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Runoff evolution according to land use change in a small Sahelian catchment

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Abstract

Significant land use changes have been observed in West Africa, particularly in the Sahel region where climatic and demographic factors have led to a rise in cultivated areas, in recent decades. These changes caused strong modifications in the water cycle and in river regimes.

By comparing the rainfall-runoff relationships for two periods (1991–1994 and 2004–2010) in two small neighbouring catchments (approx. 0.1 km^2 each) of the Sahel, this study highlights the different hydrological consequences of land use change, particularly vegetation clearing and the consequent degradation of topsoil.

Runoff increased in the upper basin, while it decreased in the lower basin, due to a strong increase in in-channel infiltration. Flood peak durations have become shorter in the downstream part of the catchment due to the huge increase of runoff water transmission losses within the gullies.

Further study will consist of equipping one of the catchments with anti-erosion devices (mainly "half-moons" and terraces) in order to evaluate the influence of anti-erosion devices on runoff and suspended load.

1 Introduction

Land use is rapidly changing in the Sahel. Natural vegetation had already almost disappeared in extended areas of Western Niger and Eastern Burkina Faso, replaced with crops and fallows. Furthermore, within the croplands, crop areas are increasing while fallow lands are decreasing Erosion processes entered a new stage where soil crusting linked to the shortening of fallow periods caused a significant increase in soil erosion and runoff within the region, accompanied with the consequent sedimentation downstream (Amogu, 2009; Le Breton, 2011; Mamadou, 2011). This led to the great extension of erosion-caused landforms: gullies and alluvial fans strongly increased in extension in the last decades.

A significant increase in runoff coefficient is attributable to soil surface features developed in the hillslopes: crusted soils, erosion crusts, algal crusts, etc. (Casenave and Valentin, 1989).

Downstream these landforms constitute new infiltration areas (Descroix et al., 2009). The new hillslope behaviour observed combine an increase in runoff at the local scale linked to soil structure degradation and crusting, and a decrease in runoff at the small catchment scale, attributable to a strong increase in transmission losses within the sandy deposit in gullies, the alluvial fans and spreading areas.

It was noticed that the Boserup theory ("more people, less erosion"), observed as an existing model in some parts of Sub Saharan Africa, e.g. in Kenya (Tiffen et al., 1994) or in Ivory Coast (Demont and Jouve, 1999), does not apply for the moment in most of the Sahel, while the Hardin "tragedy of the commons" (Hardin, 1968) is partially observable, soil tenure being always under a traditional system without private property (Descroix et al., 2008). However, some examples of land reclamation successes show that the main trend is reversible, as it has been observed in the Central Plateau of Burkina Faso (Reij et al., 2005; Reij et al. 2009) and in Eastern parts of Niger (Larwanou et al., 2006; Di Vecchia et al., 2006; CRESA, 2006; Reij et al, 2009). In some cases, a rise in water table is attributable to the new spreading sills (near Keita in Niger, CRESA, 2006) and to land reclamation (Reij et al., 2005, 2009), while it is due to land degradation in some endorheic areas of the Sahel (Massuel et al., 2006; Leblanc et al., 2008; Descroix et al., 2009).

A strong land use change has led to a degradation of soils and vegetation in the Sahel during the last few decades. Some authors have found a "re-greening" of this region (Rasmussen et al., 2001; Anyamba and Tucker, 2005) others have observed a decrease in albedo (Govaerts et al., 2008). However, Hein and De Ritter (2006) showed that using the RUE concept (rain use efficiency) helps to make satellite information more consistent with the numerous studies which highlighted a severe decrease in vegetation cover over the Sahel (Ada and Rockström, 1993; Loireau, 1998; Chinen, 1999; Le Breton, 2011; Leblanc et al., 2008 among others) and corroborates previous

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observations of Hountondji et al. (2004) in Niger. Hiernaux et al. (2009) determined that in spite of land clearing, in some places, total biomass was increasing because of the higher value of millet biomass compared with that of natural vegetation. Numerous studies have demonstrated the influence of land cover changes on the hydrological regime, at the point scale (Casenave and Valentin, 1989; Vandervaere et al., 1997, etc.), at the hillslope scale (Peugeot et al., 1997; Esteves and Lapetite, 2003), and at the basin scale (Albergel, 1987; Amani and Nguetora, 2002; Mahé et al., 2003; Descroix et al., 2009; Amogu, 2009; Amogu et al., 2010). There is a general agreement that increasing soil crusting has led to increasing runoff coefficients and a rise in runoff and flood irregularity in some parts of the region in spite of the decrease in rainfall. In some endorheic areas, this has led to a rise in the water table (Leduc et al., 2001; Leblanc et al., 2008; Favreau et al., 2009). Karambiri et al. (2003) showed that the surface features caused runoff and severe water erosion in a small catchment in Northern Burkina Faso.

The aim of this paper is to compare, in small Sahelian catchments, the land use changes and the water cycle evolution, especially in runoff production, during the last two decades, in order to determine whether land use change has caused hydrological changes at the small basin scale.

2 Material and methods

2.1 Study area

The Tondi Kiboro experimental catchments are located 70 km east of Niamey, Niger, on the western part of the Iullemeden sedimentary basin (Fig. 1). In a landscape of dissected laterite-capped plateaus, the experimental site is located on a catena formed by a plateau with loamy-clayey soils and low slopes, the breakaway at the edge of this plateau (slopes 4–8%) and a 2 km-long sandy hillslope. The drainage network is composed of parallel gullies that concentrate the water running off from the plateau.

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The major surface features identified in the catchment area are the following: tiger bush, bare soils stripes of this tiger bush, edge slope, on the plateau; sandy structured soils in crops and fallow and crusted soils in degraded crops and fallows on the sandy hillslope. The gullies include sandy deposit in increasing extension.

2.2 Hydrological measurements

Three basins near the village of Tondi Kiboro, in south-western Niger, were equipped and monitored from 1991 to 1994 and from 2004 to 2010. Two of them are nested (“amont” and “aval”); their respective sizes are 46 800 m^2 for the upper basin “amont” and 110 540 m^2 for the total one at the “aval” station (including the first one); the third one (“bodo”), is a 121 800 m^2 one, where the second observation period is only 4 years long (2007–2010). Stream gauge stations were equipped with “Chloe” (Elsyde, Paris, France) water level recorders during the first period, and “Thalimedes” (OTT, Kempten, Germany) water level recorders during the second period. Recording rain gauges were of the same type (PM3030 of Précis Mecanique, Bezons, France) for both periods, but data loggers were Oedipe type (Elsyde) during the first period and HoBo type (Onset, Pocusset, MA, the USA) during the second period.

These devices monitored rainfall and runoff and measured the duration of each running event.

