimmen. Eine klassische Abgrenzung des zum jeweiligen Zeitpunkt vorherrschenden Faktors konnte jedoch definiert werden. Zeitliche Muster der Niederschlagsintensität, insbesondere die Verteilung hinsichtlich Anzahl und Dauer der Impulse, Gesamtlänge des Ereignisses, Rezession und durchschnittliche Intensitätswerte kombiniert mit der zeitlichen Variation der Wasserbewegung hangabwärts bestimmen weitgehend die Reaktion auf Niederschlagsereignisse von hoher Intensität. Die räumliche Variabilität der bodenabhängigen Faktoren, z. B. hydraulische Eigenschaften und Hanglänge, beeinflusst Ereignisse von geringer Niederschlagsintensität. Das Vorherrschen der zeitlichen Faktoren im Voltabecken kann auf die Niederschlagsereignisse von hoher Intensität, gleichbedeutend mit tropischen Stürmen, zurückgeführt werden, die oft die Manifestierung der räumlichen Faktoren verhindern. Ein weiterer Bodenfaktor, der die Reaktion beeinflusste, ist der anfängliche Bodenfeuchtigkeitsstatus. Dieser Einfluss wird jedoch ebenfalls begrenzt, da er schnell

durch die hohe Niederschlagsintensität überlagert wird. Bei Ereignissen von geringer Niederschlagsintensität könnte eine hohe anfängliche Bodenfeuchte die Abflussmenge signifikant erhöhen.

Das entwickelte Modell wird hilfreich sein bei Untersuchungen über Oberflächenabfluss, Erosion durch Wasser sowie Nährstoffdynamik unter komplexen mikrotopographischen Bedingungen, mit räumlich variierenden bodenhydraulischen Eigenschaften und bei zeitlich dynamischer Niederschlagsintensität, wie sie in vielen tropischen Wassereinzugsgebieten vorkommen. Es stellt auch ein nützliches Instrument für die Unterstützung von Entscheidungsprozessen im Zusammenhang mit Bodenbewirtschaftungstechniken zur Kontrolle von Oberflächenabfluss und Bodenerosion zur Verfügung.

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LIST OF SYMBOLS AND ABBREVIATIONS

Symbol	Description	Dimension	Applied unit
U	flow velocity in the x-direction	L T^{-1}	cms^{-1}
V	flow velocity in the y-direction, m/s	L T^{-1}	cms^{-1}
S_{ox}	ground slope in the x-direction	L L^{-1}	°
S_{oy}	ground slope in the y-direction	L L^{-1}	°
S_{fx}	friction slope in the x-direction	L L^{-1}	
S_{fy}	friction slope in the y-direction	L L^{-1}	
q_x	uh-x-momentum	L^2 T^{-1}	cm^2s^{-1}
q_y	vh y-momentum	L^2 T^{-1}	cm^2s^{-1}
H	height/depth of flow (m)	L	cm
i, j	Timesteps; i = first and j = last time steps	T	S
q_{xb}	value of q_x at boundaries;	L^2 T^{-1}	cm^2s^{-1}
q_{yb}	value of q_y at boundaries;	L^2 T^{-1}	cm^2s^{-1}
h_b	value of h at boundaries	L	cm
$\overline{q_x}$	filtered variable (q_x)	L^2 T^{-1}	cm^2s^{-1}
$\overline{q_y}$	filtered variable (q_y)	L^2 T^{-1}	cm^2s^{-1}
$\overline{h}$	filtered variable (h)	L	cm
F_{xx}	flux of x-momentum in x-direction;	-	-
F_{xy}	flux of x-momentum in y-direction;	-	-
G_{xy}	flux of y-momentum in x -direction		-
G_{yy}	flux of y-momentum in y-direction	-	-
Q_x	flux of height in x-direction	L	cm
Q_y	flux of height in y-direction	L	cm
F_{xxb}	F_{xx} at boundaries	-	-
F_{xyb}	F_{xy} at boundaries	-	-
G_{xyb}	G_{xy} at boundaries		-
G_{yyb}	G_{yy} at boundaries	-	-
h_0	initial constant height	L	cm
h_m	microtopography height	L	cm
npy	no of point on y axis	-	-
npx	no of point on x axis	-	-
CFL	Courant–Friedrichs–Lewy parameter	-	-
g^{n-1}	Flow generic variable	L^2 T^{-1}	cm^2s^{-1}
α	time filtering coefficient	-	-
Δt	time step length	T	sec
Δs	grid length (dx=dy=Δs)	L	cm
k_{diff}	artificial diffusion coefficient	-	-
G	Gravitational acceleration	L^2 T^{-1}	m^2 s^{-1}
F_{rsu}	flux for the friction slope in the x-direction	L	
F_{rsv}	flux for the friction slope in y-direction	L	
$S_e(\psi)$	effective saturation /reduced water content	L^{-3} L^{-3}	m^{-3} m^3
θ_r	residual volumetric water contents	L^{-3} L^{-3}	m^{-3} m^3
θ_s	saturated volumetric water contents	L^{-3} L^{-3}	m^{-3} m^3
V_{obs}	observed runoff volume	L^3	Liter

