Journal of Hydrology, 151 (1993) 173–191

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Hydrological processes in a small humid savanna basin (Ivory Coast)

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(Received 14 August 1992; revision accepted 29 March 1993)

Abstract

The paper describes the natural framework of the Booro-Borotou ($1.36\,km^2$) basin: geomorphology, geology and soil, vegetation and surface features, precipitation and evapotranspiration. Several experiments (rainfall simulation, surface runoff traps), together with the observation of internal storage and floods, show the complexity of runoff processes. Discussion confirms that, in this elementary watershed, water emerging as runoff travels by multiple routes.

Introduction

The study of hydrological processes has greatly advanced in recent years owing to the encouragement of hydrologists working mainly in temperate or forest regions (Dunne, 1983; Klemes, 1986, 1988). Dubreuil (1985, 1986) recently summarized the work done for over 30 years by the French Institute of Scientific Research for Development in Cooperation (ORSTOM) in nearly 300 small basins of the intertropical region. Most of these studies had practical objectives related to exceptional floods, but physical flow processes were also observed. During the last 10 years, ORSTOM researchers, including hydrologists and soil scientists, have developed their studies of physical processes, particularly in a tropical context, by fieldworks using more refined techniques and research methods. These studies refer to the major zones described by Dubreuil: arid and semi-arid regions, dense forests, dry savannas and humid savannas. Between 1982 and 1987, a multidisciplinary team of researchers, hydrologists, soil scientists, botanists and specialists in agriculture and soil fauna, studied soil–plant–atmosphere processes, in a small

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humid savanna basin at Booro-Borotou in the northwest region of the Ivory Coast. This scientific study was important in a region with encouraging prospects for development. The small basin context (the term 'small' basin here means 'first-order basin') has been adopted as it takes into account all the hydrodynamic functions, both in production and transfer, without allowing either to predominate.

Results obtained in the Booro-Borotou basin will be presented, together with a brief description of the difficulties inherent in identifying hydrological processes, knowledge of which is essential for an understanding of how the basin works (Chevallier, 1988; Planchon, 1989). In essence, the basin synthesizes interactions within the limited ecosystem of the catchment studied. However, this formulation may be inverted and the ecosystem regarded as the resultant of the interactions which created, organized and transformed the basin.

The natural framework

The Booro-Borotou basin lies in the northwest of the Ivory Coast near the town of Touba, several kilometers from the Guinean border (Fig. 1). It is part of the upper drainage basin of the Sassandra River which drains the western part of the Ivory Coast. The basin is very compact and covers an area of 1.36 km^2; altitudes range from 425 to 474 m on a large plateau with some emergent reliefs.

The hydrological and rainfall records extend from April 1984 to March 1988, i.e. four complete hydrological years.

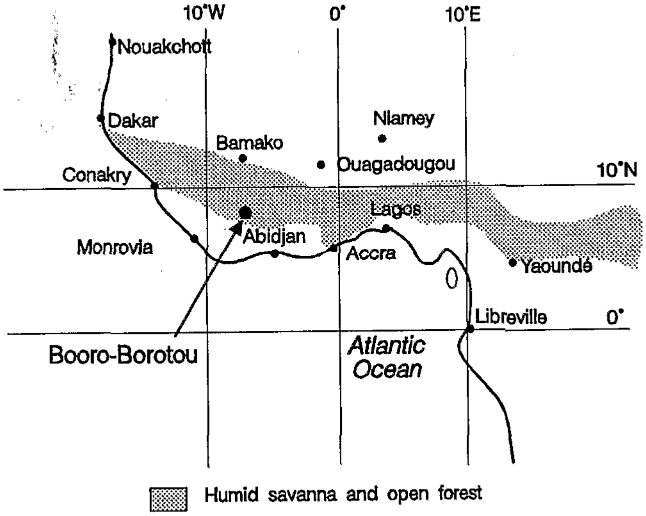


Fig. 1. Situation map.

