Deconvolution of the flood hydrograph at the outlet of watershed Kolondieba in the south of Mali

Dao Amidou[1], Kamagaté Bamory[1], Mariko Adama[2], Séguis Luc[3], Maiga Hamadoun Bokar[2], Goula Bi Tié Albert[1], Savané Issiaka[1].

[1] University of Abobo-Adjamé, Laboratory of Geosciences and Environment (LGE), 02 BP 801 Abidjan 01(Ivory Coast)
2 National School of Engineer (ENI-ABT), DER Geology, Unit: Water and Environment, BP 242 Bamako (Mali)
3 HydroSciences Montpellier, University of Montpellier 2, 34095 Montpellier cedex 5, (France)

ABSTRACT

As part of the international research program RIPIECSA (Interdisciplinary and Participative Research on the Interactions between Ecosystems, Climate and Societies in Africa), we proposed to make the deconvolution of the flood hydrograph at the outlet of the watershed Kolondieba (3050 Km²), in order to know the runoff process. To achieve this, monitoring of physicochemical parameters: pH, temperature (T° C), Electrical Conductivity (EC) and Total of Dissolved Solids (TDS) was performed in different water compartments (rainfalls, surface water, outlet, shallow aquifers and deep aquifers) over the period 2009 to 2011. The determination of the origin of the runoff by the method EMMA (End Members Mixing Analysis) based on EC-TDS diagrams from the mixture of different floods of the river, gave a linear configuration. That showed a bipolar origin consists of rapid flows from rainfalls (Qr) and delayed flows from shallow aquifers (Qd). The deconvolution of the hydrograph made with the EC and TDS, chemical tracers which are best described the dynamic of the floods, gave a contribution of 77% against 23% respectively at Qr pole and Qd pole on the period from August 1st to October 31st 2010 (period of higher level water). Over the same period, in 2011, the runoff increased of 3% in Qr pole due to 6.8% shallow aquifers discharge deficit. The ratio of the contribution of poles Qr and Qd varies from one to three in 2010 and four-fold in 2011.These results show that groundwater don't contribute enough in the hydrodynamic equilibrium at the outlet of watershed Kolondièba. However, the direct flow from the rainfall, heavily influenced by the surface statement (quite degraded by the intensification of cotton culture) governs the runoff process at the outlet. That causes the cessation of the runoff during dry season.

Keywords: deconvolution, flood hydrograph, runoff process, watershed Kolondieba

1. INTRODUCTION

West Africa is a vast territory where climate is governed by the movement of the Atlantic monsoon. This part of Africa is hit in recent decades by a drought more or less severe depending on whether the climate is arid and semi-arid [9, 10, 17]. The ongoing drought since the early 70's seems to be the result of strong climate variability due to disruption of the probable Monsoon. Several research programs have enabled scientists to better understand the instability of climate in West Africa, coupled with the action of human being and their impact on water resources. These include among others the program HAPEX-Sahel (Hydrological and Atmospheric Pilot Experiment in the Sahel); international program of land surface-atmosphere observation that was conducted in western Niger and the Sahel region of West Africa. It was about improving the understanding of the role of general circulation in the Sahel, and in particular the effects of interannual fluctuations of land surface conditions in this region and thus to have more precise ideas on how traffic general is related to persistent drought that affected the Sahel. There is also the AMMA program (African Monsoon Multidisciplinary Analyses) which aims to improve our understanding of the West African monsoon and its impacts on the physical, chemical and biological at the regional and global provide the scientific knowledge base that will establish the links between climate variability and health issues, water resources and food security and to define appropriate monitoring strategies. The interdisciplinary research conducted under the program RIPIECSA, the latest; takes care of the multiple interactions between climate, ecosystems and societies. It aims to study the dynamics of human factors, environmental and climate changes to identify likely scenarios of future developments.

Climate change on the watershed of Kolondièba is characterized by two major rainfall ruptures occurred in 1969 and 1992. These two changes have resulted in a deficit of respectively about 20% and an excess of nearly 17%. The hydrological response to the excess rainfall is over 100% after 1992 [1]. During the peak rainfall, floods look like natural disaster by destroying the crops in the lowlands and the groundwater level rises. But shortly after the end of the rainy season, groundwater drop significantly and the wells are going dry somewhere causing the cessation of flow at outlet.

At a given time, the water collected at the outlet of a watershed comes from several sources: direct surface flow from the rainfall, delayed flow from shallow aquifers and low flow from deep aquifers [18].

