The influence of hedgerow systems on the hydrology of agricultural catchments in a temperate climate

Philippe Mérot

Review article

Agriculture and Environment

The influence of hedgerow systems on the hydrology of agricultural catchments in a temperate climate

Philippe Merot*

Unité Sol et Agronomie de Rennes-Quimper, Inra, 65 route de Saint-Brieux, 35042 Rennes cedex, France

(Received 9 September 1998; accepted 31 August 1999)

Abstract – The bocage landscape is an ancient system of organising rural areas by using a hedge network enclosing fields and meadows. It is one form of hedgerow systems used as a windbreak, water and erosion barrier, or ecological corridor in numerous regions around the world. Its hydrological impact in temperate countries is poorly known, although paradoxically often cited as important. This paper is a literature review of researches concerning the hydrologic effects of hedgerow systems mainly conducted in the region of Brittany, in France, for the last 20 years. The actual or potential evapotranspiration seems little modified by hedges at the catchment scale for a bocage with a hedge density of approximately 100 $m.ha^{-1}$. However, local effects are observed on the actual evapotranspiration around the hedges in summer. No effect on the annual rainfall has been measured, but the spatial heterogeneity of the rainfall distribution increases close to the hedge. The bocage has a buffering effect on quick flow during storm runoff of high frequency, modifying the Hortonian overland flow and the contributing flow on saturated areas. The bank and the hedge surrounding the bottom land are the key factor for hydrological effects. Water erosion is limited in bocage landscape, with no exportation outside the catchment. © 1999 Inra/Éditions scientifiques et médicales Elsevier SAS

landscape / hydrology / hedge / storm runoff / erosion

Résumé – Le rôle du bocage sur l'hydrologie de bassins versants ruraux en climat tempéré. Le bocage est un mode d'organisation de l'espace rural représenté par un réseau de haies enclosant les parcelles. Il fait partie de ces systèmes linéaires boisés utilisés dans de nombreuses régions pour protéger cultures et sols du vent, du ruissellement et de l'érosion. Son rôle hydrologique en pays tempéré est relativement méconnu, bien que paradoxalement cité comme important. Il se manifeste à différents niveaux du cycle de l'eau: L'évapotranspiration réelle ou potentielle semble peu modifiée à l'échelle du bassin versant par le bocage, du moins aux densités actuelles, de l'ordre de 100 $m.ha^{-1}$. On observe cependant des effets estivaux locaux sur l'ETR, au voisinage de la haie, Aucun effet sur la pluviosité annuelle n'a été mesuré, mais les haies entraînent de fortes hétérogénéités locales des précipitations à leur proximité. Le bocage joue un rôle tampon sur les écoulements rapides des eaux en période de crue, du moins pour les événements de forte

Communicated by Christian Roth (Australia)

* pmerot @roazhon.inra.fr

fréquence. Cela joue tant sur le ruissellement hortonien que sur ruissellement de zones contributives. Différents modélisations spatiales ont permis de généraliser ces résultats. C'est essentiellement le talus de ceinture de fond de vallée qui joue un rôle prépondérant. L'érosion hydrique est limitée en zone de bocage à un transport au sein des parcelles, sans exportation externe au bassin versant.

paysage / bocage / hydrologie / crue / érosion

1. Introduction

In many areas around the world, hedgerow systems have been constructed to mark the boundaries of the estates, to contain or shelter the cattle, etc. This paper deals with one particular type of hedgerow network, called the bocage, that is typical in western Europe. The bocage shows a great diversity both in the nature of the hedges: low hedges, shrub hedges or tree hedges, planted on banks reinforced with stones or on banks of solid earth or directly on the soil [59], and in the structure of the hedge network in terms of density, orientation and connectivity [11]. In France, institutional or individual land consolidation has led to the thinning out, degradation and even the disappearance of bocage in many areas: more than 200 000 km of hedges have disappeared over the last 50 years in Brittany (28 000 km^2). However, following a series of studies [11, 34, 46, 50], there has been renewed interest in bocage, firstly by ecologists and more recently by land use specialists confronted with the new functions of agriculture [4, 49]. The role that bocage could play as a purifying system for non point source pollution [45], or for limiting the diffusion of atmospheric pollutants [38] is also currently discussed. This is leading to policies for reconstituting a new bocage network.