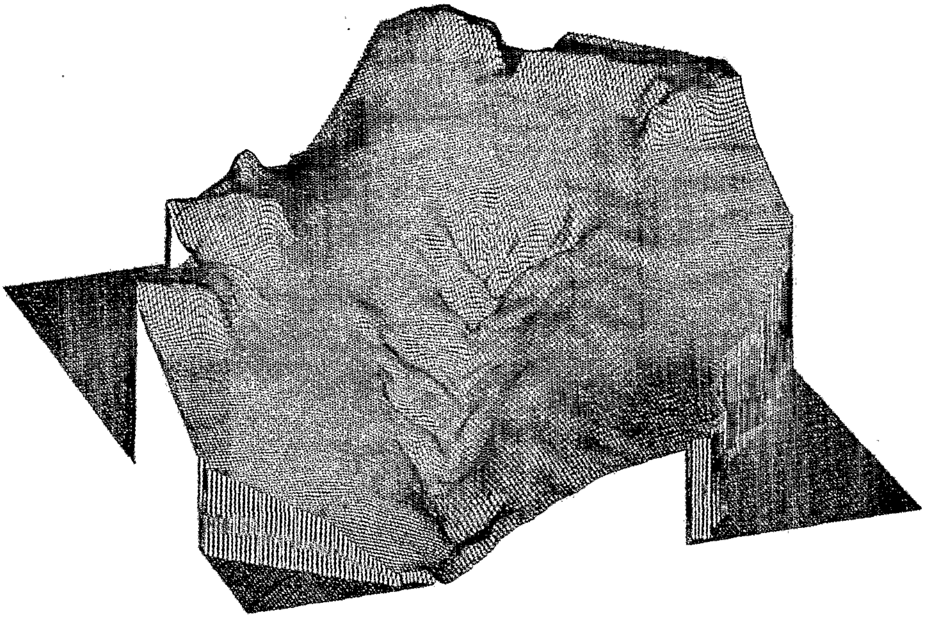


Fig. 2. Geomorphology of the Booro-Borotou basin.

Geomorphology

The main features of the relief are as follows (Fig. 2):

(1) A single, almost permanent watercourse is at the center of the basin in the main channel. The bottom of the valley is narrow (a few dozen meters), very slightly sloping (average lower than 1°) and markedly convex transversally.

(2) The right and left bank hillslopes are mostly very regular and convex. Secondary drainage elements, only activated during storm events, have developed in the depression perpendicular to the main channel. These depressions are more marked on the right bank; they are rarely more than 100 m and always less than 200 m long. The following structure is noted with respect to the main channel: (i) the hillslope tops, more than 15 m above the main channel, are slightly sloping (2°); (ii) the mid-hillslope, between 12 and 15 m, coincides with a sudden break on the slope and may be considered the morphological trace of a major characteristic line of the basin; (iii) the lower part of the hillslope, less than 12 m above the channel, is convex, with a slope of more than 3°.

(3) Four plateaux dominate the basin to the west and south. They cover a small area (several hectares) and their edges are steeply inclined (over 10°).

Geology and soil

The watershed of Booro-Borotou, like the surrounding area, lies on migmatitic gneiss. The soils were established by erosion of the original ferralithic domain, the only remnants of which are the four plateau shields. Pedogenetic and hydrological processes have resulted in soils impoverished in iron and clay and give rise to three different systems corresponding to the geomorphological organization (Fritsch et al., 1990b):

(1) ferralithic upstream, in which the soils are red and permeable with high clay and gravel contents;

(2) ferruginous at mid-hillslope, in which soils are ochre, with much gravel and a structure that is generally massive and often compacted;

(3) hydromorphic downstream, in which the soils in the low part of the hillslope and the valley bottom form a large sandy reservoir in which the groundwater fluctuates; this system extends into the secondary channels.

Vegetation and soil surface features

Soil surface features are directly related to vegetation and include the elementary surface organization of soil, its spatial extent and seasonal development (Planchon et al., 1987).

Six classes of vegetation are described (Mitja, 1990):

(1) the riverine forest on the hydromorphic soils of the valley bottom;

(2) four classes of savanna (wooded, open wooded, shrub and grass) which are classified according to the presence, absence and height of trees. All these savannas had been farmed and later abandoned, possibly a long time in the past. They differ according to type of soil (ferralithic or ferruginous) and how long ago they were abandoned. Bush was burned every year;

(3) a cultivated zone which, during the period of the study, covered 7–8% of the watershed surface. Annual crops are planted mainly during the wet season by hand or with animal traction (Camara, 1989). The main crops are rice, peanuts, beans, yams, manioc, cotton, maize, and tomatoes.

There is practically no animal husbandry, so that, for example, soil structure has not been influenced by herd movement.