So, what is the level of connection between groundwater and the runoff in watershed Kolondieba? The aim of the paper is to know the runoff process at the outlet by making the deconvolution of the hydrograph to separate the components of the flood.

2. PRESENTATION OF STUDY AREA

Watershed Kolondièba, an area of 3050 km^2 located in southern Mali is a sub-basin of Bani (main tributary of the Niger River in Mali). It lies between longitudes 7.34 ° W - 6.82 ° W and latitudes 10.15° N - 11.08° N.

The terrain consists mostly of plains and lowlands varying between 320 m and 465 m from downstream to upstream (Fig.1). The basin is drained by a dense hydrographic network which regime is not permanent, compared to the Donga catchment in Benin located in the same Sudanese climate where runoff still continue during the year [3]. The rainfall average is 1125 mm between 1960 and 2011; this is a basin of the wettest area of Mali. However, shortly after the end of the rainy season, the piezometric level greatly reduced and wells dry somewhere causing the cessation of flow. Several missions to soil surveys conducted in the watershed during RIPIECSA program have shown that soils are generally ferruginous. Indurated levels of oxides of aluminum and iron mostly covered with a thin layer of debris. The breastplates are gritty or conglomeratic. The main economic activity in the watershed is the culture of cotton which acreage increased by 987% from 1960 to 1997 [7]. This activity severely damages the soil and espose it to erosion and increased hortonien overland flow.

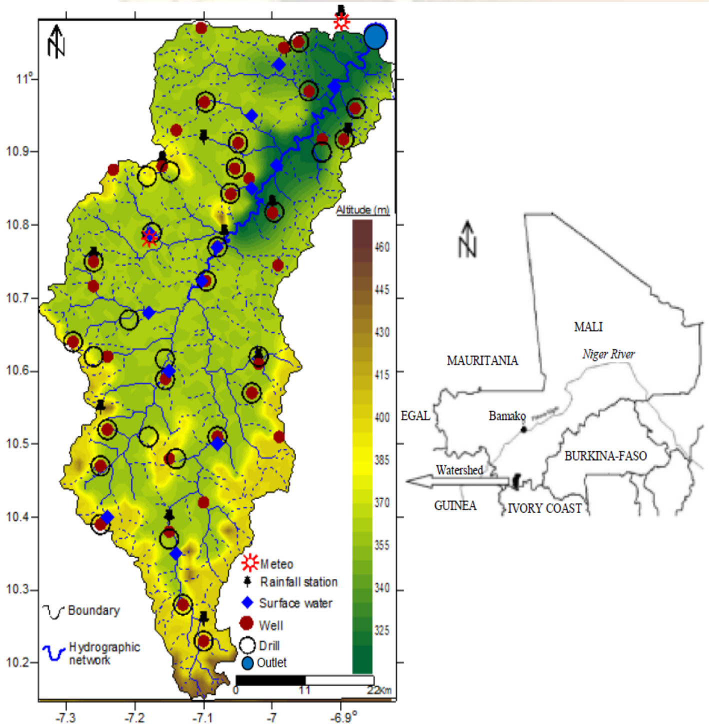

Fig.1. Localisation of the Kolondieba watershed and details of the measuring network

3. DATA AND METHODS

3.1 Data

The rainfall data are recorded from 13 rainfall stations distributed over the watershed (see Fig.1) and the height of observations varies from one station to another. The longest column of data belonging to the rainfall station of Kolondieba near the outlet extends over the period 1960-2011. These data were used to assess the impact of climate variability on surface water in the watershed of Kolondieba [1]. On the experimental period (2009-2011), annual rainfall averages is about 1125 mm on the first two years but in 2011 it was down causing a rainfall deficit of about 33% and piezometric deficit of 6.8%. Decadal monitoring to observe the seasonal fluctuations of piezometric level was performed from 36 wells assigned to shallow aquifers. The depth of the wells goes from 10 to 12 m [5]. Deeper water is from 34 drills made by Helevetas-Mali during emergency program of rural water, consists of granitic cracked in crystalline basement (Fig.2). In addition, 17 surface water points located in lowlands were selected for monitoring the physicochemical parameters (pH, temperature (T°C), Electrical Conductivity (EC) and Total Dissolved Solids (TDS)) measured *in situ* using a multimeter CRISON MM 40.

