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The hydrology of inland valleys in the sub-humid zone of West Africa: rainfall-runoff processes in the M'bé experimental watershed

Mutsa C. Masiyandima,[1†] Nick van de Giesen,[2] Sitapha Diatta,[3] Pieter N. Windmeijer[4] and Tammo S. Steenhuis[1]*

[1] *Department of Biological and Environmental Engineering, 226 Riley–Robb Hall, Cornell University, Ithaca NY 14853, USA*
[2] *Center for Development Research, Bonn University, Walter-Flex-Str. 3, D-53113, Bonn, Germany*
[3] *West Africa Rice Development Association, 01 B.P. 2551, Bouaké 01, Côte d'Ivoire*
[4] *Research Strategy, Wageningen University, Postbus 9101, 6700 HB Wageningen, The Netherlands*

Abstract:

Inland valleys with wet lowlands are an important water source for farming communities in the sub-humid zone of West Africa. An inland valley and surrounding contributing watershed area located in the sub-humid zone near M'bé in central Côte d'Ivoire was instrumented to study surface runoff and base flow mechanisms. Four flumes at different distances down the main stream and more than 100 piezometers were installed. Measurements were taken during two rainfall seasons in 1998 and 1999. Under initial wet conditions, a typical single-peak hydrograph was observed. Under low antecedent moisture conditions, however, runoff was characterized by a double-peaked hydrograph. The first peak, which occurred during the storm, was caused by rain falling on the saturated valley bottom. The second peak was delayed by minutes to hours from the first peak and consisted of rain flowing via the subsurface of the hydromorphic zone that surrounds the valley bottom. The duration of the delay was a function of the water table depth in the hydromorphic zone before the storm. The volume of the second peak constituted the largest portion of the stream flow.

KEY WORDS surface runoff; shallow groundwater; peak flow; inland valleys; West Africa; variable source area hydrology; double hydrographs; saturation excess overland flow

INTRODUCTION

Runoff water is of particular importance to rice-based farming systems in the sub-humid region of West Africa. Water is detained on the field for supplementary irrigation of crops. When in excess, water has to be channelled off the fields in order to avoid crop damage. Predicting the rainfall-runoff processes as a function of watershed characteristics is important for proper water management.

Knowledge of the processes involved in runoff generation and the conversion of rainfall to stream flow has slowly evolved since Horton (1933) identified one of the 'principal components' of stream flow in which storm runoff occurs when the rainfall intensity is in excess of the infiltration rate. Hursch (1936) later identified the other 'principal component' as subsurface storm flow. Since that time, it has become obvious that storm flow consists of portions of both principal components. Many field studies have been conducted to identify the portions of each using hydrograph separation techniques (Burns *et al.*, 2001). Initially, graphical techniques were popular for hydrograph separation (de Zeeuw, 1983), but, during the last 30–40 years, separation techniques involving isotopes (Crouzet *et al.*, 1970), chemical tracers (Hooper and Shoemaker,

* Correspondence to: Tammo S. Steenhuis, Cornell University, Department of Biological and Environmental Engineering, 226 Riley–Robb Hall, Ithaca, NY 14853, USA. E-mail: tss1@cornell.edu
† Currently at International Water Management Institute, Private Bag X813, Silverton 0127, South Africa.

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1986; Caine, 1989), and stream temperature (Kobayashi, 1985) have been used extensively to distinguish the old water (or subsurface flow) from the new water (or precipitation). However, the validity of this technique in the absence of supporting hydrometric measurements is increasingly being questioned (Buttle and Peters, 1997; Buttle, 2001). A promising new method for determining old and new water components is the 'data-based mechanistic' (DBM) modelling approach introduced by Mwakalila *et al.* (2001). DBM modelling is especially well suited for the tropics, since it requires no prior knowledge of the hydrological system. This is important, considering that most hydrological research has taken place in the temperate climate zone and the hydrological knowledge of the tropics has stayed far behind (Chevallier and Planchon, 1993; van de Giesen *et al.*, 2000).

In the past, hydrological research in West Africa has focused on flood frequency analysis (Rodier and Auvray, 1965) and surface conditions under which runoff is generated (Casenave and Valentin, 1992). A double-peaked hydrograph observed in northern Côte d'Ivoire by Dubreuil (1960, 1985) has generated strong interest among hydrologists. Double, or delayed, hydrographs have also been observed in western Japan for a shale and serpine watershed (Onda *et al.*, 2001), as well as in the low-relief hillslopes with thick colluvium in Somerset, UK (Anderson and Burt, 1978; Weyman, 1974 quoted by Onda *et al.*, 2001; Calver *et al.*, 1972 quoted by Dunne, 1978). Anderson and Burt (1978) also noted that, in the Dunne and Black (1970) experiments in Sleepers River Catchment in northeastern USA, the subsurface flow produced a small delayed response after the first peak. Both Anderson and Burt (1978) and Chevallier and Planchon (1993) noted that the second discharge peak coincided with the highest rise of groundwater to the surface. However, in neither case, is the exact mechanism for the second peak well understood (Casenave, 1978; Lafforgue, 1982; Dubreuil, 1985).

The two processes of surface runoff generation are saturation overland flow and infiltration excess runoff (Dunne and Black, 1970; Dunne, 1978; Moore *et al.*, 1986; Hibbert and Troendle, 1987). In the sub-humid zone in West Africa, infiltration rates are generally high and the storm duration short. Most of the infiltration excess infiltrates after the storm ends and before it reaches an open water body. As a result, infiltration excess runoff hardly contributes to total stream flow (van de Giesen *et al.*, 2000). In addition, the valley bottom fringe, or hydromorphic zone, of inland valleys has a low water-holding capacity. Soil in the valley bottom rapidly becomes saturated during a storm (Dubreuil, 1985), sometimes expanding the saturated valley bottom area. Further rainfall on the saturated area results in saturation overland flow. This process, which has been described in reference to temperate regions, is variable in time and space, and is also referred to as the 'variable source area' process (Frankenberger *et al.*, 1999).