2.3 Soil moisture monitoring

A set of devices was installed in order to monitor soil moisture in the gullies and in their surrounding areas, and was provided data from 2004 to 2010:

- soil moisture monitoring stations: soil moisture was measured at two places (gully and fallow) up to 3 m deep; soil suction and TDR (time domain reflectometry) sensors were used to monitor soil moisture in real-time;

- neutron probe access tubes provided monthly information (weekly during the rainy season) in 11 sites of the Tondi Kiboro basins; 4 of them were located in gullies and spreading areas, up to depths of 10 m , and for two of them, up to depths of 25 m;

- a recording piezometer was used to monitor the water table level under the main gully (the mean depth of the water table was 46 m from the surface).

2.4 Data analysis

Land use mapping was carried out using aerial pictures, taken from a plane in 1993 and from a PIXY® (IRD) drone in 2007. The precision and definition of pictures were sufficient to recognize all the vegetal formations without any doubts. The contours were determined and digitalized using a GIS. The vegetation maps were made and compared using Arc GIS®.

NAZASM, an event-scale rainfall-runoff, conceptual-empirical model that calculates runoff amounts using a least square calibration method was presented by Nouvelot (1993) and described and used by Descroix et al. (2002), and Descroix et al. (2007) and here in Appendix A. It allows determining the main hydrological processes by defining the impact of Antecedent Precipitation Index on the stream flows, as well as gives the soil current water content, the maximum runoff coefficient and the α parameter which is the soil water content depletion index. Chevalier (1983) estimated that the α parameter must be fixed as 0.5 in the Sahel and in most semi-arid areas. Recent studies in other tropical areas (northern Mexico) showed that the spatial and temporal variability of this parameter gives more information about the main runoff generation process at hillslopes and catchments scales (Descroix et al., 2007). It can range from 1 to very small values; under 0.01, it characterizes "Hewlettian" processes (saturation excess overland flow, also called Cappusian processes, Cappus, 1960; Hewlett, 1961), and above 0.1, Hortonian areas (infiltration excess overland flow; Horton, 1933); between 0.1 and 0.01, it indicates a mix of both kinds of processes. The main purpose of using NAZASM here is to determine whether the hydrodynamic behaviour of soils and basins studied here changed significantly in time.

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Trends, ruptures and persistence were analyzed using the Khronostat software (IRD, 2002). According to Kendall and Stuart (1943), the analysis of a time series is aimed at improving the understanding of the statistical mechanisms that have generated that series of observations. All authors agree on the breakdown of a typical time series into four parts: a trend, a periodicity (more or less regular fluctuations around a trend), an autocorrelation or a memory effect (the magnitude of an observation depends on those of the previous observations and a random, non-systematic, irregular component, that is to say due to chance).

The KhronoStat software (IRD, 2002) was designed in the framework of a study on climatic variability and is thus focused on the analysis of hydrometeorological series. The tests presented are extracted for the most part from the technical note n° 79 "Climatic change of the World Meteorological Organization" (WMO, 1966), and from Kendall et Stuart (1943). The first tests (Buishand u test and Pettit test) concern the random character of the series. If a series is declared not to be random, tests will be necessary to try and determine the non-random nature present in the series, for example the second tests for the detection of a jump at an unknown date (IRD, 2002). The Mann-Kendall "rank" test is used to determine whether the series has a trend or not; the Hubert test can proceed a segmentation of a series of data if this series includes trends and ruptures. The variables included in these trends and rupture analyses are the following: annual rainfall, runoff coefficient in 4 areas: the 3 basins (amont, aval and bodo) as well as the intermediary basin (the downstream area of aval basin, e.g. the part of aval basin not included in the amont catchment), and runoff depth in the same four areas.

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3 Results

3.1 Land use changes

Figure 2 and Table 1 show the evolution of land cover over the Tondi Kiboro catchments. There is little variation on the small upper basin (46 800 m^2) but a significant decrease in fallow lands in the lower part of the northern basin (aval). Fallow was replaced with degraded fallow, which is characterised by bare, mostly crusted soils. Degraded fallow , which covered 16% of the "aval" basin in 1993, reached 38% of the total area in 2007. In the same period, downstream of both "Bodo" and "Aval" catchments (and out of the map of Fig. 2) "sandy deposit" area doubled between 1993 and 2007. Upstream from the stream gauges, the sandy deposit are included in the "gully" class (Fig. 2). The "gullies" area did not change significantly during this period, but the volume of stored sand in the gully significantly increased in volume (field observations of the authors). Neither degraded fallow nor sandy deposit was observed in 1965 (a comparison was made based on CORONA pictures). These two classes have mostly replaced crops and fallows, which decreased strongly in spite of the increase in population.

In the Bodo catchment, the area of degraded fallow and crops increased from 22% to 33% between 1993 and 2007.

3.2 Runoff coefficients

Table 2 presents the rainfall, runoff and runoff coefficient per sub-basin in both periods (1991–1994 and 2004–2010). Runoff coefficient values did not change at the outlet of the Aval basin; it did not increase at the seasonal time scale (non significant evolution). At the outlet of the upper basin (Amont station), on the contrary, the runoff coefficient was significantly higher on average during the 2004–2010 period (period 2) than during the 1991–1994 period (period 1), increasing from 0.36 to 0.43. Almost the same evolution was observed in the Bodo catchment from period 1 to period 2 (here only 2007–2010), with the runoff coefficient increasing from 0.38 to 0.47. It is noteworthy

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that in the nested basins (Amont and Aval stations) the changes in runoff coefficient occurred in the parts of the basin where land cover did not change significantly. Table 2 also indicates the equation of the rainfall/runoff relationship and the coefficient of determination (R^2) taking into account the amount of rainfall (P) and the square of this amount (P^2), commonly more adapted, because runoff coefficient increases generally with the total rainfall amount of a rain event, due to progressive soil saturation. At the event time scale and using the single rainfall/runoff relationship, there is a more significant increase in the runoff coefficient at the "amont" station (from 0.56 in 1991–1994 to 0.73 in 2004–2009) and at the "bodo" station (0.53 to 0.87) than at the "aval" station (0.43 to 0.46).

3.3 Stream flow duration

The duration of each flood is added in order to calculate the total duration of stream flows during a rainy season at each station. Table 3 gives the total duration of flows during period 1 and 2. The duration of stream flows did not change significantly between the 2 periods in the upper "Amont" of the nested basins. On the contrary, it decreased significantly at the outlet of the basin (Aval station), decreasing from 28 to 18 h per year. And it decreased even more strongly at the "Bodo" station, from 63 to 26 h (period 2 = 2007–2010 in this case). In the nested basins, the difference between the duration in the Amont and in the Aval station also increased, highlighting the fact that floods have a shorter duration downstream than on the upper part of the basin.

3.4 Soil moisture monitoring

Values of wetting front are very different from one land use to another. Every year during the 2004–2010 measuring period, the wetting front reaches more than 8 m in the bush part of tiger bush on the one hand (Table 4), due to the deep root system and dense vegetation, under gullies and spreading areas on the other hand, due to the sandy deposit where water is retained before infiltrating more deeply into the soil.