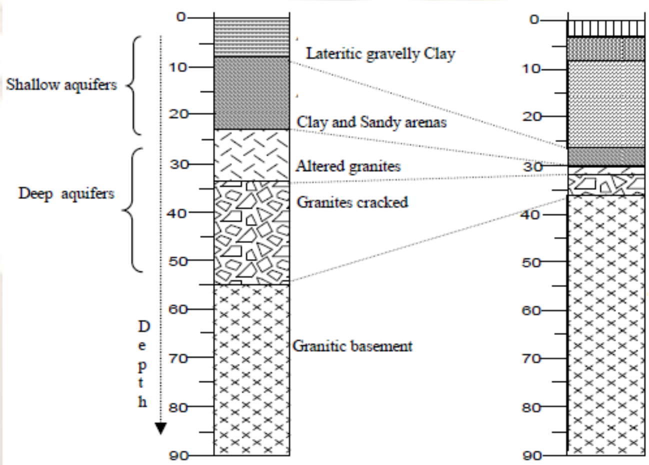

Fig.2. Lithostratigraphic cross of drills located in the watershed (depth in meter)

1.2 Methods

The method used to determine the origin of runoff, is the EMMA (End Members Mixing Analysis) developed by [13]. Its application is by the representation of an XY chart (mixing diagram).The signature of the chemical species of all samples collected at the outlet by crossing them in pairs. The origin of the flow is determined in the following configurations: For two-pole configuration, the two hydric compartments are represented by two points and all possible mixtures are the segment limited by two points. For three-pole configuration, the position of the three hydric compartments forms a triangle. For four-pole configuration, the positions of the four hydric compartments form a tetrahedron. Beyond three tracers:

we are in a hyper-space and it is difficult to visualize the diagram EMMA [14].

The deconvolution is a computational method for separating components of a hydrograph with physical or chemical tracers [14]. This technique of decomposition is applied in the 5 following conditions: mass conservation of water, perfect tracers, differentiation of the components of the mixture, stable tracers, knowledge of the mixing quality and its components. Based on the mixing model considered is governed by two fundamental laws of mass conservation [2, 4, 6, 16], we have the following equations:

- Equation of water mass conservation

$$Q_T = Q_1 + Q_2 + Q_3 + Q_i \quad (1)$$

with, Q_T = instantaneous runoff measured at the outlet,

Q_1 = Contribution of the *first* compartment to the runoff at the measurement moment,

Q_i = Contribution of the *ith* compartment to the runoff at the moment when the sample is measured.

- Equation of mass conservation of solute *i*

$$Q_T.C_{iT} = Q_1.C_{i1} + Q_2.C_{i2} + Q_3.C_{i3} + Q_i.C_{ij} \quad (2)$$

Where C*ij* is the concentration of latter tracer in the compartment *j* and C_{iT} concentration at the runoff of tracer *i*.

4. RESULTS AND DISCUSSION

4.1 Choice of tracers

The study of physico-chemical parameters (pH, T°C, EC and TDS) from the floods is compared with those from a well (assigned to shallow aquifer) located near the outlet. That local groundwater is not representative of the basin but allows a better understanding of the runoff process. Indeed, the Static Level (HL) of the groundwater is very sensitive to rainfall, it rises during rainfall events and decline before the start of the recession (Fig.3). It follows the rise of the water level (H) of the runoff. This means that the emptying of shallow aquifers may contribute to flooding as well as rainfall. The EC at the outlet is intermediate between the rainfall and groundwater (Fig.3a). Before the exceptional flood, it is around 40 μScm^{-1}, value obtained during the survey at the outlet in inter-flood period. At the beginning of the flood, it tends towards the rainfall EC suggesting a drop in hydraulic gradient stanching the contribution of groundwater [8, 15]. Its minimum is reached before the peak of the flood; this is not the case at the outlet of Donga watershed in Benin where it is synchronous with the peak [3]. That can be explained by the difference of areas and the morphological parameters so the flow transfer time. The TDS follows the same pattern as the EC, its quantity tends to the values of rainfall in the early flood and back to those of the web during the decline (Fig.3b). The pH and temperature vary little over the rise and fall (Fig.3c, 3d). Thus, among the four (4) physico-chemical parameters monitored at the outlet, the EC and TDS best describe the dynamics of floods, so they are used to determine the origin of the runoff.