At Booro-Borotou, three main types of surface features are noted (Valentin et al., 1986) which, like vegetation, are closely related to past and present human activity:

(1) zones without crusting, located on the plateaux and slopes, in the riverine forest, on a zone of dense bushy savanna on the left bank, and finally in the valley bottom. In particular, there is a strip, several meters wide (called a

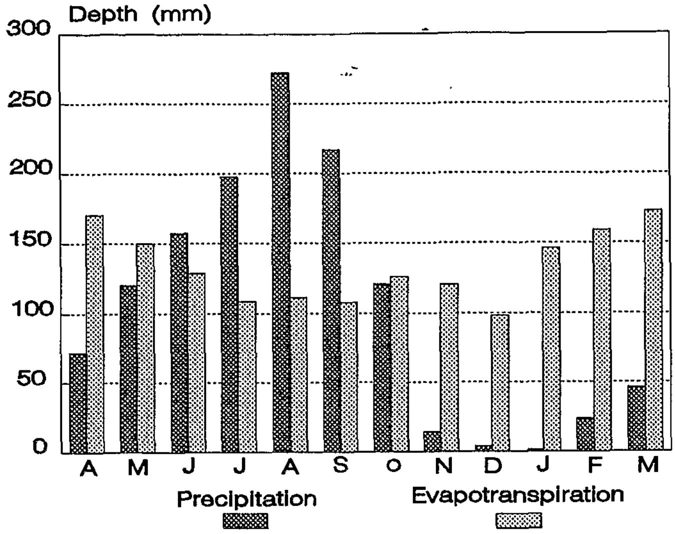


Fig. 3. Mean monthly rainfall and potential evapotranspiration.

stop strip), on the edge of the riverine forest, where no sign of surface reorganization or surface flow is seen;

(2) zones with seasonal crusting, related both to competition between soil fauna (termites, earth worms) and to precipitation in the higher parts of the watershed, or to field cultivation practices;

(3) zones where crusting is permanent, either naturally (clearings at the top of the hillslopes and mid-hillslope savannas) or owing to human activity (formerly cultivated clearings).

Precipitation and evapotranspiration

The Booro-Borotou region is part of a tropical subhumid climatic zone, with two seasons: a dry season, from October to April and a rainy season, from June to September.

The annual mean rainfall at Touba is 1360 mm. Figure 3 shows mean monthly rainfall observed in the Booro-Borotou basin. The daily rainfall with an annual return period is 74 mm, and with a 10-year return period is 126 mm. Figure 3 also shows monthly potential evapotranspiration calculated using the Penman formula (1948) based on daily observations made between 1984 and 1988 at a synoptic climatological station, installed approximately 2 km northeast of the basin (Chevallier, 1988); the annual mean is 1600 mm. Precipitation only exceeds potential evapotranspiration during the period from June to September. Comparison of these observations with water storage in the non-saturated soil zone (measured with a neutron moisture probe) shows that these four months correspond to the only period in which non-saturated storage increases continuously. Except for this period, a balance is established between storage in the unsaturated zone, flow and loss by actual evapotranspiration.

Materials and methods

Soil scientists and hydrologists usually study pedogenetic phenomena or flow production on a hillslope scale, taking into account spatial and dynamic evolution from the top of the slope to the valley bottom where subsurface flows and surface runoffs are concentrated (Kirkby, 1978). This catenary concept was adopted as the basis for the instrumental network installed at Booro-Borotou.

Runoff production: rainfall simulation

Infiltration of simulated rainfall was studied on 1 m^2 plots, distributed throughout the watershed, using a small simulator for storm intensities between 30 and 150 mm h^{-1}, taking into account the size and kinetic energy of natural raindrops (Asseline and Valentin, 1978). Simulations were repeated in different seasons, on different soils and with different storm sequences (Valentin et al., 1990).

Surface flow: mini-traps

Since the beginning of the study of the Booro-Borotou basin, surface runoff from the upper or middle areas of the basin was observed to infiltrate before reaching the water course. In an attempt to describe this phenomenon, runoff gauges, called mini-traps, were installed. The principle is simple. A furrow 30 cm long, perpendicular to the slope, collects in a 60 l tank the water which runs across the furrow. These traps allow observations of non-concentrated flows. However, since collection over a length of 30 cm can not be considered representative of unit flow through a contour line, the precise location of each trap is very important. An initial site was chosen in an exact topographic survey. The definitive site was decided during or immediately after a storm event, by looking for traces of heavy surface runoff close to chosen points. Two basin slopes were equipped, the ‘savanna site’ with 12 such traps in an open uncultivated savanna, and the ‘field site’ with 14 traps in a rice field (Fig. 4).

The precise volume collected in each tank is difficult to interpret owing to the small size of the device, which makes it sensitive to local conditions.