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The second class of land use in terms of infiltration is constituted by all the other non degraded environments (Table 4): millet crops, fallow and areas surrounding the *faidherbia albida* trees ("gaos"); the last class (less than 1.5 m deepening of wetting front) is constituted by bare soils: the natural bare soils of the bare strip of tiger bush and the degraded, crusted soils on fallow and cropped areas (ERO crust). The date of reaching the maximum value of soil water content does not vary in the same way: the bare soil areas of tiger bush reaches its maximum water content value first (around 22 August on average), then all the other land uses reach their maximum water content level in mid September, except the spreading areas where the wetting front continues up to 5 October on average.

The piezometric monitoring data show that during each rainy season, the wetting front reaches the water table some weeks after the beginning of the rain, due to the easy infiltration under gullies and spreading areas.

3.5 Modelling the rainfall-runoff relationship using the NAZAS model

The Nazas model (NAZASM) aims to improve the modelling of the rainfall-runoff relationship in catchments where both Hewlettian and Hortonian runoff generation processes are active. It is based on the Antecedent Precipitation Index. and calculates a theoretical soil moisture content at the beginning of the rainfall event. The model parameters are H_{max} the maximal soil water content (in mm), P_{max}, the maximal rainfall amount which does not produce runoff, K_{max}, the maximal runoff coefficient, and α, the depletion index of soil moisture. Values of all the parameters are given in Table 5 and in Appendix B. A validation/calibration process of these parameters was conducted following a split sampling approach by constituting two sub-data series, the first one including the events n, $n+2$, $n+4$, $n+6$, etc, the second one including the events $n+1$, $n+3$, $n+5$, etc. The runs made with each one of these two data sets are compared in order to verify whether they produce similar results. The description of the NAZAS model is given in Appendix A.

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It can be observed that:

- H_{max} decreased in all basins between period 1 and period 2, probably in relation with the soil degradation (that caused a decrease in the soil water holding capacity);
- An increase in P_{max}, is measured between period 1 and 2, likely attributable to the rise in infiltration under the gullies;
- Maximal runoff coefficient K_{max}, increased in both "bodo" and "amont" basins; this is possibly linked to soil crusting. It did not change (0.7) in the "aval" basin probably due to the strong infiltration rate in this reach of the creek;
- The α parameter increased in the 3 basins between period 1 and period 2: this evolution is likely to be related to the decrease in the soil water holding capacity (caused by the crusting processes) and the increase in Hortonian "infiltration excess" type runoff.

3.6 Trends and ruptures

Despite the time shortness of the data, an analysis of trends, persistence and ruptures was carried out for rainfall, the runoff coefficient and the runoff depth in the four catchments: amont, Aval and the intermediary catchment, e.g. the part of the aval catchment located downstream of the amont catchment stream gauge in the northern basin, and the Bodo catchment.

Table 6 summarizes the results. In summary:

- annual rainfall series did not show neither trend, rupture nor segmentation;

Concerning the hydrological parameters:

- no evidence of rupture was noticed (Buishand and Pettit tests);

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- a small positive trend was observed on 2 basins (Aval and Bodo) on runoff coefficient (with a 90% threshold confidence);

- in all the cases, the segmentation proposed by the Hubert test includes the whole series, indicating that there is no significant segmentation possible

Figure 3 shows the evolution of the total yearly discharge divided by the total flow time. It shows a clear trend: in the three basins, the volume of discharge per hour increased between period 1 and period 2. It increased significantly in the Aval basin where the runoff coefficient did not increase between the two periods due to the strong increase in infiltration within the sandy creek bed.

4 Discussion

When comparing the land cover maps of 1993 and 2007 (Fig. 2; see also Table 1), we can notice large changes in land cover distribution; this leads to significant changes in surface features and soil hydrodynamic behaviour. These have been determined by Casenave and Valentin (1989) giving for each category a runoff coefficient. In the same basin, Mamadou (2011) and Le Breton (2011) observed the following runoff coefficients (Table 7) at the plots scale (10 and 100 m^2).

It was noticed that there is no change in rainfall annual amount (Table 6) during the two observation periods (1991–1994 and 2004–2010); moreover, it was previously shown that the mean rainfall intensity did not change significantly in last decades (Amogu et al., 2010). Le Barbé et al. (2002) demonstrated that the West African drought begun in 1968 was characterised by a decrease in the annual number of rainfall events, without any change in the intensity or the total amount distributions of the events.

However, the rise in runoff coefficient observed between both observation periods was due to some events where runoff coefficients were equal or higher than 100%: 5 in the Bodo catchments and 2 in the Aval catchments; this was observed only two times in both basins in the first observation period. This was caused by an increase in the area of catchments, and this explains why the catchment where land use evolved less is the one where increase in runoff is the highest. This evolved sufficiently to provoke a change in connectivity. In some cases (major rainy events), the catchments connectivity is modified in the tiger bush plateau and additional bare soil areas were, for these events, connected to the studied basin. In certain cases, an overflowing of a bare soil strip can provoke a lateral bypassing of a vegetated strip causing a temporary (for some minutes) extension of the catchment area of the gully. But the appearance or increase in this kind of connection is commonly linked to the land use changes, particularly the shortening of a vegetated strip by wood cutters, leading to modifications in the catchment's water collecting areas, and to an apparent increase in runoff coefficient, exceeding 100% in extreme cases.

Neutron counting regularly processed in the vegetated strip of Tiger Bush, gullies and spreading areas showed a high annual soil moisture variability up to a depth of 10 m, while all the other parts (millet, fallow, degraded areas), had slight changes only up to a depth of 2 m (Table 4 and Fig. 4).

Figure 2 and Table 1 show a strong increase in the area of degraded crops and fallows, characterised by "degraded soils". As these soils are crusted and have a low infiltration capacity, these land use changes could explain the increase in runoff coefficient at the small basin scale. The fact that the runoff coefficient of the Aval basin did not increase as expected considering Table 7 and Fig. 2 is due to another consequence of land degradation: the deposit of significant volumes of sand at the bottom of gullies favouring infiltration over runoff. In the Wankama basin, (14 km north of Tondi Kiboro), Descroix et al. (2011) showed that in a 150 m long section of the creek, 20 000 m^3 of water infiltrated each year in the creek bed, and this constituted 53% of the volume discharged at the upstream edge of the considered reach. In the same neighbouring basin, Le Breton (2011) showed that there was a great extension of gully networks between 1950 and 2004. This was also observed in Northern Burkina by Karambiri et al. (2003). Peugeot et al. (1997) showed that there was no infiltration under the Tondi

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Kiboro basin, talking about the fields and degraded areas; but they envisaged the role of gullies in infiltrating significant volumes of water. In this same basin, Esteves and Lapetite (2003) noticed that between 1991 and 1994, "infiltration through the bottom of the gully between two gauging stations led to considerable runoff water transmission losses". Gullies and sandy deposits as spreading areas have been determined as likely areas of deep infiltration and water table recharge (Leblanc et al., 2008; Favreau et al., 2009; Descroix et al., 2011). Downstream of the Aval and Bodo basins a small pond collects the streams from these basins; as there is no outlet from this pond, and it dries up some hours after the rainfall event, it could be considered that most of stream water measured at Aval and Bodo stations infiltrates under this pond: more than 10 000 $m^3 yr^{-1}$ on average from each of the two gullies, more than 13 000 $m^3 yr^{-1}$ in the Aval catchment, and more than 28 000 $m^3 yr^{-1}$ in the Bodo catchment (Table 8). These values are almost identical to those measured in the Wankama basin (Descroix et al., 2011).