The current study was carried out in the M'bé experimental watershed, located in central Côte d'Ivoire. The sloping impermeable layer that is present in most inland valleys (such as the M'bé experimental watershed) facilitates subsurface flow processes (Sloan and Moore, 1984). The impermeable layer restricts vertical flow, resulting in water accumulation and the build up of a perched water table, and, eventually, the development of subsurface flow towards the valley bottom. This subsurface flow is an important part of the runoff volume and plays a major role in agricultural water management, particularly in lowland rice production. In this paper, the subsurface flow process from the M'bé experimental watershed is described, explaining the double hydrograph. Stream discharge measurements are compared with corresponding groundwater levels in the valley bottom and on the side slopes.

METHODS

Description of the study site

Observations of runoff were made in the M'bé experimental watershed located in central Côte d'Ivoire (7°52′N, 5°06′W), about 400 km north of Abidjan (Figure 1). The watershed has an area of 130 ha and is about 1 km wide along most of its length. It is comprised of a valley bottom that is inundated in the rainy season, a hydromorphic zone with shallow groundwater, and drier upland areas. The inundated valley bottom area is about 1200 m long with a width from about 20 m in the valley head to over 50 m at the outlet. Altitude in the watershed ranges from approximately 265 m above sea level (a.s.l.) in the valley bottom to approximately 310 m a.s.l. at the crests. Land use includes areas under natural grass fallow, forest, and rain-fed and irrigated rice cultivation.

On the basis of rainfall distribution, three rainfall regimes are distinguished in the Côte d'Ivoire. These are: the bimodal regime, with two rainfall seasons in the south; the pseudo-bimodal regime in the centre; and the monomodal regime, with one distinct rainfall peak in the north (Figure 1). The rainfall pattern at M'bé is pseudo-bimodal with a rainfall peak from April to August, followed by the short dry season and then the second rainfall season from September to November. The 70 year (1923–93) mean annual rainfall for Bouaké Airport, located 15 km southeast of the watershed, is 1139 mm. Mean annual rainfall for the M'bé experimental watershed for the period from 1992, when the site was first commissioned, to 1999 is 967 mm. Rainstorms are usually very intense and last less than 30 min.

The watershed cross-section from the upland to the valley bottom (Figure 2) comprises four major physiographic units. The uplands or crests comprise the interfluves, with flat to almost flat slopes (0–2%), and gentle upper and mid slopes of 2–4%. The slopes overlie a fairly impermeable iron pan (cuirasse) at about 80–120 cm below the surface. The cuirasse is very close to the surface at the edge of the uplands and appears as a shoulder outcrop in some locations. Its lateral extent and continuity are not well established. Closer to the valley bottom is the hydromorphic zone, with a width of 25–50 m. In this area, there is an impermeable clay layer at a depth of about 1·5–2 m. The hydromorphic zone has flat to gentle slopes (1–4%). Generally, this zone is moist and has high perched groundwater levels for most of the rainfall season. The valley bottom area is almost flat, with slopes less than 1%. It forms an ephemeral stream that is also the central drainage channel for the watershed. In this zone, the perched groundwater table is close to the surface. Since the surface is saturated during the rainfall season and the piezometric head in the deep groundwater is slightly above the perched groundwater, it is likely that the perched and deep groundwater are connected through the shallow clay layer at a few locations.

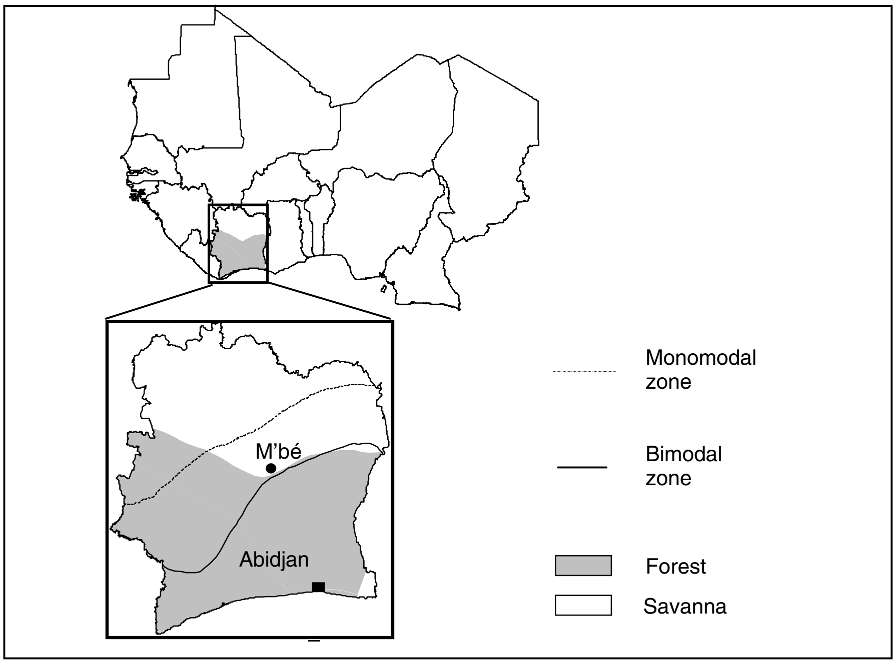

Figure 1. Map of Côte d'Ivoire showing the location of the M'bé experimental watershed