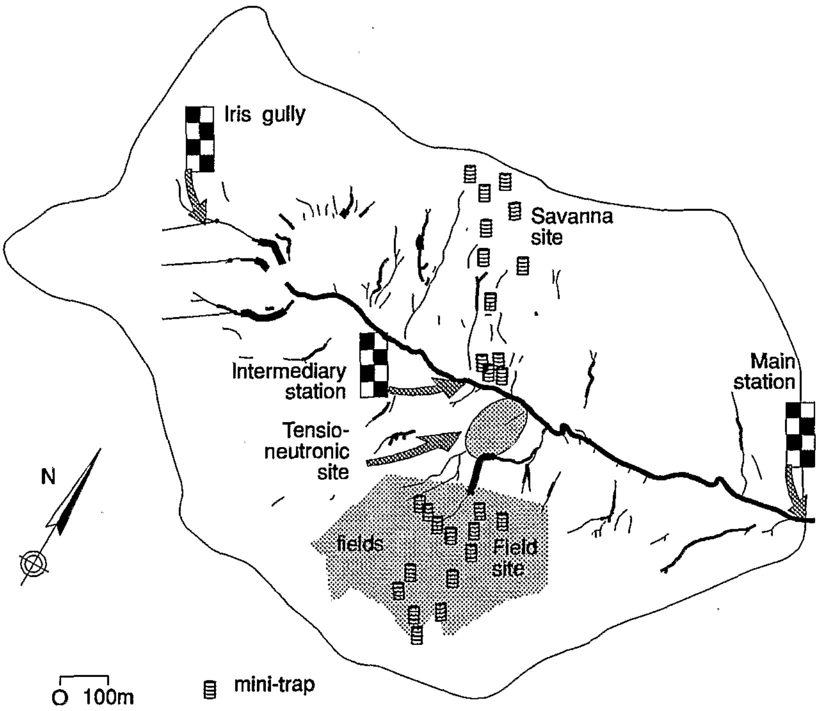


Fig. 4. Location map of the mini-trap sites, sites of tensiometers and access tubes, and water gauge station.

Furthermore the trap creates an obstacle on the slope line, so that the true length of collection is greater than the trap length. Therefore, the quantitative interpretation of results is doubtful scientifically. More recent experiments performed in Burkina Faso by one of the authors, using 1 m^3, 200 and 60 l tanks, showed that the volume collected did not lead to significant differences in results. Therefore it would be useful to know how often, during a rainy season, the tank was found to be empty, to be partially filled or to have overflowed. The results are evaluated qualitatively, as a percentage of all the storm events of a rainy season together, for each of the mini-traps. The interpretation of these results is based on the following principles.

(1) If a given storm leaves a tank empty, this could be either because no runoff occurred higher up the slope or because runoff occurred but infiltrated before reaching the tank. Therefore, an empty tank following a storm can only be interpreted as a local property of the site, giving in effect the site's infiltration capacity.

(2) If the volume of water collected is less than 60 l, it cannot be attributed to generalized runoff. This means simply that the local infiltration capacity is exhausted.

(3) If a given storm causes the tank to overflow, this occurrence must

depend both on the local infiltration capacity and on its position on the slope. All other factors being equal, a mini-trap at the bottom of a slope should overflow more often than one at the top.

Interflow: piezometers, neutronic tubes and tensiometers

The subsurface hydrodynamic functioning has been studied at the bottom of the slope in a secondary depression perpendicular to the axis of the main valley (Fig. 4). Five measuring sites were equipped with a set of tensiometers, one piezometer and an access tube over 2 m deep for a neutron probe. Studies of general pedological structure (Fritsch et al., 1990a) showed that, at the hillslope bottom and in the valley bottom of the Booro-Borotou basin, a large sandy reservoir exists which may follow the slope up to the mid-slope break. This reservoir crops out on the soil surface in the lowest part of the basin. This type of sand pocket, with great interstitial macroporosity, favors rapid movement of the stored water, conversely to what happens in clay or clay–sand soils with greater overall storage, where transport is limited by the micropore structure.

Riverflow: hydrometric stations

River flows are recorded at two gauging stations (Fig. 4): (1) the main station which commands the total surface of the basin (1.36 km^2); (2) an intermediary station which controls surface runoffs at the head of the basin (0.45 km^2).

The base flow in these stations appears after the beginning of the rainy season, when the level of the groundwater table is sufficient to recharge the river. This flow is usually interrupted in December or January. Bush fires in the basin prolong this flow for several weeks and maintain the water table level in the talweg (Chevallier, 1991). Not all of these storm events cause floods. The shapes of the flood hydrographs vary according to the initial conditions of the basin and the storm characteristics. On average, 1.5% of the annual precipitation runs off in the form of floods and 6.3% is base flow; the rest is mainly lost to evapotranspiration.

Results

Rainfall simulation

The rainfall simulation experiments showed that infiltration varied according to the distance along the hillslope to the channel axis (Table 1).