These areas could be responsible for part of the acceleration in the water table recharge noticed in this region in the last 20 years (Leduc et al., 2001; Leblanc et al., 2008). The increasing contribution of deep infiltration under the gullies and spreading areas should explain the increasing rise in water table levels in these basins (Séguis et al., 2004; Massuel et al., 2006; Favreau et al., 2009; Descroix et al., 2011).

Such increases in runoff coefficient were observed early in small experimental catchments in Burkina Faso (Albergel, 1987) and in "regional size" catchments such as the Sirba River, tributary of Niger River, (Mahé et al., 2003) or the Nakambé River (Mahé et al., 2005) one of the upper branch of Volta river, and more recently in small tributaries of the Niger River (Amogu, 2009; Amogu et al., 2010).

Values of the α parameter in Antecedent Precipitation Index calculation measured in this study are consistent with the fixed value of 0.5 for the Sahel area (Chevallier, 1983). This matches with values observed in degraded semi-arid areas of Northern Mexico with dominant Horton-type processes in hydrology (α parameter higher than 0.1) (Descroix et al., 2002). The decrease in H_{max}, the maximal soil water content the soil water holding capacity in the basin is supposed to be related with the soil crusting; this trend was observed by Casenave and Valentin (1989) at the local scale, and by Amogu et al. (2010) at the regional scale. The significant accumulation of sand in the gullies in the lowest parts of the catchments, that causes the increase in P_{max}, the maximal rainfall amount which does not produce runoff, has been observed in the Tondi Kiboro catchments during the two periods (Esteves and Lapetite, 2003; Descroix et al., 2011), by the strong decrease in runoff coefficient between the upstream station (Amont) and the downstream one (Aval), and confirmed by soil moisture monitoring at up to 3 m soil depth, neutron counting (max 20 m), piezometric measurements (the water table, up to 50 m); this was also observed in the Wankama catchment, 15 km northward from Tondi Kiboro (Descroix et al., 2011). K_{max} (the maximal runoff coefficient) increased sufficiently in the "Bodo" catchment between the two observation periods to compensate the infiltration in the downstream reach of the basin where sandy deposit filled the bottom of the gully. As it has been shown, this is linked to changes in connectivity, causing temporary increase in the catchment area. The sandy accumulation in the valleys was observed by Leblanc et al. (2008); its influence on deep infiltration was suggested by Esteves and Lapetite (2003) and Massuel et al. (2006) and measured by Descroix et al. (2011).

Finally, the duration of stream flow have been decreasing at the Aval and Bodo stations, and this is probably linked to the effect of infiltration below the channel, which significantly diminishes the total volume at the outlet of the catchments.

5 Conclusions

Comparing data measured at the beginning of the 1990s (1991–1994) and data collected in the mid-2000s (2004–2010) made it possible to determine a series of modifications that have occurred in the water cycle in small Sahelian basins (from 4 to 12 ha). The main changes that were observed are the following:

– An increase in discharge and runoff coefficients in small catchments in the Sahel, as has been observed previously at the regional scale;

– This increase is lower or non-existent in the downstream part of the catchments, where simultaneously a strong and deep infiltration is measured under the bed stream in these areas. Each year more than 42 000 m^3 of water infiltrates under the spreading area shared by the two basins (mean 2004–2010), while this value was 37 000 m^3 in 1991–1994; gullies and spreading areas have been confirmed as deep infiltration areas by soil moisture monitoring ;

– A decrease in the duration of runoff and floods, from 28 to 18 h per year for the Aval catchment and from 63 to 26 h per year in the Bodo catchment; then more water runs in a shortened period of time;

– Modelling the rainfall-runoff relationship showed an increase in runoff coefficients and values of the α parameter (evidence of decrease in soil water content depletion); H_{max} decreased between the two periods, due to soil crusting, which caused a decrease in soil water holding capacity. Paradoxically, the use of the NAZAS model highlights an increase in P_{max} (maximal rainfall amount which does not produce runoff) due to the high water volumes infiltrated in newly extended sandy deposit areas (gullies and spreading areas). This can be explained by land use changes, because bare and degraded soils areas increased significantly between period 1 and period 2.

This coupled land use and hydrologic cycle evolution is common in the Sahel, and the increase in runoff, particularly, is observed at all the spatial scales. This work describes the processes at the elementary (some hectares) catchment scale.

The Aval basin was treated with anti-erosive devices since 2010; in the coming years, we aim to compare the evolution of runoff in the equipped and non-equipped catchments.

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Appendix A

The Nazasm model (in Descroix et al., 2002a, Journal of Hydrology, 263, 114–130

(i) The following rainfall-runoff relation is assumed to hold for any rainy event, n:

$$\sqrt{Rd_n} = K_n(P_n - P_{0n}) \quad \text{with} \quad P_n > P_{0n} \tag{A1}$$

where Rd_n and P_n are the runoff depth and the rainfall amount respectively, both expressed in mm. K_n (in $\text{mm}^{-1/2}$) is a parameter depending on the soil surface hydraulic conductivity, on the catchment area and on the proportion of the catchment contributing to runoff. P_{0n} (mm) is the rainfall below which there is no runoff.

Because it has been observed that all the measured values of $\sqrt{Rd_n}$ and P_n were included between two straight lines, K_n can be expressed as:

$$K_n = K_{min} + [(K_{max} - K_{min})/(P_{0max} - P_{0min})] \cdot (P_{0max} - P_{0n}) \tag{A2}$$

Where K_{max}, K_{min}, P_{0max} and P_{0min} correspond to the maximum and minimum values, respectively, of K and P_{0n} for either the plots or the catchments.

(ii) By assimilating the soil to a reservoir, P_{0n} can be expressed as :

$$P_{0n} = C(H_{max} - \text{API}_n) \quad \text{with} \quad \text{API}_n \leq H_{max} \tag{A3}$$

where C is a parameter taking into account most likely rainfall intensity and indirectly the catchment heterogeneity, the water storage of the soil surface (including vegetation and litter) and the mechanical effect of raindrops on the soil. H_{max} is the maximum water storage of the reservoir (mm) and API_n (mm) is its actual level at a given time.

(iii) Following the definition of the Antecedent Precipitation Index (Kohler and Linsley, 1951, Chevallier, 1983), API_n is calculated as :

$$\text{API}_n = (\text{API}_{n-1} + P_{n-1}) \exp(-\alpha \Delta t) \tag{A4}$$

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where $\Delta t = t_n - t_{n-1}$ is the time (day and/or fraction of day) elapsed between the end of the previous rain event P_{n-1} and the beginning of the current one (P_n).