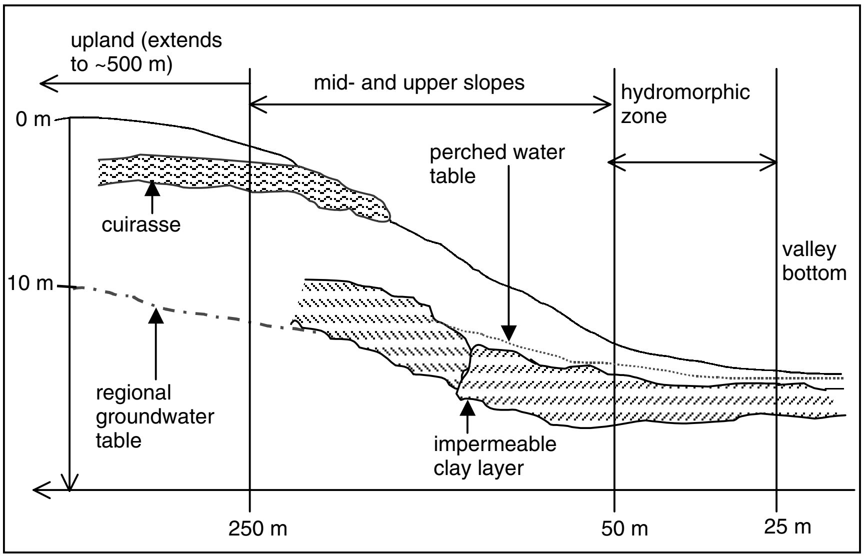

Figure 2. Schematic cross section of the M'bé experimental watershed showing the upland, slope, hydromorphic, and valley bottom areas during the rain season (not to scale)

Spatial variability of soils in the watershed is more pronounced in the transition from uplands to the valley bottom than along the length of the watershed (Hakkeling *et al.*, 1989). The uplands consist mainly of deep, well-drained sandy clay to clay soil with a weak sub-angular blocky structure. On the slopes, there are well-drained loamy and sandy soils overlying the impermeable cuirasse. In the hydromorphic zone, soils are predominantly sandy, with a high hydraulic conductivity of around 10 m day^{-1} and low drainable porosity. The valley bottom has a thick clayey surface layer overlying a sandy layer.

Hydrometric data

From the beginning of 1998 through October 1999, discharge, rainfall amounts, and depth to groundwater were measured in the M'bé experimental watershed. Discharge was measured at four stations in the valley bottom using H-flumes located at approximately 400 m, 775 m, 900 m, and 1200 m from the valley head (locations F1, F2, F3, and F4 respectively in Figure 3). The valley head was taken as the most upstream point where saturated conditions exist during the rainfall season. Measurements at gauge F1 were started in April 1998 after the onset of rainfall. Owing to delays in instrument installations, stream flow measurements at gauges F2 to F4 began in June 1998. Water height in the flumes was measured twice daily and the average was taken as the daily runoff rate. The majority of the rainstorms occurred at night. Consequently, most of the peak flow rates were not observed. In 1998, partial stream flow records were obtained for three storm events with more than 20 mm of rain, when discharge measurements were taken at 30 min intervals during the day in order to capture the prolonged high flow rates.

Between 27 September and 8 October 1999, a continuous flow recorder was used to obtain continuous runoff records at measuring station F2. Flow records for five runoff events were obtained. During this period, perched groundwater levels were also measured continuously in the hydromorphic zone at 25 m and 50 m from the valley bottom, and on the slopes at 100 m from the valley bottom (piezometers W1, W2, and W3 respectively in Figure 3). The perched water table height is measured in the valley bottom near the F3 measuring station (piezometer W4 in Figure 3).

In 1998, rainfall was measured in the watershed with a recording rain gauge. In 1999, this gauge malfunctioned and only total daily rainfall amounts were available at three locations in the watershed (P1, P2, and P3 in Figure 3). Rainfall intensities were also recorded 1 km from the site. This gauge gave the

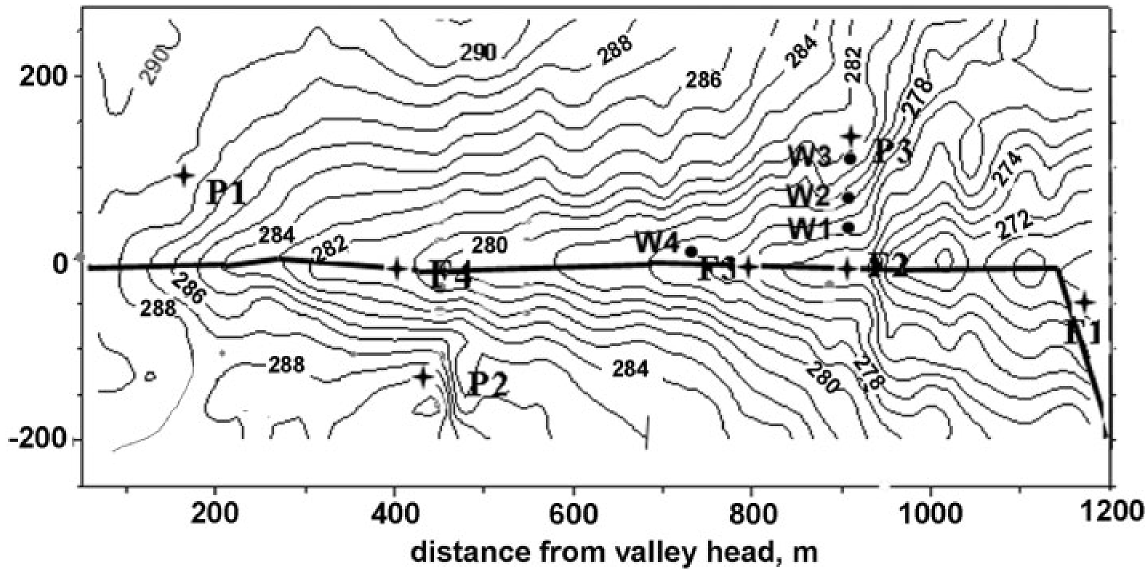

Figure 3. Topographic map and instrument location for the central part of the M'bé experimental watershed. P1, P2, and P3 are the locations of the rain gauges. W1, W2, W3, and W4 are the piezometer locations. F1, F2, F3, and F4 are the locations of the stream discharge measurements