Symbol	Description	Dimension	Applied unit
V_{sim}	simulated runoff volume	L^3	Liters
C_e	coefficient of efficiency	%	%
Q_i	observed runoff discharge at time i	$L^3\ T^{-1}$	Liter s^{-1}
$\bar{Q}$	mean runoff rate of the particular rainfall-runoff event	$L^3\ T^{-1}$	Liter s^{-1}
$\hat{Q}_i$	runoff discharge predicted by the model at time I	$L^3\ T^{-1}$	Liter s^{-1}
N	number of time step in the computation	-	-
G	gravitational acceleration, 9.81	$L\ T^{-2}$	ms^{-2}
F	Darcy–Weisbach friction factor	-	-
R_e	Reynolds-number	-	-
K_o	resistance parameter, which relates to the ground surface characteristics.	-	-
ν	kinematic viscosity of water = 10^{-6}	$M\ L^{-1}\ T^{-1}$	ms^{-1}
N	Manning's roughness coefficient	-	-
k	Dimensionless extinction coefficient	-	-
$R(t)_{ri}$	interception-reduced rainfall intensity	$L\ T^{-1}$	mm hr^{-1}
I(t)	instantaneous infiltration rate [m/s]	$L\ T^{-1}$	mm s^{-1}
S	Sorptivity [$m/s^{½}$]	$L\ T^{-1/2}$	mm $s^{-1/2}$
C	effective hydraulic conductivity [m/s]	$L\ T^{-1}$	mm hr^{-1}
FEM	Finite Element Method	-	-
FDM	Finite Difference Method	-	-
FVM	Finite Volume Method	-	-
A_1 B_1, A_2 & B_2	Long Plots (LP)	L	m
A_3 & B_3	Medium plot (MP)	L	m
A_4 & B_4	Short Plot (SP)	L	m
RQ	Runoff Coefficient	$L^{-3}\ L^{-3}$	%
UD	Runoff Discharge per unit area	$L^{-3}\ m^{-2}$	Lit m^{-2}

1 GENERAL INTRODUCTION

1.1 Surface runoff, infiltration process and rainfall partitioning in the tropics

Surface runoff (flux at a point in space), often used interchangeably with the term overland flow (a spatially distributed phenomenon), resulting from the rainfall-runoff transformation process plays a significant part in the hydrological cycle (process) in West Africa as in many other tropical regions. It is recognized as an essential component of most erosion and catchment water balance models (van Dijk, 2002) and is a critical factor controlling rill erosion and gully development (Hudson, 1995).

Overland flow significantly influences the amount of water available in the rivers, streams and ponds, and determines the size and shape of flood peaks (Troch et al., 1994), and, when properly managed, could be converted into valuable water resources for agricultural production in floodplain farming. This could be very useful in most sub-Saharan African countries, facing a consistent trend of declining or fluctuating annual rainfall totals, which is affecting food production under rainfed agriculture (Joel et al., 2002; Le Barbé and Lebel, 1997; Rockström and Valentin, 1997; FAO, 1995;).

Surface runoff in the form of long-term water availability and extreme flows are also very important in designing hydraulic structures in civil engineering works (Lidén and Harlin, 2000). It determines the magnitude of sediment transport in water erosion process (Kiepe, 1995; Lane et al., 1997), and resolves the transport and fate of nutrients and agro-chemicals, which reside on the soil surface (Jolánkai and Rast, 1999). Consequently, adequate understanding and knowledge of its dynamics constitute one of the most important and challenging problems in hydrology and are quintessential in understanding several other catchment processes.