Table 1
Infiltration index of simulated rainfalls versus distance from the main channel axis

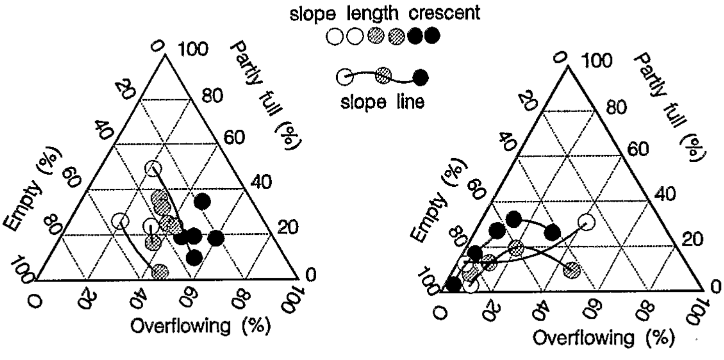
Distance from the main channel axis (m)	Infiltration index (%)	
	February (dry season): worked soil	November (end of rainy season): natural soil
30	99	88
48	96	84
78	93	80
109	88	71
130	88	40
143	65	43
235	42	45
287	55	52
309	78	65
326	66	61
361	96	98
417	70	97

The infiltration coefficient of the simulated rainfall diminished from between 90 and 100% to 40% over a distance of 0 to 200 m, and increased from 40 to 100% between the 200 m line and the top of the hillslope. This characteristic distance of 200 m corresponds precisely to the mid-hillslope break, and to the hardened ferruginous soils where infiltration conditions are not nearly as good as those of the red ferralithic soils on the heights of well-structured hillslopes, or those of soils at the sandy hillslope bottom, where fauna are most active and the surface crust is absent.

However, knowledge of runoff derived from 1 m^2 plots does not automatically allow the hydrological response of the entire hillslope to be determined. Combination of such results and their extrapolation to the basin scale gave good results in semi-arid regions, when flow processes were ignored (Albergel, 1987; Casenave and Valentin, 1992); however, the context was one where runoff coefficients were high on relatively homogeneous surfaces, with increasing impermeability from upstream to downstream and no roughness. These conditions do not apply at Booro-Borotou, where hillslopes present minimum infiltrability at mid-slope.

Mini-traps

The results of the 1987 rainy season obtained at the two main measuring sites are reported on triangular charts (Fig. 5). Each dot represents a mini-trap.



(a) Field site

(b) Savanna Site

Fig. 5. Mini-traps: observation results.

The position on the chart indicates the percentage of storms during the rainy season, in which the trap was empty, partially filled (i.e. with a volume less than 60 l) or overflowing. The mini-traps at the top of the slope are represented by a white dot and those at the bottom by a black dot. The mini-traps on the same slope line are linked by a fine line, when the runoff has not been disturbed crossing a farm road.

The field site represents only 7% of the basin surface. It is noted that the closer mini-traps are to the bottom of the slope, the more often they overflow, whereas the percentage of empty mini-traps lies between 20 and 60%. It is a homogeneous site, installed in the upper part of the basin, upstream from the slope break. Experimentation shows that runoff is accumulated over the site; if the water does not infiltrate upon reaching its point of impact on the soil, it is unlikely to infiltrate during its later course downstream.

The savanna site, on the other hand, is much more heterogeneous, and the proportion of empty mini-traps is between 70 and 100%. This reflects the variety of surface features and soils at the site. Furthermore, all measuring points are in the corner of the triangle which corresponds to ‘often empty, rarely overflowing’. Finally, the results do not follow any pattern related to position along the slope. Therefore, it is a heterogeneous and generally permeable site, in which no generalized runoff is seen — the runoff produced at one place in the basin may infiltrate lower down, either because it uses the heterogeneous environment for this purpose or because it arrives at a more permeable zone. Thus, the following paradoxical result occurs: whereas the results obtained with simulated rainfall and fine analyses of soil surface features show a strong local tendency to runoff, this is still limited in general to the whole basin by zones favoring later infiltration, especially in sandy soils in the lower part of the slope.