approximate start of the rainstorm but not the rainfall distribution, because the rainstorms were convective with large spatial variation in rainfall over short distances.

Since the direct runoff and subsurface flow patterns for the M'bé experimental watershed were unique, it was impossible to apply standard hydrograph separation techniques. Therefore, we applied the method of de Zeeuw (1983), in which the estimated contributions of direct runoff and subsurface runoff were summed up to give the total observed discharge. This implies that the estimated overland discharge deviates from the observed total discharge as soon as the subsurface flow starts. Also, the estimated subsurface discharge is only equal to the total discharge when the overland flow component becomes negligible. Since the beginning of the subsurface flow and the end of the surface flow are not known, this method involves a considerable amount of judgement. However, as will become obvious later, the differences in relative proportions of estimates of overland and subsurface flow are small as a result of the individual choices of ending and starting points.

RESULTS

The total rainfall of 1045 mm in 1998 was relatively large. Stream flow from the watershed started on 23 April, after a cumulative rainfall of 203 mm had fallen (Figure 4a). The stream stopped flowing at the end of November 1998, approximately 1 month after the end of the rainfall season (Figure 4). The response of all four stream gauges is similar. The discharge for each gauge scales approximately with the distance to the valley head. The 1999 season was fairly dry and there was little runoff before 15 August (Figure 4). The total runoff computed from the daily average stream discharge was about 40×10^3 m^3 in 1998, or a yield of 3%. On 1 October 1999 the total stream flow was only 7×10^3 m^3, or slightly more than a 1% yield. The water yield for 1998 is conservative, as it was based on two readings during the day, whereas peak runoff occurred during the night. A large number of storms that caused runoff occurred during the night time; as a result, the high flow recorded the next morning did not indicate peak outflow. Figure 5 shows the three rainfall–runoff records for the F2 flume in detail for 1998, in which the rain started during the day and for which partial runoff records existed up to 5 p.m. The peaks for the three storms occurred at approximately the same time

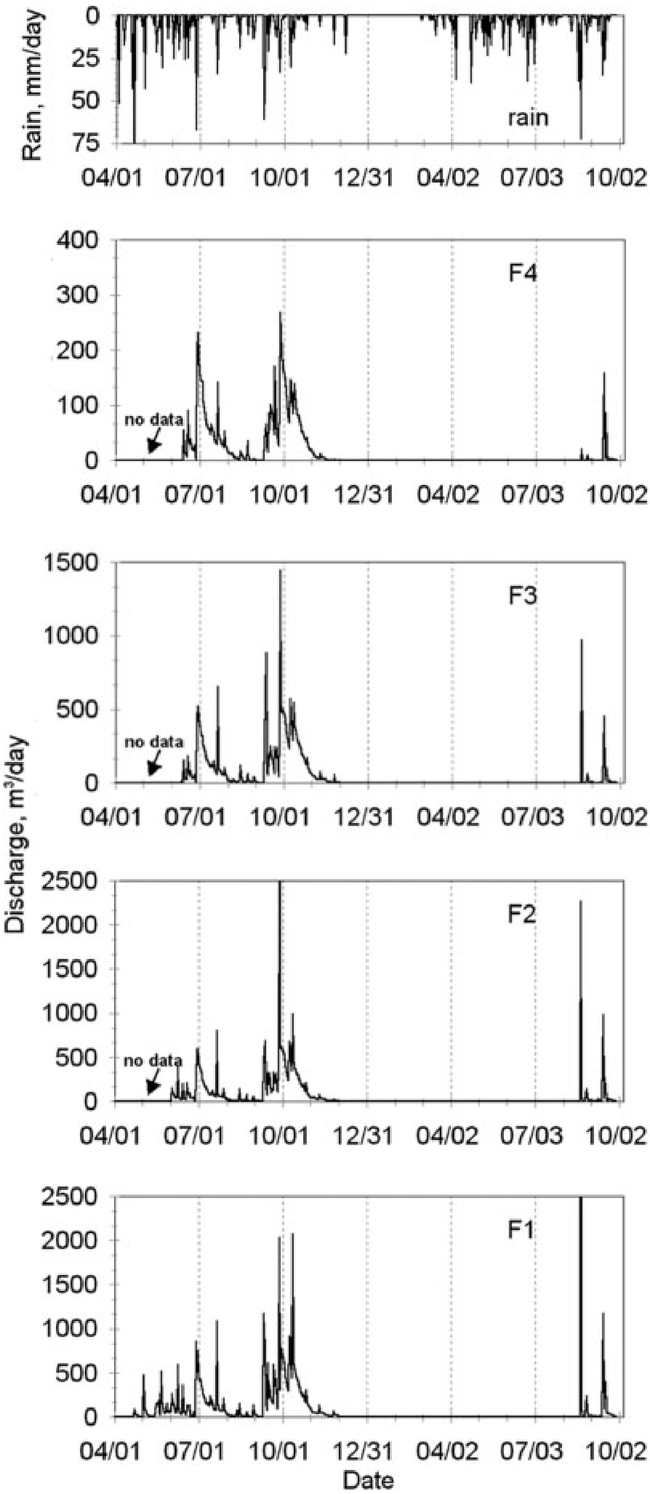

Figure 4. Stream discharge and rainfall at locations F1, F2, F3, and F4 in Figure 3

and were within the measurement intervals. The initial rapid recession of the stream flow hydrograph from peak flow for all three storms was striking. Only the 12 October 1998 event had a long enough record to show that the flow started to increase again after the initial rapid decline, resulting in a second peak without accompanying rainfall.