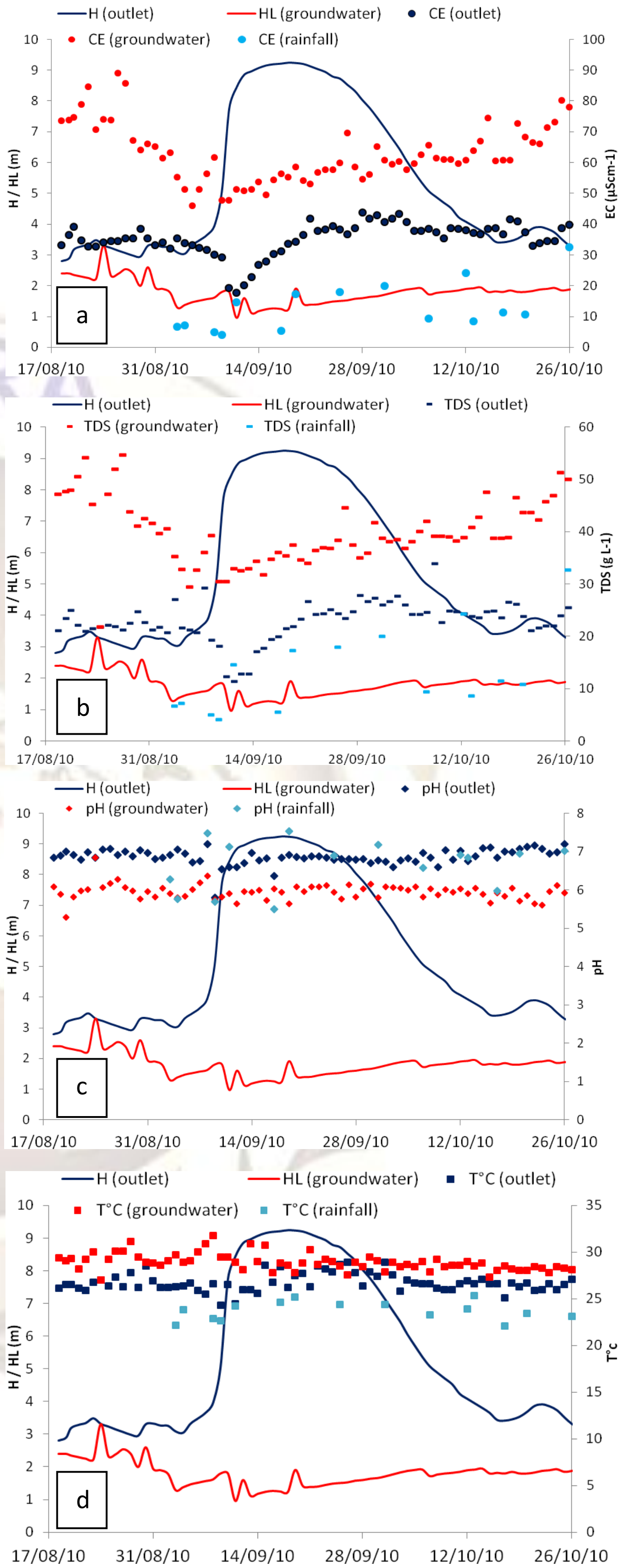

Fig.3. Temporal evolution of physicochemical parameters (EC, TDS, pH, T°c) in rainfall, groundwater and at the outlet function of water level (H) of the flood and the Static Level (HL) of the groundwater

4.2 Determination of the origin of the runoff

Three floods were selected during higher water period (August-October) in two contrasting hydrological cycles 2010-2011(Fig.4a) and 2011-2012 (Fig.4b) to study the mixing diagram at the outlet.