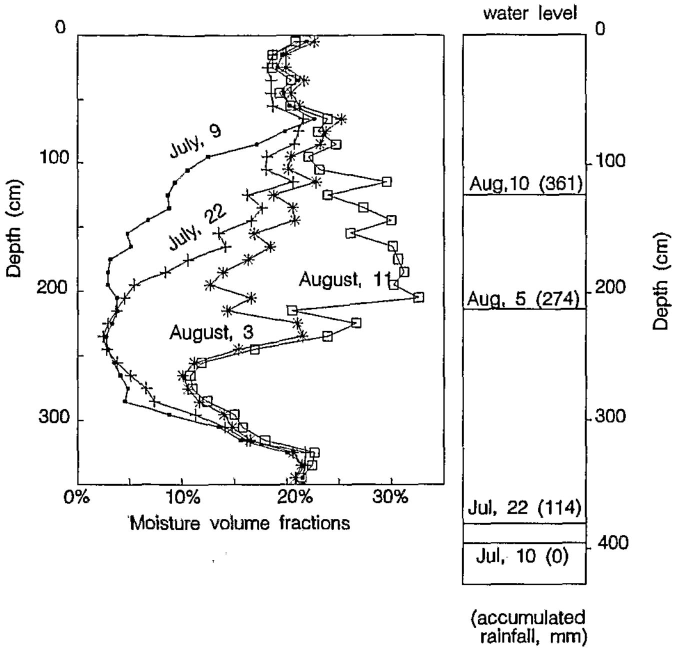


Fig. 6. Rainy season observations (1985) at site 8; moisture volume fractions and precipitation.

Tensiometers, neutrons probe access sites and piezometer sites

The study of moisture profiles measured at sites equipped with access tubes, piezometers and tensiometers, demonstrates the existence of two types of processes (Fritsch et al., 1990b). A particularly good example (Fig. 6) is given by a site midway between the slope break and the watercourse, with clay–sand horizons to the first 125 cm, overlying a sandy reservoir up to a depth of 285 cm, with an impervious clay floor below 335 cm. At the beginning of the rainy season, the surface horizons are found to be almost saturated, and the wetting front descends slowly (over three months). This corresponds to the first type of process in clay. At the end of the rainy season, very rapid saturation occurs through the bottom (clay floor) of the sandy reservoir which in 1985 became completely saturated in three weeks. In this second type of process the wetting front moves in the opposite direction, rising instead of descending. Furthermore, at the time of this recharge, water storage increases by more than rainfall input (Chevallier, 1988). Inflow must therefore take place upstream laterally, through concentrated flow channels; this is confirmed by the forms of chemical degradation of the soil (which loses iron and clay).

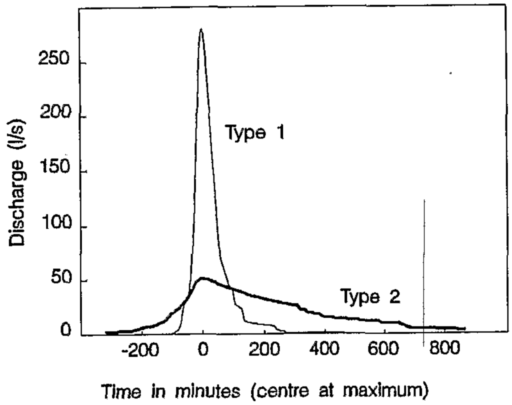


Fig. 7. Main station, standard floods hydrographs.

Finally, the possibility of saturation of outcropping or suboutcropping sandy soils in the valley bottom is noted, and, consequently, the formation of a variable contributing area (according to Hewlett and Hibbert, 1967), in which, necessarily, rapid surface runoff occurs.

Floods

A ‘flood’ is defined here as a significant flow increase at the outlet of a basin following either an isolated precipitation event, or a rapid succession of separate precipitation events. Over four years of study, 87 events were identified, 30 of which had flows with a total volume higher than 0.5 mm and a single peak (Table 2).

For each flood, a reduced unit hydrograph was built up by: (1) scaling on the discharge axis to obtain a total flood volume of 1 mm; (2) fixing the zero of the time axis at the instant of the flood peak. By examining these hydrographs, different shapes, which can be used to identify extremes, can be observed (Fig. 7). This unit hydrograph does not correspond to the model proposed by Sherman (1941), because, even if it corresponds to a single storm, this is not necessarily rectangular, nor does it last less than the watershed concentration time.

A logical approach is to relate these flood shapes to particular processes within the basin by which rainfall is transformed into runoff, and thence to flow paths which are more efficient, for each storm type, in transporting flow to the catchment outlet. It is observed that the shape of flood does not vary with position along the channel — the types of flood observed at the basin outlet, and those observed at a hydrological substation, lying in the upstream third of the watercourse, are similar. The type of functioning is

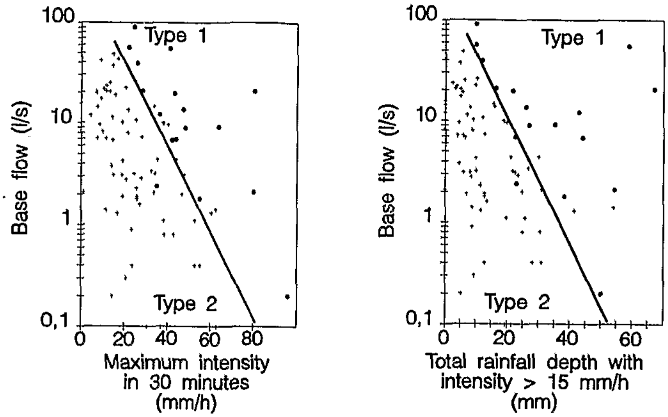


Fig. 8. Dependence of flood shape on rainfall characteristics and base flow.

therefore determined as long as the hillslope/valley bottom continuum is active.