Continuous runoff response to the five rainstorms between 27 September and 8 October 1999 (Figure 6) were in agreement with the observation of the three incomplete flow records from 1998. Runoff was only observed at F2 in the valley bottom because of lack of additional pressure transducers. The rainfall totals for runoff events A, B, C, D, and E were 21 mm, 38 mm, 18 mm, 7 mm, and 8 mm respectively. The average duration of each rainstorm was estimated to be 30 min, but this may have been longer as no recording rain gauge was available at the site. A double-peak hydrograph resulted from the first three rainstorms, with the first peak generated during or soon after cessation of rainfall and the second up to 5 h after the rainstorm had passed. Event A, on 29 September 1999, followed a 10 day dry period during which the groundwater had receded to minimum levels. Two discharge peaks were observed, with the second peak about 5 h after the first (Figure 6a). The broad hydrograph of the first peak indicates that the storm duration probably was longer than the estimated 30 min. Event B was observed 3 days later at the same gauging station for 38 mm of rainfall (Figure 6b). The delay to the peak of the second runoff pulse was 2·5 h. For event C, on 4 October, 18 mm of rainfall was recorded (Figure 6c). The second pulse delay was 4 h. However, as discussed later, the sudden decrease in discharge after the second peak was attributed to a temporary blockage of the flume and the actual delay was more likely 1·5 h. For runoff events D and E, on 6 and 7 October, the rainfall was

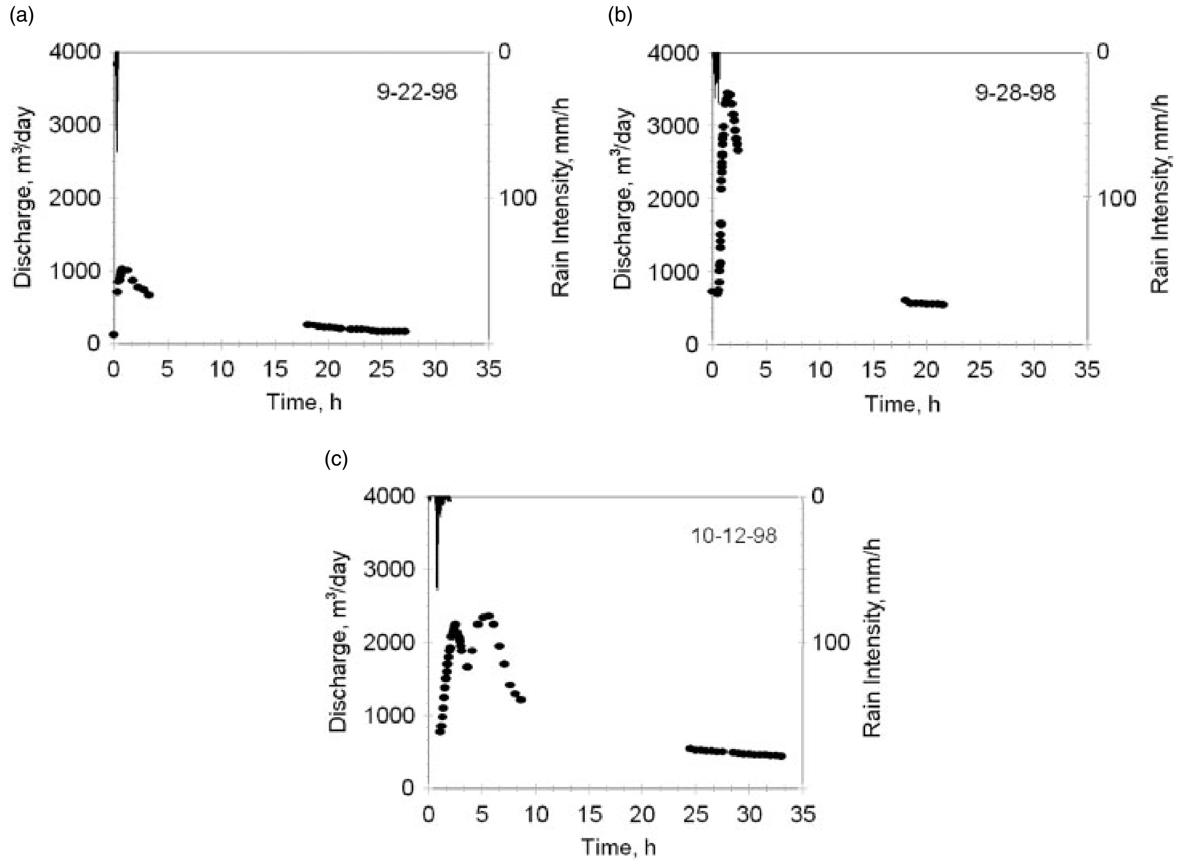

Figure 5. Stream discharge (solid circles) and rainfall (bar graph): (a) 22 September 1988; (b) 28 September 1998; (c) 12 October 1998