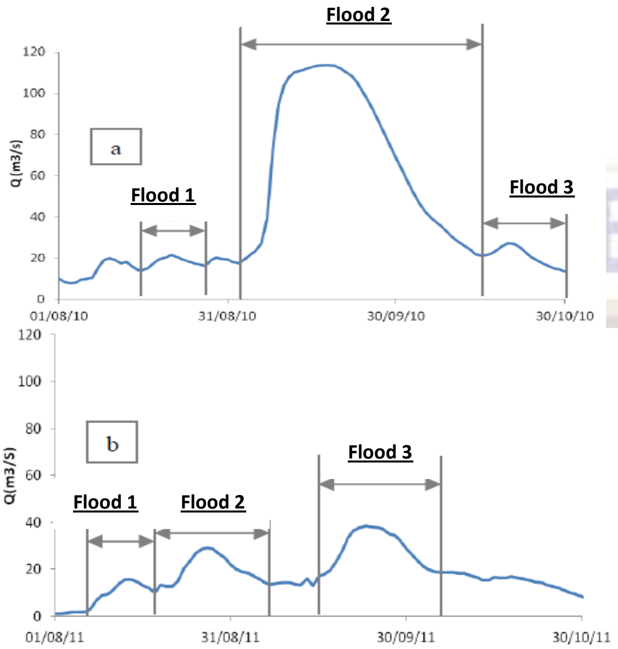

Fig.4. Flood targeted for EC and TDS mixing diagrams in the hydrograph at the outlet: a) 2010-2011 cycle, b) cycle 2011-2012

EMMA diagram of EC and TDS is linear as well as during flood (Fig.5a) and drying up (Fig.5b), at which moment the runoff is mainly from groundwater [11, 12]. The cycled points are potential pollution generated by chemical inputs used in cotton cultivation such as the NPK fertilizer types and chlorinated derivatives.

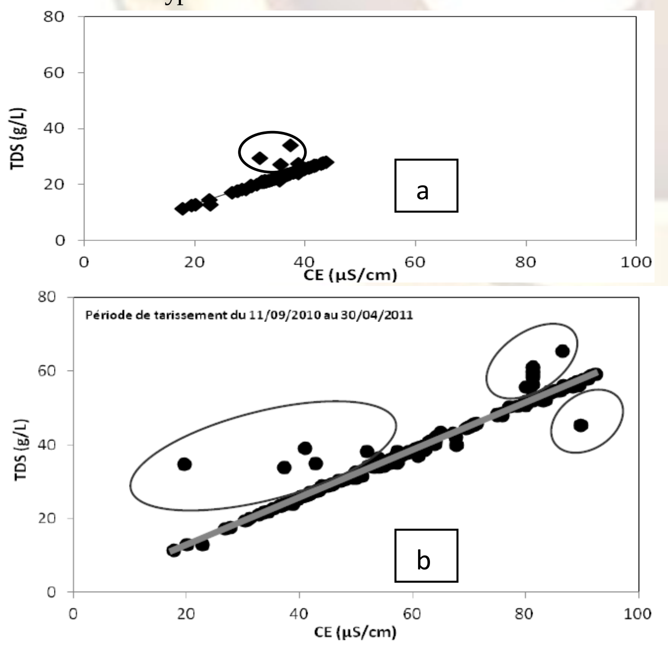

Fig.5. Diagrams EMMA at the outlet: a) during the rising of flood; b) during the drying up

End-Members of the EC-TDS diagram during the floods (see Fig.5a) and the drying up period (see Fig.5b) are comprised of couples (17.79, 11.39) and (92.4, 59.2). These values are close to rainfall and seepages (emptying of superficial groundwater assigned to shallow aquifers); deep aquifers don't contribute (Table.1).

Table 1. Mean values of physicochemical parameters in different water compartments focused on the experimental period (2009-2011)

Origin	EC (µS cm^{-1})	TDS (g L^{-1})
Rainfall	18.94 ± 10.47	12.79 ± 06.74
Outlet	42.97 ± 18.89	27.48 ± 11.80
Seepages	47.29 ± 22.88	29.76 ± 14.73
Shallow aquifers	124.10 ± 83.76	79.14 ± 53.65
Deep aquifers	134.30 ± 84.91	87.21 ± 56.20

Mineralization at the outlet during the drying up period depends on water level at the outlet (Fig.6). Indeed, on cycles (2010-2011) and (2011-2012), the EC is the same for a given water level. Therefore, the End-Members obtained at the end of the 2010-2011 cycle can be considered valid for the 2011-2012 cycle. Under these conditions, the tracers selected to fulfill the aforementioned deconvolution are better. Thus, the flow at the outlet depends on the one hand, to the direct runoff consists of rapid flows from surface (Q_r) assigned to rainfall, and the other, delayed flow (Q_d) which is attributable to subsurface water from shallow aquifers.