The parameter α (day^{-1}) is the inverse of the characteristic time of soil moisture depletion.

Introducing Eq. (4) into Eq. (3) and then into Eq. (1), gives:

$$\sqrt{Rd_n = K_n\{P_n - C[H_{max} - (\text{API}_{n-1} + P_{n-1}) \exp(-\alpha(t_n - t_{n-1}))]\}} \quad \text{(A5)}$$

The model (Eq. 5) has seven parameters (C, H_{max}, α, K_{max}, K_{min}, P_{0max}, P_{0min}) to be determined. This was achieved by splitting the time series of observed (P_n, Rd_n) values in two parts (one event out of two): one half being used for the calibration of the parameters by best fitting between calculated and measured values of runoff depths, and the other one for the validation, the values of the parameters being kept unchanged.

The model is initialised at the beginning of the rainy season where API_0 is assumed to be zero.

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Table 1. The land cover in each catchment in 1993 and in 2007.

	BODO 12.1 ha		AMONT 4.6 ha		AVAL 6.7 ha	
1993	hectares	%	hectares	%	hectares	%
tiger bush (vegetated strip)	1.40	11.57	1.10	22.31	0.00	0.00
bare soil in tiger bush	3.91	32.31	1.39	28.19	0.20	3.27
Gullies (including sandy deposit)	1.47	12.15	0.09	1.83	0.32	5.23
vegetated plateau edge	0.48	3.97	1.38	27.99	0.76	12.42
degraded crops and fallow (crusted soils)	2.72	22.48	0.97	19.68	1.46	23.86
Crops and fallow	2.12	17.52	0.00	0.00	3.38	55.23
2007	hectares	%	hectares	%	hectares	%
tiger bush (vegetated strip)	1.65	13.64	1.00	20.28	0.00	0.00
bare soil in tiger bush	2.46	20.33	1.62	32.86	0.20	3.27
Gullies (including sandy deposit)	1.68	13.88	0.13	2.64	0.31	5.07
vegetated plateau edge	0.48	3.97	1.13	22.92	0.77	12.58
degraded crops and fallow (crusted soils)	4.03	33.31	1.05	21.30	3.88	63.40
Crops and fallow	1.8	14.88	0.00	0.00	0.96	15.69

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Table 2. Rainfall, runoff and runoff coefficients for the three basins and for periods 1 and 2.

1991–1994						
amont	Rain (mm)	Runoff (mm)	RC	rainfall/runoff	r^2 $R = aP + b$	r^2 $R = aP^2 + b$
1991	440.50	178.21	0.40	$R = 0.65P – 3.3$	0.87	0.85
1992	425.50	100.50	0.24	$R = 0.36P – 1.49$	0.86	0.82
1993	459.50	139.88	0.30	$R = 0.43P – 1.97$	0.82	0.9
1994	653.26	300.60	0.46	$R = 0.67P – 2.59$	0.9	0.93
TOTAL 1991–1994	1997.76	719.20				
Mean 4 years	512.75	180.33	0.36	$R = 0.56P – 2.61$	0.82	0.88
aval	Rain	Runoff	RC	rainfall/runoff	r^2 $R = aP + b$	r^2 $R = aP^2 + b$
1991						
1992	425.50	73.52	0.17	$R = 0.33P – 2.27$	0.74	0.66
1993	452.00	108.78	0.24	$R = 0.37P – 1.64$	0.81	0.86
1994	660.04	215.67	0.33	$R = 0.5P – 2.22$	0.86	0.90
TOTAL 1992–1994	1537.54	396.88	0.26			
Mean 3 years	512.51	132.65	0.26	$R = 0.43P – 2.3$	0.79	0.84
bodo	Rain	Runoff	RC	rainfall/runoff	r^2 $R = aP + b$	r^2 $R = aP^2 + b$
1991	492.00	262.00	0.53	$R = 0.65P – 1.7$	0.67	0.69
1992	417.00	127.00	0.30	$R = 0.39P – 1.1$	0.69	0.70
1993	475.00	103.00	0.22	$R = 0.41P – 2.6$	0.80	0.73
1994	555.00	249.00	0.45	$R = 0.59P – 2.6$	0.75	0.87
TOTAL 1991–1994	1939.00	741.00	0.38			
Mean 4 years	484.75	185.25	0.38	$R = 0.53P – 2.14$	0.68	0.78

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Table 2. Continued.

2004–2010						
amont	Rain (mm)	Runoff (mm)	RC	rainfall/runoff	r^2 $R = \mathrm{a}\,P + b$	r^2 $R = \mathrm{a}\,P^2 + b$
2004	533	251.30	0.47	$R = 0.64\,P–2, 9$	0.83	0.80
2005	400	94.79	0.24	$R = 0.56\,P–3.4$	0.86	0.80
2006	561	229.80	0.41	$R = 0.78\,P–5.4$	0.81	0.78
2007	524	288.38	0.55	$R = 0.76\,P–3.95$	0.79	0.72
2008	611	333.84	0.55	$R = 0.83\,P–5.4$	0.94	0.91
2009	437	189.40	0.43	$R = 0.83\,P–5.4$	0.80	0.84
2010	428	133.60	0.30	$R = 0.45\,P–1.72$	0.85	0.92
TOTAL 2004–2010	3493	1521	0.43			
Mean 7 years	499	217	0.43	$R = 0.73\,P–4.5$	0.84	0. 83
aval	Rain (mm)	Runoff (mm)	RC	rainfall/runoff	r^2 $R = \mathrm{a}\,P + b$	r^2 $R = \mathrm{a}\,P^2 + b$
2004	533	171	0.32	$R = 0.63\,P–3.2$	0.72	0.84
2005	400	65	0.16	$R = 0, 31\,P–1.7$	0.80	0.74
2006	561	132	0.24	$R = 0.51\,P–4.3$	0.80	0.77
2007	524	127	0.24	$R = 0.46\,P–4.06$	0.82	0.78
2008	611	193	0.32	$R = 0.52\,P–3.8$	0.89	0.89
2009	461	103	0.22	$R = 0.41\,P–2.6$	0.74	0.71
2010	424	79	0.19	$R = 0.27\,P–1.04$	0.86	0.92
TOTAL 2004–2010	3513	870	0.26			
Mean 7 years	502	171	0.26	$R = 0.46\,P–3.1$	0.77	0.79
bodo	Rain (mm)	Runoff (mm)	RC	rainfall/runoff	r^2 $R = \mathrm{a}\,P + b$	r^2 $R = \mathrm{a}\,\mathrm{P}^2 + b$
2007	523	154	0.30	$R = 0.53\,P–4.5$	0.89	0.78
2008	611	377	0.62	$R = 1\,P–7.32$	0.88	0.86
2009	425	195	0.46	$R = 1\,P–7.5$	0.84	0.84
2010	416	207	0.50	$R = 0.72\,P–2.63$	0.90	0.93
TOTAL 2007–2010	1975	933	0.47			
Mean 4 years	494	233	0.47	$R = 0.\ 87\,P–7$	0.81	0.82

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Table 3. Total duration of stream flow in hours per year.

hours/ year					mean								mean
basin	1991	1992	1993	1994	91–94	2004	2005	2006	2007	2008	2009	2010	04–10
AMONT	20.64	28.8	36.96	53.04	34.9	31.2	17.4	36.5	50.6	46.03	23.2	12.5	34.2
AVAL		16.32	25.68	42.24	28.08	24.6	13	20	18.6	21.8	11.3	8.13	18.2
difference		12.48	11.28	10.8	11.52	6.6	4.4	16.5	32	24.23	12	4.3	16
BODO	58.7	50	44	98	62.67				25.0	34.0	18.7	19.4	25.9

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Table 4. Mean depth reached by the wetting front per year and per land use ; the date of occurrence of the maximum depth is noticed (the rank of the day from 1 January).