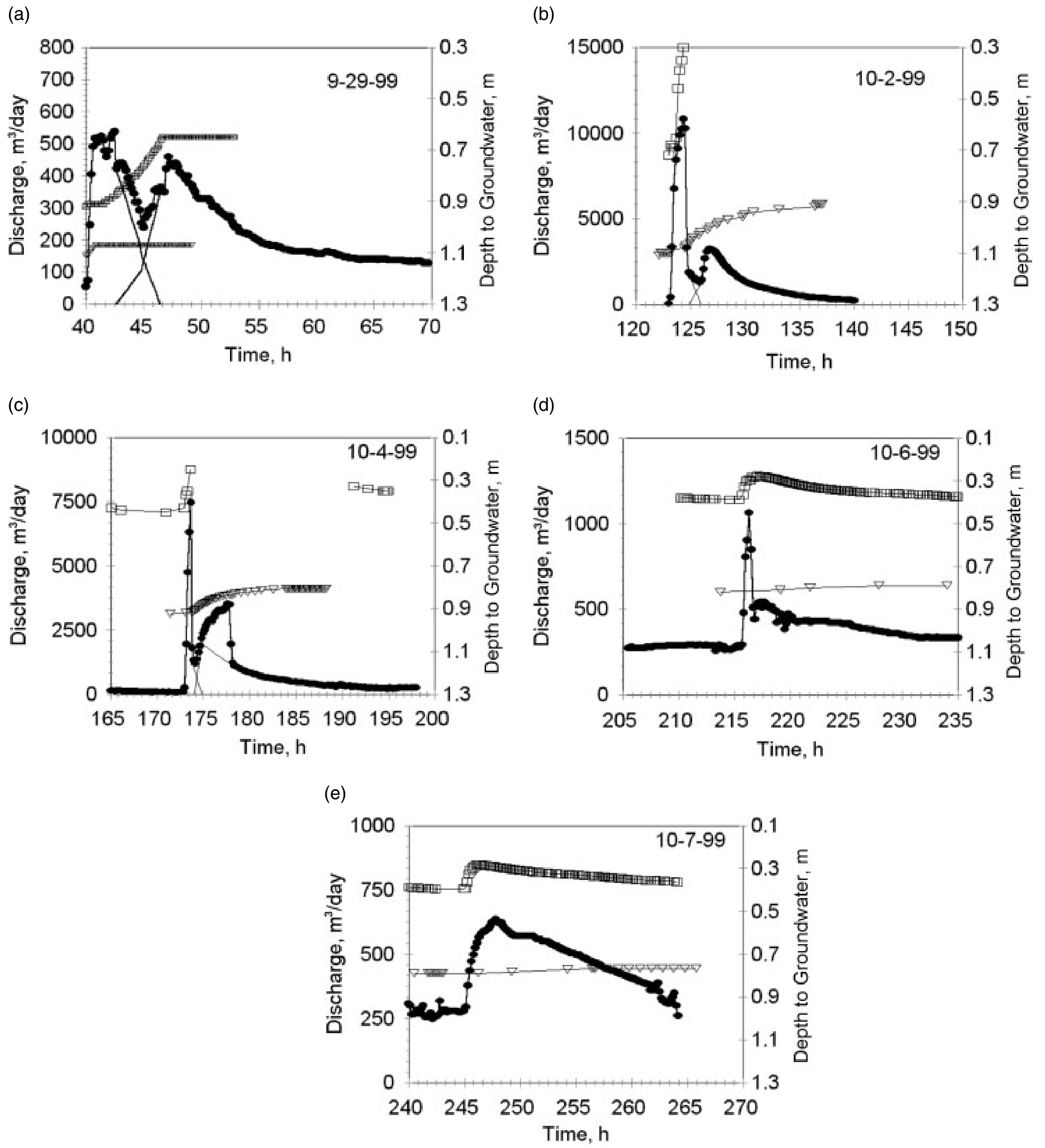

Figure 6. Stream discharge at F2 (solid circles) and depth to perched groundwater at 25 m from the valley bottom at W1 (open rectangles) and 50 m from the valley bottom at W2 (open triangles) for: (a) event A, starting on 29 September 1999; (b) event B, starting on 2 October 1999; (c) event C, starting on 4 October 1999; (d) event D, starting on 6 October 1999; and (e) event E, starting on 7 October 1999. The thin dashed lines for events A, B, and C are extensions of the first and second peaks and are used for calculation of the contributions of saturated surface runoff and interflow. The thin line in event C shows the correction made for blockage of the flume. The time on the x-axis is hours since the continuous measurement began on 27 September 1999, at 11 a.m

7 mm and 8 mm respectively (Figure 6d and 6e) and no distinct pulse of delayed runoff was observed for these rainstorms. However, the recession of the stream flow hydrograph was 'damped', and discharge was noticeably constant for a period of time, after which normal recession proceeded.

The perched groundwater levels observed between 27 September and 7 October 1999 in the hydromorphic zone at 25 and 50 m distance from the valley bottom near flume F2 are shown in Figure 6. The perched groundwater levels at 25 and 50 m in the hydromorphic zone increased shortly after the storm started. The perched water table in the 50 m piezometer increased slightly during the storm but remained constant until the next storm. At the 25 m location, the perched groundwater decreased sometime after the rain stopped. This is especially clear for events D and E, for which complete recession records existed (Figure 6d and 6e). The perched groundwater table depth at 100 m from the valley bottom stayed constant (not shown). In the valley bottom, the perched levels remained near the surface during part of the rainy season and were slightly below the surface during the remainder of the year (Figure 7).

DISCUSSION

Overland flow from the valley bottom during rainfall resulted in a rapidly generated peak, with rapid recession. Before this recession was completed, a pulse of runoff generated a delayed peak during some of the observed storms. The cause of the second discharge peak is intriguing, and is a consequence of the subsurface flow from the hydromorphic zone surrounding the valley bottom, as will be discussed later.