Substantial progress has been made in understanding the surface runoff process and its impact on the global water cycle in some parts of the world. However, very little has been done in sub-Saharan Africa countries (van de Giesen et al., 2000), particularly in West Africa, where only few examples exist of detailed hydrological studies that use sub-daily information on small experimental catchments (<10 km2) (Chevallier and Planch, 1993).

There is a general consensus among researchers that the Hortonian or 'infiltration excess' runoff mechanism, dominates the generation of runoff in tropical catchments, while the Dunne's or 'saturation excess' mechanism applies to the flood plains and valley bottoms (Esteves and Lapetite, 2003; Masiyandima et al., 2003; Joel et al., 2002; Peugeot et al., 1997; Dunne, 1978). By definition, Hortonian overland flow occurs at a point on he ground surface when the rate of rainfall exceeds the infiltration capacity of the soil and there is a sufficient gradient to facilitate the flow. This process is well defined and understandable at a point scale, but the model representation of the process is mostly done at a far higher resolution, i.e., the catchment or regional scale when done deterministically (Fiedler, 1997).

Understanding and modeling of surface runoff processes, requires the selection of appropriate spatial and temporal discretization, to reduce scale discrepancies, between observation and application. It is also essential in formulating appropriate hydrological models that can most effectively simulate water balances for large areas with the use of available computer resources. Such models are useful tools in flood forecasting and in improving the atmospheric circulation models (Schmidt et al., 2000). However, most large-scale models cannot incorporate detailed and physically based descriptions of the processes because of unknown boundary conditions, but with appropriate scale definition, this problem can be solved.

Surface runoff process, as can be seen from the two widely accepted concepts, is strongly influenced by the infiltration and percolation characteristics of the soil in a catchment, implying, that surface infiltration or overland flow processes cannot be adequately understood if the infiltration behavior of the soil in the catchment is not properly studied. Infiltration properties among other biophysical factors determine the amount of rainfall that flows on the surface as overland flow. In continental United States, it is generally held that 70% of the annual precipitation infiltrates and the remaining contributes to the stream flow through surface runoff (Chow, 1964). Infiltration process in soil has received more attention in hydrological studies than any other component, and this has led to the development of several conceptual and empirical models to describe the process. Commonly used conceptual infiltration models include models based on the Richards equation, Green-Ampt model, Philip two-term model, Parlange model, etc., while the empirical models include the Kostyakov model, Horton model, Holtan model, Overton model, Soil Conservation Service (SCS) model, Hydrologic Engineering Center (HEC) model among many others (Singh, 1988).

These models have been frequently compared and divergent results on effective models have been reported, depending on experiment locations among other factors. Quite clearly, the classical point scale infiltration theory (e.g., Green-Ampt Smith-Parlange, and the Philip Two Term model (PTT) is often used in physically based hydrologic models (Fiedler and Ramirez, 2000).

1.2 Research goals and objectives

Within the context of the GLOWA Volta Project, (http://www.glowa-volta.de), which was set up to develop a decision support system (DSS), for sustainable water management in the Volta Basin, providing a comprehensive monitoring and simulation framework that will assist decision makers; to evaluate the impact of manageable (irrigation, primary water use, land-use change, power generation, trans-boundary water allocation) and less manageable (climate change, rainfall variability, population pressure) factors on the social, economic, and biological productivity of water resources; the overall goal of this research work is to provide the details about surface runoff formation, transmission and dynamics for the decision support system.

Therefore the objectives are:

1. To establish by the means of field studies, the dominant runoff formation mechanism in the basin;
2. Study the effect of the catchment heterogeneous structure (vegetation, geometric attributes and spatial variation of hydraulic properties) on surface runoff processes;
3. Determine possible influence of observation scale on the processes;
4. Develop a process based model capable of representing the observed surface runoff processes; and consequently
5. Evaluate the influence of temporal factors (varying rainfall intensity, surface runoff routing) on scale effect.

A combination of scaled-plots experiments, detail catchment monitoring and process-based numerical investigations is considered necessary to understand these interactions. It is hypothesized that runoff process responds variably to spatial and temporal variation in catchment hydraulic properties and rainfall properties. The