	2004		2005		2006		2007		2008		2009		2010		depth			date		
LULC	depth	date	depth	date	depth	date	depth	date	depth	date	depth	date	depth	date	mean	SD	date	day	SD	N
TB bush	9.6	258.0	8.1	280. 4	8.1	288.2	7.5	239. 0	8.8	241.6	6.0	258.6	5.7	249.7	8. 0	1. 2	261. 0	16/9	20. 0	5
TB bare soil	1. 3	239. 5	0. 7	219. 5	1. 2	232. 5	1. 4	239. 8	0. 7	241. 3	0. 8	240. 0	0. 7	243. 5	1. 0	0. 3	235. 4	22/8	8. 4	4
ERO crust	1. 1	259. 3	0. 8	241. 7	1. 9	284. 0	1. 7	256, 0	1. 4	269. 5	0. 9	255. 0	2. 1	261. 0	1. 4	0. 5	260. 9	16/9	14. 4	3
gao	3. 5	256. 6	2. 6	243. 9	2. 3	260. 2	3. 1	231. 3	3. 5	273.0	1.6	257.7	2.8	258.7	2.8	0.7	254.5	10/9	14.4	6
fallow	2.3	266.3	1.4	240.8	2.1	265.5	1.6	244.8	1. 9	266. 4	1. 4	261. 2	1. 1	248. 3	1. 7	0. 4	256. 2	12/9	11. 6	21
millet	2. 7	265. 8	1. 9	250. 7	2. 8	271. 4	2. 5	260. 4	2. 8	277. 7	2. 0	272. 3	1. 1	251. 0	2. 3	0. 6	264. 2	20/9	9. 7	9
gully	12. 4	266	8. 3	251	12. 4	230	7. 4	251	10. 4	290	6. 4	254. 0	6. 4	281. 0	9. 1	2. 6	260. 4	16/9	19. 9	1
spread. Area	9. 9	283. 3	7. 4	270. 9	8. 4	292. 8	7. 8	279. 0	10. 8	278. 6	8. 3	292. 4	2. 7	260. 0	7. 9	2. 6	279. 6	5/10	8. 6	5
mean	5. 3	261. 9	3. 9	249. 9	4. 9	265. 6	4. 1	250. 2	5. 0	267. 2	3. 4	261. 4	2. 8	256. 7	4. 5	0. 8	259.3	259.0	7.6	
(day)		17/9		5/9		21/9		6/9		23/9		17/9		13/9			15/9	15/9		
Rainfall (mm)	533		400		561		524		611		437		424							

Values in red were partially reconstituted, *N* is the number of neutron probe measurements site (between 10 and 25 depths documented at each site).

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Table 5. Parameters values given by Nazasm model for each basin and each period of observation (*calibration and validation as well as detailed year per year data are given in appendix*).

	H_{max}	P_{max}	K_{max}	α	r^2 CRd/ORd	r^2 P/Rd	K	Number events
TOTAL of THE TWO PERIODS								
TK AMONT	58	30	0.83	0.39	0.88	0.98	0.64	371
TK AVAL	78	24	0.75	0.60	0.85	0.97	0.56	331
TK BODO	62	30	0.82	0.60	0.82	0.98	0.69	251
MOYENNE TOT	66.3	27.8	0.80	0.52	0.85	0.97	0.65	
1991–1994								
AMONT	68	30	0.75	0.37	0.89	0.97	0.55	154
AVAL	79	22	0.71	0.52	0.86	0.97	0.43	109
BODO	59	28	0.75	0.41	0.79	0.98	0.57	125
MOYENNE 91-94	68	26.7	0.74	0.43	0.85	0.97	0.52	
2004–2010								
AMONT	52	32	0.89	0.4	0.87	0.99	0.73	217
AVAL	70	24	0.70	0.75	0.80	0.98	0.74	222
BODO	50	30	0.90	0.80	0.89	0.98	0.82	126
MOYENNE 04-10	57	26.7	0.83	0.65	0.86	0.98	0.76	

P = rainfall amount; Rd = runoff depth; CRd = calculated runoff depth; ORd = observed runoff depth

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Table 6. Results of trends, persistence and rupture tests in the Northern basin (amont and aval stations).

	Buishand	Pettit	Rank	Hubert
RAINFALL	NNN	NNN	NNN	1991/2010
RC amont	NNN	NNN	NNN	1991/2010
RC aval		NNN	NN**Y**	1992/2010
RC intermediary		NNN	NNN	1992/2010
RC bodo		NNN	NN**Y**	1991/2010
RD amont	NNN	NNN	NNN	1991/2010
RD aval	NNN	NNN	NNN	1992/2010
RD intermediary	NNN	NNN	NNN	1992/2010
RD bodo		NNN	NNN	1992/2010

RC = runoff coefficient; RD = runoff depth; TK intermediary = the catchment included between the two stream gauge stations AMONT and AVAL; TK aval is the total catchment.
N in the Buishand and Pettit tests columns means that there is no rupture detected in the series, neither with 99% nor with 95% and 90% of confidence level, and the series have a random character. When there is no letter, the test could not be realised for technical reason (no sufficient sampling generally).
N in the Rank test column means that there is no trend detected in the series (neither with 99% nor with 95% and 90% of confidence level). Y means that a trend is detected, here in two cases with a 90% confidence level.
The years in Hubert test column mean the segmentation found of the statistical series; this method is based on the trend in the average of the values; here in all the cases, the segment includes the whole series; thus there is no segmentation in the series, suggesting the series are stationary.

Table 7. Runoff coefficient observed in plots (average of 4 repetitions per class, and 5 measurement years 2004–2008) (after Le Breton, 2011; Mamadou, 2011).

	Kr %	erosion kg/ha
millet	3.8	373
fallow	10.5	881
ERO crust	60	5566
ALG crust	26	863

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Table 8. Total volume of observed stream flow per basin and per year (m^3) for periods 1 and 2.

Basin	amont	aval	bodo
1991	8340		31892
1992	4703	8127	15472
1993	6546	11904	12565
1994	15227	23840	30370
mean 1991–1994	8704	14624	22575
2004	11411	21800	
2005	4448	7014	
2006	10461	14590	
2007	13497	14857	18807
2008	15624	21261	45875
2009	8888	11316	23799
2010	5977	8642	25179
mean 2004–2010	10133	13707	28415

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Table B. Results of modelling per year including calibration/validation.