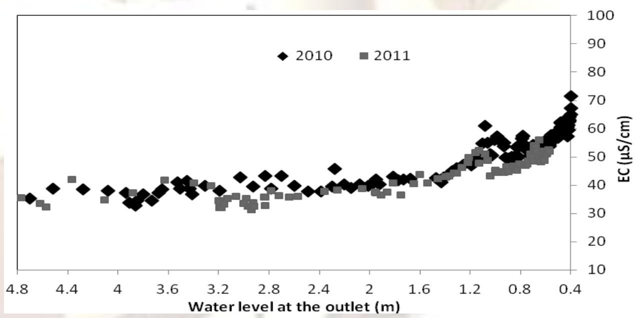

Fig.5. Relationship between water level (H) and EC during the drying up at the outlet

4.3 Deconvolution of the flood hydrograph

4.3.1. Separating the hydrograph components

The results of deconvolution show that the different hydrochemical clusters evolves in the same order for both tracers (EC or TDS) during the contrasted hydrological cycles (2010-2011 and 2011-2012). Rapid flow (Q_r) and delayed flow (Q_d) evolve concommittamment except during the start of the exceptional flood (flood 2) where the contribution of subsurface is fairly delayed by a large influx of surface (Fig.6, 7). The finding shows that the groundwater undergoes a perpetual drain like the Donga basin where they drain all the hydrological cycle, hydrographic network [3], but their contributions to the runoff are not sustainable over the basin of Kolondièba. This can be attributed to several reasons not least, the morphometric parameters of basin, land use and EvapoTransPiration.

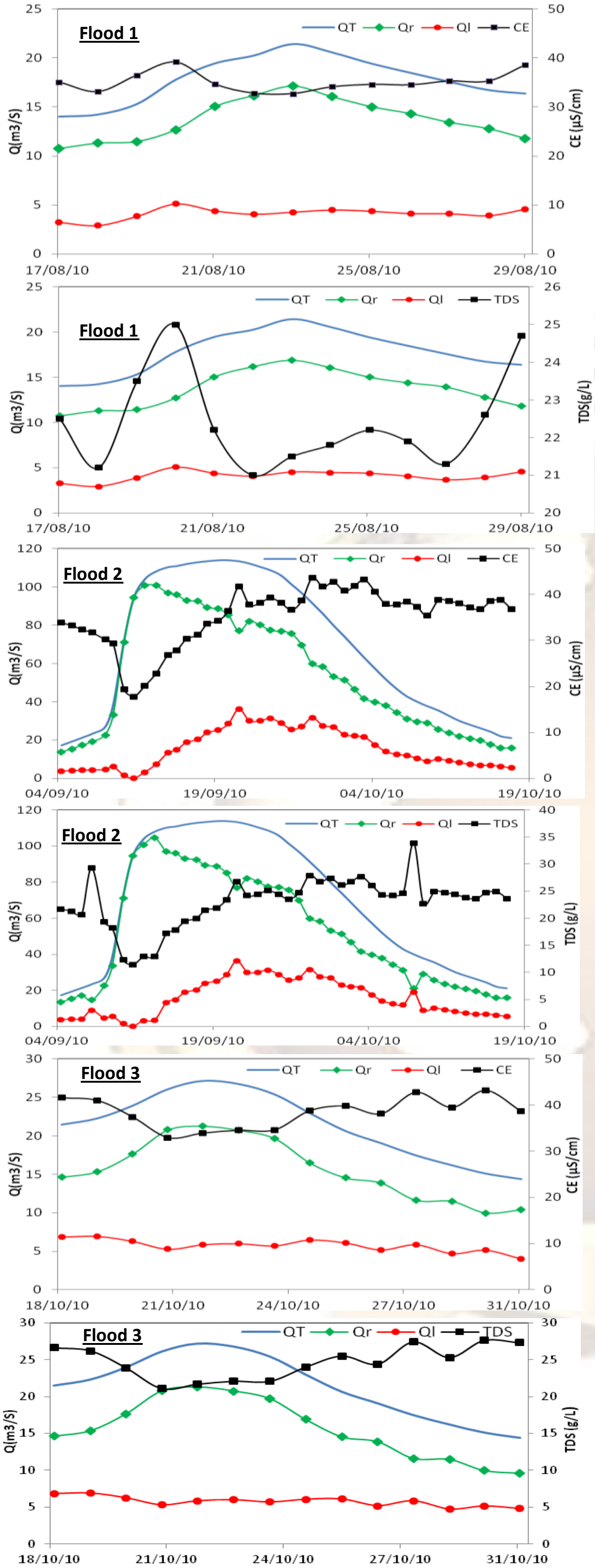

Fig.6. Results of the deconvolution of the flood hydrograph for the period from 01/08/2010 to 31/10/2010 (QT = Total discharge, Qr = rapid discharge, Ql = delayed discharge, CE= electrical conductivity)