A principal components analysis did not permit flood shape to be associated satisfactorily with factors describing precipitation (duration, shape, intensity) or the receiving environment (base flow, antecedent precipitation index, duration of soil water movement). However, it is possible to distinguish between the floods with shapes at either end of the range by taking into account (1) the base flow, and (2) the maximum storm intensity in 30 min, or the depth of the storm occurring at intensities above 15 mm h^{-1} (Fig. 8). This shows clearly that flood shape is related closely to the state of the groundwater reservoir when this is involved, considering that the base runoff is directly correlated with water table level, which is confirmed by piezometric observations.

Discussion

Both rainfall simulation and mini-traps show the variability of infiltration in the basin, not only of local infiltration but especially of infiltration of part or all of the surface runoff which began further upslope. What becomes of this water? What are the infiltration processes? The influence of vegetation is definitely dominant. The plant cover on the soil creates a micro-relief through which the surface runoff must find its way. Furthermore, even though the soils are generally supposed to be homogeneous, a very heterogeneous distribution of pore openings can be observed on the surface.

(1) On the summits of the micro-reliefs, formed by herbaceous tufts, there is an absence of a crust formation and the presence of macropores resulting from faunal activity (Tano and Lepage, 1990), which makes soils particularly permeable.

Table 2
Selected events for analysis of the floods

Date	Flood volume (mm)	Peak of discharge ($l\,s^{-1}$)	Flood duration (min)	Flood shape	Base flow ($l\,s^{-1}$)	Precipitation volume (mm)	Precipitation duration (min)	Intensity in 30 min ($mm\,h^{-1}$)
18 August 1985	11.10	4150	148	1	20.5	82.7	304	80.4
21 August 1987	4.03	1260	566	1	2.06	55.0	205	80.2
27 September 1987	2.60	1050	189	1	9.11	42.4	275	64.0
3 August 1985	1.89	466	394	1	6.75	54.8	431	41.9
30 August 1985	1.78	315	349	1	13.5	45.6	182	47.2
14 September 1984	1.73	183	492	2	4.4	57.0	254	35.1
5 August 1985	1.58	570	205	1	12.1	43.4	289	26.0
16 June 1984	1.56	682	201	1	0.19	56.4	200	95.7
13 September 1986	1.30	201	558	2	3.44	40.0	149	32.4
27 July 1985	1.25	466	218	1	1.81	54.4	222	38.3
31 August 1987	1.20	115	859	2	7.98	31.2	300	21.7
1 September 1984	1.13	61.9	836	2	2.75	41.8	489	21.0
31 October 1985	1.09	70.7	884	2	7.08	28.3	(–)[a]	11.4
11 July 1985	1.04	265	343	1	2.40	33.7	148	35.0

15 August 1987	1.00	65.5	1041	2	0.45	52.5	327	52.6
3 September 1985	0.92	119	550	2	20.5	35.6	331	(–)[a]
12 September 1985	0.88	173	363	1	19.6	24.8	54	43.0
13 August 1985	0.85	119	420	2	13.8	32.1	331	31.4
29 September 1987	0.84	201	328	1	20.8	19.9	50	28.1
17 October 1984	0.82	111	479	2	2.06	39.7	153	33.7
12 October 1987	0.79	60.5	160	2	10.2	22.5	215	19.3
2 September 1987	0.79	63.7	963	2	10.7	20.4	179	25.4
2 October 1984	0.76	131	445	2	3.13	34.8	279	47.7
8 October 1987	0.69	63.5	1009	2	11.9	18.9	161	(–)[a]
30 September 1986	0.66	44.9	1281	2	2.00	29.4	172	46.6
4 September 1985	0.62	442	114	2	91.0	16.7	207	24.4
20 June 1987	0.60	136	363	2	0.00	70.1	252	73.7
17 August 1987	0.52	23.7	1273	2	2.32	24.2	256	25.6
3 September 1987	0.51	66.9	766	2	19.00	14.4	208	15.9
12 September 1986	0.50	18.4	1513	2	1.56	19.6	149	27.2

[a] Malfunction in recorder system.

(2) Between these reliefs there is a surface crust favoring surface runoff.

Depending on the depth of the surface flow and therefore storm intensity but also on micro-relief, density, infiltration or runoff may be alternately favored.