	HMAX	PMAX	KMAX	ALPHA	r^2 LC/LO	r^2 P/LR	K	number
AMONT				($C = 0.1$)	(1)	calculated	calculated	of events
1991	50	23	0.85	0.35	0.89	0.98	0.64	34
1992	60	30	0.49	0.5	0.89	0.98	0.36	35
1993	100	36	0.68	0.25	0.84	0.97	0.42	29
1994	60	30	0.84	0.28	0.94	0.97	0.68	56
1991–1994	56	29	0.72	0.3	0.86	0.98	0.57	154
CAL91-94	61	20	0.8	0.5	0.84	0.96	0.55	77
VAL91-94	90	40	0.89	0.4	0.94	0.97	0.6	77
2004	50	19	0.89	0.5	0.84	0.99	0.64	25
2005	69	30	0.79	0.7	0.88	0.95	0.55	33
2006	46	25	0.93	0.3	0.84	0.99	0.78	33
2007	35	17	0.88	0.4	0.82	0.98	0.77	27
2008	42	40	0.94	0.56	0.96	1	0.83	32
2009	42	32	0.94	0.56	0.84	0.99	0.85	32
2010	50	20	0.67	0.65	0.9	0.98	0.46	34
2004–2010	52	32	0.89	0.4	0.87	0.99	0.74	218
CAL04-10	46	35	0.85	0.4	0.86	0.99	0.74	109
1VAL04-10	60	31	0.95	0.45	0.87	0.98	0.74	109
AVAL								
1992	95	22	0.63	0.4	0.78	0.98	0.33	27
1993	90	25	0.67	0.6	0.84	0.97	0.37	29
1994	75	20	0.85	0.6	0.94	0.96	0.52	53
1992–1994	75	20	0.75	0.6	0.87	0.96	0.44	109
CAL92-94	84	20	0.7	0.3	0.85	0.96	0.37	55
VAL92-94	56	25	0.66	0.6	0.89	0.98	0.52	55
2004	45	12	0.9	0.2	0.79	0.97	0.64	23
2005	80	23	0.52	0.7	0.84	0.95	0.31	35
2006	95	33	0.81	0.7	0.86	0.97	0.52	36
2007	105	22	0.8	0.3	0.85	0.96	0.46	28
2008	95	30	0.83	0.8	0.93	0.98	0.52	32
2009	95	20	0.83	0.9	0.79	0.99	0.71	34
2010	60	30	0.39	0.7	0.91	0.98	0.27	34
2004–2010	70	24	0.7	0.75	0.8	0.98	0.47	222
CAL04-10	65	30	0.58	0.6	0.83	0.98	0.43	111
1VAL04-10	60	20	0.75	0.7	0.79	0.99	0.52	111

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Table B. Continued.

	HMAX	PMAX	KMAX	ALPHA	r^2 LC/LO	r^2 P/LR	K	number
BODO								
1991	70	40	0.95	0.05	0.85	0.97	0.82	36
1992	35	21	0.48	0.8	0.69	0.99	0.39	33
1993	80	25	0.68	0.6	0.84	0.98	0.41	27
1994	64	26	0.84	0.45	0.87	0.97	0.62	39
1991–1994	62	18	0.9	0.35	0.77	0.96	0.59	125
CAL91-94	55	30	0.6	0.3	0.73	0.98	0.47	76
VAL91-94	45	35	0.8	0.3	0.79	0.98	0.71	76
2007	95	30	0.7	0.3	0.91	0.96	0.46	28
2008	38	35	1.1	0.5	0.9	0.99	0.99	32
2009	38	40	1.1	0.5	0.85	0.99	1.02	31
2010	40	30	0.9	0.5	0.93	0.99	0.73	34
2007–2010	50	30	0.9	0.8	0.92	0.98	0.68	126

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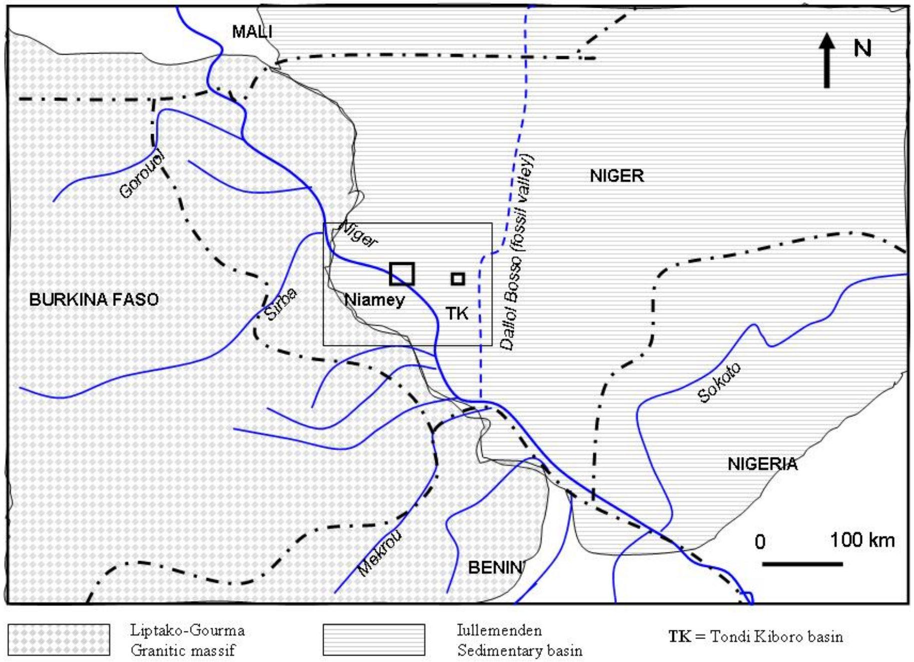

Fig. 1. Location of the Tondi Kiboro experimental catchment.