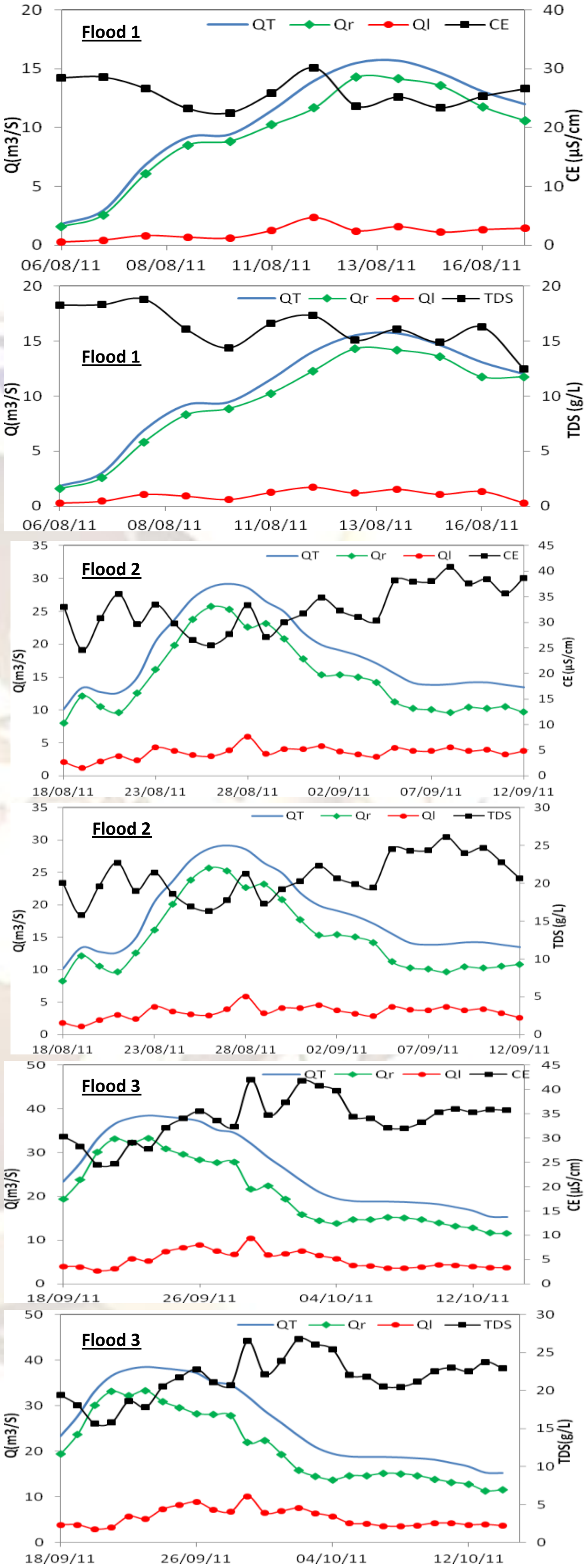

Fig.7. Results of the deconvolution of the flood hydrograph for the period from 01/08/2011 to 31/10/2011 (QT = Total discharge, Qr = rapid discharge, Ql = delayed discharge, CE = electrical conductivity)

4.3.2. Quantification of the contribution of water compartment

On August 01 to 31 October, the contribution of hydrochemical poles is variable among different floods (Tab.2, 3, 4, 5). During the 2010-2011 cycle, the pole Q_r contributes about 77%, an equivalent water volume (Vr) of 258x10^6 m^3 as against 23% at the pole Q_d corresponding to a volume of water (V_d) of 76x10^6 m^3, the total water volume (V_T) is 334x10^6 m^3 (Tab.2, 3).