Boundaries defining characteristics of relief, soil, surface features and vegetation do not coincide, and spatial variability is more complex than the toposequential organization usually adopted to model processes producing flow. At Booro-Borotou, runoff is determined by processes in three areas:

(1) in the heavily wooded zones at the top of the hillslope where plant cover and micro-relief do not have much influence and there is great infiltrability (northern half of the left bank, and uncultivated part of the right bank). However, the probable interception of rainfall by vegetation may be important here and it has not been measured. This area has very little or no surface flow;

(2) in the limited forested zones on the east part of the left bank, and mid-hillslope, where infiltrability is much lower. Here the surface flow infiltrates into the sandy soils (stop strip), before rejoining the main watercourse;

(3) in the cultivated part, where there is abundant surface flow, which may enter the main watercourse.

Downstream from the slope break, another factor, which hitherto has had only limited effect, comes into play: flow concentration. Almost 80 routes were counted in which runoff is concentrated within the catchment, ranging from small gullies to much larger channels, all of them beginning in mid-hillslope. Flow measurement devices placed on the beds of these routes showed that all are actually functional; within them, the heaviest discharge comes at the head of the incision, with rapid infiltration of the flow further downstream, discharge always disappearing before reaching the valley bottom.

The water table in the sandy reservoir of the hillslope bottom is the key to discharge at the basin outlet. There are very rapid fluctuations:

(1) surface runoff is formed upstream from the mid-hillslope break and infiltrates downstream into the drainage system or into the stop strip;

(2) natural and fauna-made macropores give rise to very high hydraulic conductivity, as shown by measurements under simulated rainfall.

This rapidity was confirmed by experiments with dye tracing of surface runoff. Dye (Rhodamine) was injected into a small gully (Iris gully, Fig. 4) at the head of the basin. Propagation of the tracer was followed visually along the gully. The dyed runoff disappeared by infiltration approximately 300 m before reaching the watercourse. During this same period, the base level in the valley bottom increased rapidly but steadily and the flooded zone advanced 100 m. The dye never reappeared. This experiment was performed twice in 1987 within a few days; in both cases the observed flood was peaked.

In the more humid context of Australian tropical forest, Bonell et al. (1981) observed that the form of surface runoff was closely related to storm intensity and to soil storage capacity in the surface horizons. These authors recorded extremely rapid water table fluctuations during storms, but also observed that the component of the hydrograph usually associated with the surface runoff included a component of 'subsurface storm flow'. The observations performed in the lower part of the basin at Booro-Borotou may reasonably be compared to Australian measurements with rapid flows which do not come from a direct general surface runoff. The rapid variations of piezometric levels in the sandy reservoirs lead one to think rather of what Ragan (1968) called the 'groundwater ridge effect' or Hewlett and Hibbert's 'translatory flow' (1967). Certainly, as in the Australian case, there is a complex combination of these effects with necessarily schematic theoretical descriptions; continuous automatic recording of piezometric levels is unfortunately lacking at Booro-Borotou to confirm these hypotheses. However, the infiltration of surface runoffs from upstream in the lower part of the basin may modify the state of the water table in a rapid, transient fashion. This causes a rapid extension of the surface which is saturated during the storm, although different from the soil topography index distribution (Beven and Kirkby, 1979).

Exceptionally, a direct contribution from the basin may arrive at the watercourse, particularly from the cultivated area, where, as has been noted, abundant surface runoff is produced. This was found on the occasion of a new tracing experiment in the gully coming from the fields, and the rapid transmission of dye to the basin outlet was clearly observed. It shows therefore that the flow processes are particularly complex since it is not only the surface flow which explains the peaked shape of certain floods.

Conclusion

This paper describes in some detail the behavior of a single hydrological system, which owing to its small size, might be expected to be very simple. Despite its small size, however, flow may take all possible paths identified by modern hydrology (Dunne, 1978; Beven, 1988): surface runoff in the sense of Horton (1933), overland flow from variable contributing areas, base flow supplied by the aquifer, or different types of rapid internal flows. These water paths are not exclusive, and may be combined according to the storm shape and the state of the receiving environment.

To understand the associated actions of the hillslopes, the groundwater storage and channel discharge, for evaluating or modeling the water resources and for the calculation of exceptional events, it is necessary to define the flow production mechanisms.

Acknowledgments

This paper was translated into English by Professors Hedy L. Hofmann and Robin T. Clarke of the Hydraulic Research Institute of the Federal University of Rio Grande do Sul in Porto Alegre (Brazil).

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REPRINTED FROM:

JOURNAL OF HYDROLOGY

Journal of Hydrology, 151 (1993) 173–191
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Hydrological processes in a small humid savanna basin (Ivory Coast)

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(Received 14 August 1992; revision accepted 29 March 1993)

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