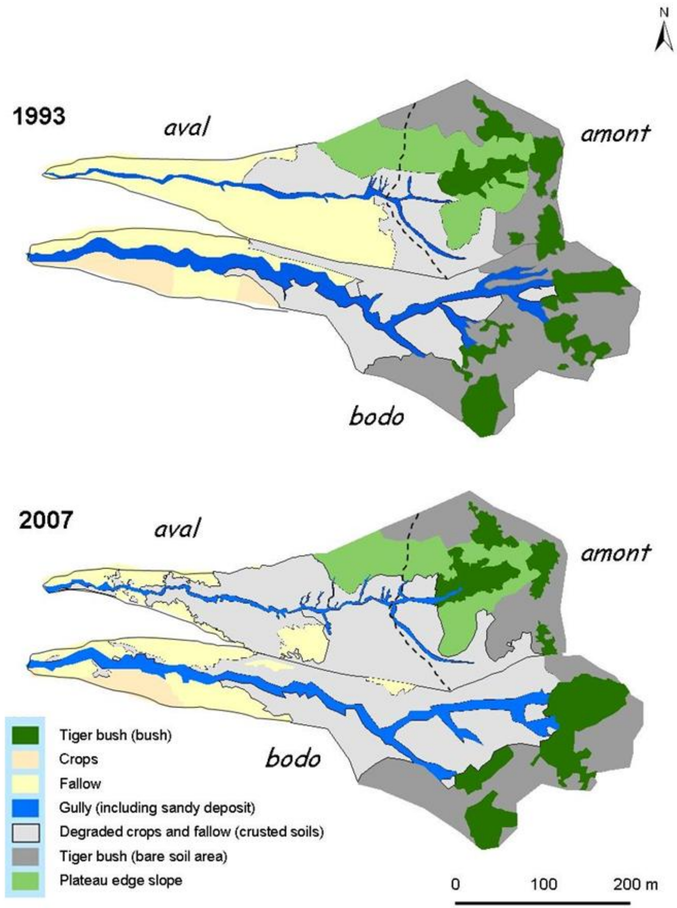

Fig. 2. Land cover and surface features in the three sub-basins in 1993 and 2007.

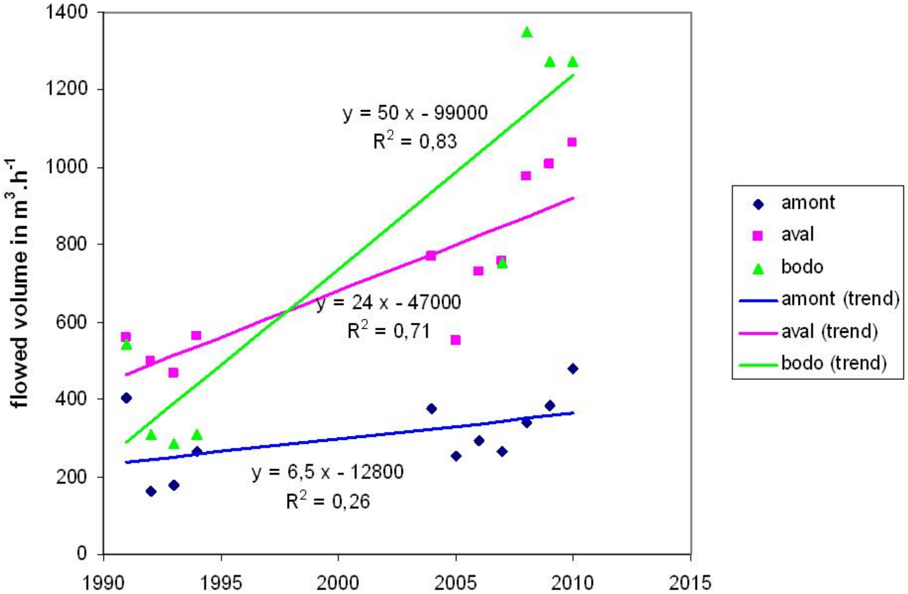

Fig. 3. Intensity of runoff: the total yearly discharge (in m^3) is divided by the total flow time (in hours), giving for each year the mean volume flowed by hour.

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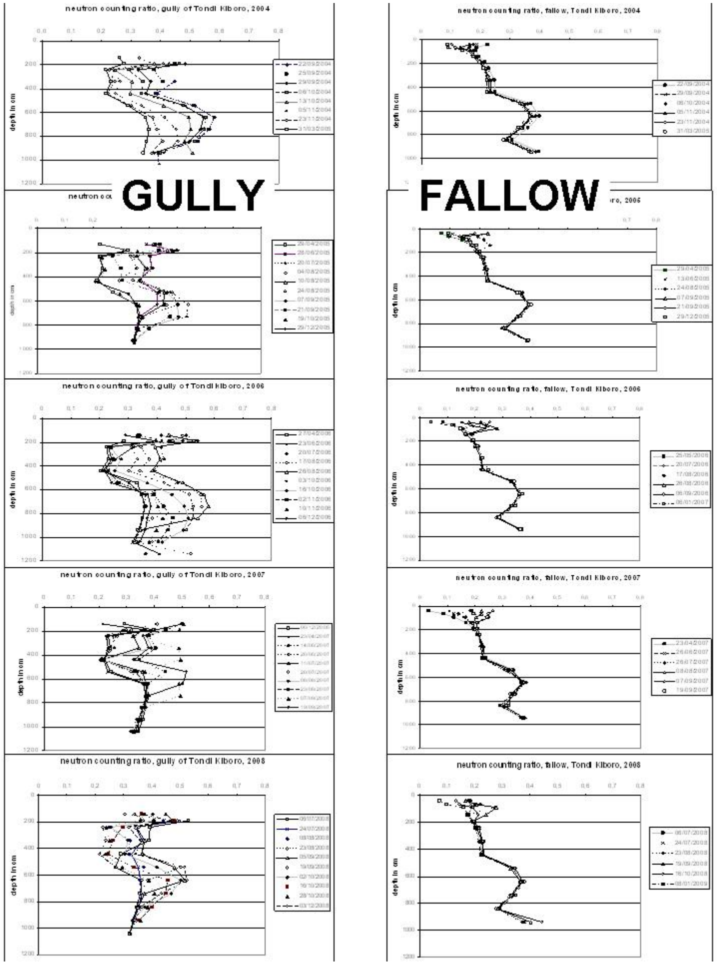

Fig. 4. Profiles of neutron probe ratio under the gully (left) and under the fallow (right).

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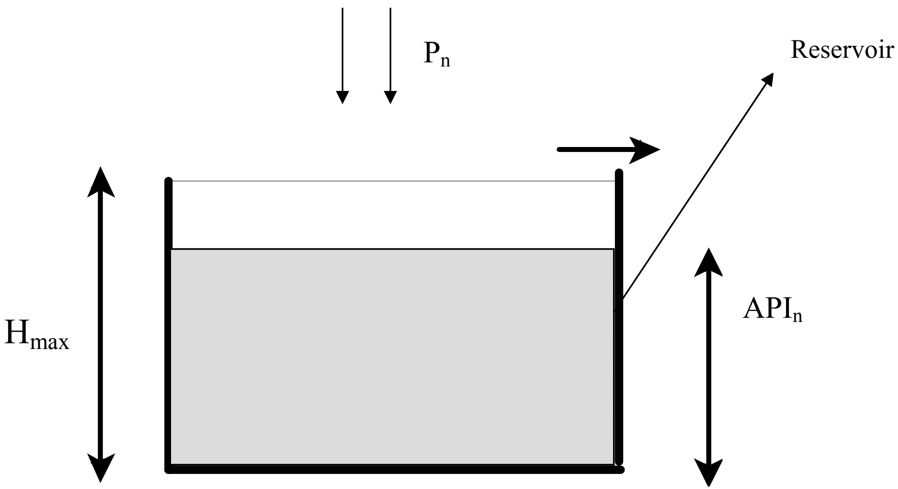

Fig. A1. Description of NAZASM model.

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