Table 2. Quantification of the contribution of water compartment on the period from 01/08/2010 to 31/10/2010 with EC

Water compartment	Rainfall		Shallow aquifers		V_T (Total volume)	
Hydrochemical pole	**%Q_r**	**V_r (10^6m^3)**	**%Q_d**	**V_d (10^6m^3)**	**(10^6m^3)**	**%**
Flood1 (17/08/10 – 29/08/10)	76.90	15.376	23.10	04.619	19.996	05.97
Food 2 (04/09/10 – 17/10/10)	77.46	202.270	22.54	58.872	261.142	78.04
Flood 3 (18/10/10 – 31/10/10)	73.09	18.869	26.91	06.946	25.815	07.71
Period 01/08/10 to 30/10/10	77.25	258.499	22.75	76.140	334.639	100

Table 3. Quantification of the contribution of water compartment on the period from 01/08/2010 to 31/10/2010 with TDS

Water compartment	Rainfall		Shallow aquifers		V_T (Total volume)	
Hydrochemical pole	**%Q_r**	**V_r (10^6m^3)**	**%Q_d**	**V_d (10^6m^3)**	**(10^6m^3)**	**%**
Flood1 (17/08/10 – 29/08/10)	77.04	15.405	22.96	04.591	19.996	05.97
Food 2 (04/09/10 – 17/10/10)	77.23	201.676	22 .77	68.647	261.142	78.04
Flood 3 (18/10/10 – 31/10/10)	73.02	18.850	26.96	06.965	25.815	07.71
Period 01/08/10 to 30/10/10	77.03	257.777	22.97	76.869	334.639	100

During 2011-2012 cycle, the contribution of Q_r increases by about 3% against a decrease of 3% at the delayed pole Q_d (Tab.4, 5). These rates are related firstly to a decrease in rainfall, which is materialized by a deficit of 33% over the 2011-2012 cycle, causing a decrease in piezometric discharge of 6.8%.

Table 4. Quantification of the contribution of water compartment on the period from 01/08/2011 to 31/10/2011 with EC

Water compartment	Rainfall		Shallow aquifers		V_T (Total volume)	
Hydrochemical pole	**%Q_r**	**V_r (10^6m^3)**	**%Q_d**	**V_d (10^6m^3)**	**(10^6m^3)**	**%**
Flood 1 (06/08/11 – 17/08/11)	89.76	9.835	10.22	1.120	10.955	07.76
Flood 2 (18/09/11 – 12/09/11)	80.97	33.697	19.03	7.919	41.616	29.48
Flood 3 (18/09/11 – 14/10/11)	79.33	48.497	20.67	12.637	61.134	43.30
Period 01/08/11 au 30/10/11	80.19	113.200	19.81	27.972	141.172	100

Table 5. Quantification of the contribution of water compartment on the period from 01/08/2011 to 31/10/2011 with TDS

Water compartment	Rainfall		Shallow aquifers		V_T (Total volume)	
Hydrochemical pole	**%Q_r**	**V_r (10^6m^3)**	**%Q_d**	**V_d (10^6m^3)**	**(10^6m^3)**	**%**
Flood 1 (06/08/11 – 17/08/11)	90.78	9.445	9.22	1.010	10.955	07.76
Flood 2 (18/09/11 – 12/09/11)	81.36	33.859	18.64	7.757	41.616	29.48
Flood 3 (18/09/11 – 14/10/11)	79.39	48.536	20.61	12.597	61.164	43.32
Period 01/08/11 to 30/10/11	80.37	113.465	19.63	27.707	141.172	100

Groundwater contribution could not reach their maximum altitude, unless they are debiting to the river system and disconnect earlier. The result is the early cessation of runoff at the outlet in January 2012 on the 2011-2012 cycle against March 2011 in the 2010-2011 cycle. The relationship between the contribution of poles Q_d and Q_r varies up to threefold over the 2010-2011 cycle and four-fold in the 2011-2012 cycle. Thus, these results confirm the very shallow groundwater inflows to the runoff.

5. CONCLUSION

The results of the deconvolution of the flood hydrograph at watershed Kolondièba show that the participation rate of water compartments contributing to the runoff is strongly influenced by rainfall variability at the interannual scale. Groundwater doesn't contribute enough in the hydrodynamic equilibrium at the outlet of watershed Kolondièba. However, the direct flow from the soil surface, heavily influenced by the surface statement (quite degraded by the intensification of cotton culture) governs the runoff process at the outlet of the watershed. That causes the cessation of the runoff during dry season.
This work is a perspective of geochemistry applied to the study of watersheds. The use of chemical tracers appears to be better adapted to calculate the volumes of the components of a flood hydrograph because they best describe the dynamics of these. The results are of great interest in the realization of hydraulic structures especially bridges and dams. The determination of uncertainties of the runoff mixing model can make better calculate the contribution of rapid flow (stormflow) during exceptional flood.

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