Saturation excess overland flow from the inundated valley bottom resulted in the immediate generation of stream flow after the rainfall started, making up the first peak. The occurrence of runoff when the valley bottom is saturated can be easily proven by comparing the overland flow in Figure 4 and the groundwater table height in the valley bottom well, W4, in Figure 7: when the groundwater table in the valley bottom piezometers reached the surface at 278·2 m on 21 April 1998 (see Figure 7), the stream started flowing (as indicated by the F1 flume in Figure 4). Subsequently, all storms that followed caused an increase in the stream discharge. Similarly, in 1999, no runoff occurred until the water table reached the surface at 278·2 m on 15 August. In both years, the stream flow stopped as soon as the water table became lower than the 287·5 m mark. Since runoff only occurred when the soil was saturated, it is obvious that saturation excess overland flow is how runoff is generated in the valley bottom. The saturation excess overland flow is consistent with the literature (Dubreuil, 1985), as well as with observations of van de Giesen *et al.* (2000) elsewhere in the M'bé experimental watershed showing that infiltration excess runoff from the mid and upper slopes infiltrates before reaching the valley bottom.

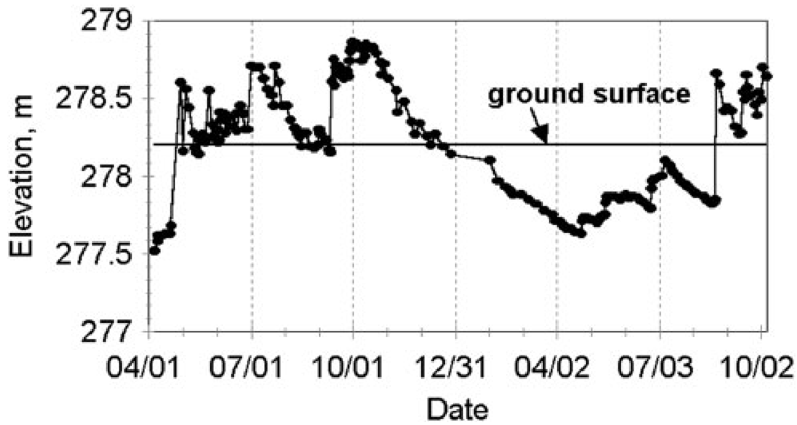

Figure 7. Groundwater table elevation for W4 (see Figure 3 for location) in the valley bottom. The thick horizontal line is the soil surface

The second runoff pulse was delayed, appearing in the valley bottom from minutes to hours after the first peak. Initial inspection of Figure 6 indicates that this response depended on the depth to groundwater on the slopes prior to rainfall (Table I). After event A, the delay of the peak of the second runoff pulse was about 5 h (Figure 6a), whereas that on 2 October 1999 was only about 2·5 h (Figure 6b). Event A occurred after a 10 day dry period, at the end of which the groundwater depth was low, at −0·9 m and −1·12 m for the piezometers at 25 m and 50 m respectively from the valley bottom (Figure 6a, Table 1). Event B occurred shortly after event A, when the groundwater table levels were shallower (−0·7 m and −1·1 m for the piezometers at 25 m and 50 m respectively; Figure 6b). Water table depth increased for event C to −0·45 m and −0·83 m for the piezometers at 25 m and 50 m respectively (Figure 6c). Contrary to expectations, the delay period for event C (4 h) was longer than that of event B. However, inspection of the runoff hydrograph (Figure 6c) shows a very sudden drop in the flow rate just after the second peak occurred, indicating that the flume must have been plugged and that the blockage removed itself. Extending the regression curve upwards, a delay period of 1·5 h is found, which is more in line with the expectations.

To describe the physical process(es) producing the second runoff peak, we need to understand why a higher groundwater table leads to a smaller delay. We first note that the groundwater table depth for the piezometers at 50 m did not decrease significantly between the storms, indicating that interflow contributions from 50 m and beyond are small. The conductivity of these soils is in the order of 10 m day^{-1} and, with a maximum slope of 4%, the amount of interflow at 50 m through these soils is minor (lateral velocity is less than 40 cm day^{-1}). Thus, for short time scales, groundwater from the mid and upper slopes has no direct effect on changes in stream flow in the valley bottom. The main interflow contributions come from the hydromorphic zone at a distance of less than 50 m from the centre of the drain. Figure 6 shows, indeed, that the water table elevations of the piezometers at 25 m increased with the onset of the rain and then decreased sometime after the rain stopped.

The timing of the increase and decrease is significantly different between events A and both D and E, for which relatively complete measurements of groundwater table depth existed at the piezometer at 25 m (Figure 6d and 6e). Close examination of the groundwater hydrograph for event A with an initial groundwater level at −0·9 m shows that the water table does not increase immediately with the onset of the rainfall, but that there is a delay of approximately 1 h between the increase in surface runoff and the rise in the groundwater table (Figure 6a). The delay is caused by the time it takes for the infiltration front of the rainfall water to move from the surface through the unsaturated zone to the groundwater table. The increase of the groundwater table after the initial delay is a function of interflow from upslope, percolation from the soil surface, and outflow. A significant finding is that the highest groundwater table coincided with the second peak of the hydrograph, which directly confirmed the dependence on groundwater level in the hydromorphic zone and the occurrence of the second peak. Regrettably, the pressure transducer malfunctioned during the decline.

For events D and E, the initial groundwater table was at −0·4 m from the surface (Figure 6, Table II), meaning that the groundwater is close to the surface. Under these conditions, the capillary fringe intersects

Table I. Water levels in piezometers in the hydromorphic zone 25 and 50 m from the centre of the valley bottom and time between the first and second peaks of the surface runoff hydrograph

Storm	Initial water table level (m)		Delay time between first and second peaks (h)
	25 m from centre	50 m from centre	
A	−0·90	−1·13	5
B	−0·70	−1·10	2.5
C	−0·45	−0·92	4 (1.5)[a]
D	−0·40	−0·83	0
E	−0·40	−0·78	0

[a] The number in parentheses indicates the delay time after adjustment for flume blockage.

the surface and a low-magnitude rainstorm will cause an immediate rise in the groundwater table (Germann, 1990; Jayatilaka and Gillham, 1996). Figure 6 shows that there is no delay in the groundwater table rise after the start of the rainfall. Consequently, the interflow peak cannot be distinguished from the saturation excess overland flow peak. Similar to event A, the groundwater table level for events D and E at the 25 m piezometer and the overland flow discharge are directly related; i.e. when the groundwater level increases, the discharge increases, and when the groundwater level decreases, the discharge decreases. The piezometer data for runoff events B and C are incomplete, but, from the limited data, the hydraulic response falls between event A and events D and E.

The contribution of saturation overland flow to the total runoff for events A, B, and C was determined graphically by hydrograph separation. The limbs of the first and second peaks were extended such that the discharge of the two individual hydrographs adds up to total discharge (Figure 6). Events D and E did not have a double peak; therefore, hydrograph separation was not possible. The ratio of saturation overland flow to total runoff is given in Table II. It is obvious from inspection that, in Figure 6b and 6c, all reasonable assumptions about the location of the lines give approximately the same percentages of subsurface and surface flow. Although the peak flow rates due to overland flow were generally much larger than for the delayed pulse (Figure 6), the volume of runoff generated from saturation excess overland flow was only between 20 and 40% of the total flow, with the proportion of saturation excess overland flow increasing for increasing rainfall amounts (Table II). The positive relationship between the proportion of saturation overland flow and rainfall amount is a direct consequence of the rice cultivation in the valley bottom. Before runoff can occur, rainfall has to fill up the storage between the bunds surrounding the paddy fields. The higher the amount of rainfall, the greater the number of paddy fields that are contributing to runoff.

In order to understand the wider implications of the findings of the M'bé experimental watershed, it is of interest to examine the physical mechanisms that can produce a hydrograph with two peaks from one storm. As noted by Dunne (1978), for the two peaks to occur, two zones in the watershed need to respond to the storm. In the zone that causes the first peak, the discharge needs to increase and decline before the second peak occurs from the other zone. This short-duration fast-responding first peak occurs only when: (a) the rainfall duration is short; (b) there is a short delay between the start of the runoff and rainfall, such as occurs when the soil is saturated or impermeable and the rainfall cannot infiltrate into the soil; and (c) the discharge declines rapidly after the storm ends, which is the case for upland watersheds with short times of concentration. For the M'bé experimental watershed, the delay is caused by travel time through the aquifer, and consequent build up of the perched water table. This is similar to the report by Anderson and Burt (1978), in which the depth of the unsaturated zone was directly linked to the time delay between the two peaks. At the same time, the lateral movement in the perched water table should be sufficiently fast so that it produces a clear second peak. The inclination of the restricting layer, therefore, is important to produce the hydraulic gradient. It is unlikely that permanent groundwater has a sufficient hydraulic gradient to produce a second peak. Onda *et al.* (2001) indicates that the time delay can also be caused by water flowing through cracks in

Table II. Contribution of saturation overland flow and subsurface flow to total runoff for events A, B, and C on 29 September, 2 October, and 4 October 1999 respectively

Event	Rainfall (mm)	Volume fraction of total runoff (%)	
		Overland flow	Subsurface flow
A	21	31	69
B	38	43	57
C	18	20 (30)[a]	80 (70)[a]

[a] The numbers in parentheses indicate the contribution after adjustment for flume blockage.

the rock. Finally, Dunne (1978) points out that when soils are shallow, such as in Vermont, the first peak will dominate the second peak and separate peaks cannot be observed.

Consequently, the system that generates a double hydrograph is: a saturated area in the uplands surrounded by highly conductive sloping lands with a seasonal perched water table on an inclined restrictive layer located within 1–2 m from the surface; and rainfall that is intense and of short duration. Obviously, this scenario for double-peaked hydrographs is not unique to West Africa. As first mentioned by Anderson and Burt (1978), the reason that there are so few reports of double hydrographs is the lack of continuous stream discharge monitoring in relatively small watersheds. It is of interest to note that, in our study, we only discovered the second peaks after we had installed the continuous recording devices. Before that, we simply could not explain the data of 1998 (Figure 5c), where the partial data did seem to indicate a second rise in stream discharge. Consequently, it is plausible that the difficulty in recording double-peaked hydrographs is the explanation for the few references in the literature.

CONCLUSIONS

From the observations of stream flow and groundwater, it was concluded that, in addition to the inundated and saturated valley bottom areas, the hydromorphic zone contributed to runoff observed in the valley bottom by way of subsurface flow paths. The subsurface flow of the observed runoff was larger than that of overland flow. The time delay between saturation excess and subsurface flow contributions depended on the soil moisture conditions and groundwater levels in the hydromorphic zone prior to the rainfall event. Subsurface runoff was generated rapidly when soil moisture and groundwater levels in the hydromorphic fringe zone were high and the peaks of subsurface and overland flow coincided. However, when the groundwater levels were low, the subsurface flow peak occurred several hours after the overland flow peak, resulting in a hydrograph with two peaks for one rainfall event.

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