The regulatory role of bocage on the water cycle is often presented as an unquestionable advantage of this type of landscape. But paradoxically, few studies have been conducted on the hydrologic role of hedges in temperate climates. On the other hand, there has been a large number of studies on the role they can play as a windbreak in more arid climates [10, 20, 63, 64], in limiting erosion during heavy rainfall [2, 18, 57] or in alley cropping in semi-arid climates [28, 35].

In Brittany, the climate is humid and temperate: The mean annual rainfall ranges from 650 to 1 200 mm, and the mean annual temperature is of 10.1 to 12.2 °C. Daily rainfall over 40 mm occurs only 3 to 6 days per year in average [37], but 180 to 210 days are rainy. The potential and actual evapotranspiration varies from 650 to 760 mm, and 450 to 650 mm per year, respectively. The aim of this paper is to present a literature review on the hydrology in the bocage landscape under a temperate climate, mainly based on researches conducted in France for the last 20 years.

2. The role of bocage among the other elements of the physical environment

A relevant assessment of the role of the bocage requires first to consider the relative importance of the other factors controlling the hydrology in temperate regions. In Brittany, the hydrology of catchments is primarily controlled by the climate (ie, the W-E and N-S rainfall gradient) and the bedrock (i.e., granite, sandstone and schist) [23]. First, the bedrock type affects low flows as it was emphasised by Schreiber and Demuth [55]: in summer time, the low flow of rivers can be ten time less on schist than on granite; for example, the specific mean monthly dry discharge for a five year recurrence reaches 0.20 and 2.35. $10^{-3}.m^3.s^{-1}.m^{-2}$ for respectively a river on schist (Coët Organ) and a river on granite (Evel) (*figure 1*), close to each other and receiving similar rainfall (981 versus 1050 mm per year) (data from [23]). The second major effect of bedrock is that the overlying soils are ten time less permeable on schists than on granite, due to a difference of texture (loamy vs. sandy loam). This influences the quick flow of the

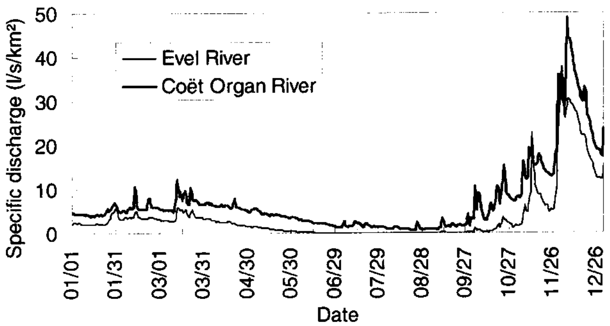

Figure 1. Role of geology on runoff. Specific discharge of the Evel River on Brioverian schist (thin line) and of the Coet Organ River on granite (thick line).

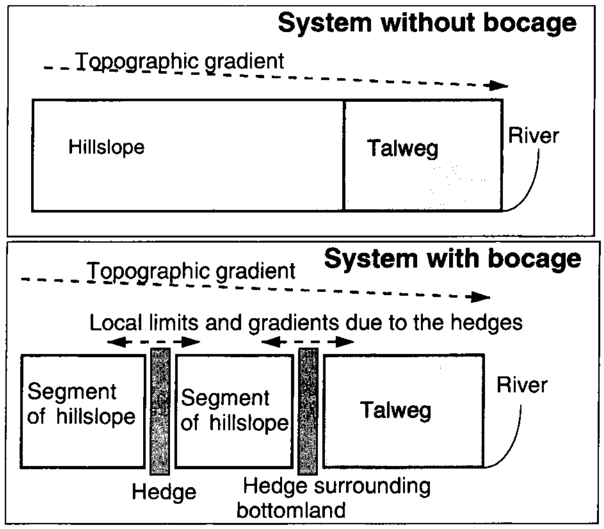

Figure 2. Schematization of the effect of bocage on the organisation of hillslopes.

catchment: the maximum decennial discharge reaches 0.235 for Evel and 0.143 $m^3.s^{-1}.m^{-2}$ for Coët Organ, for a decennial daily rainfall of 52 and 49 mm, respectively; Merot and Buffin [42] showed in a study of 21 catchments that the variability of the monthly discharge on schist is twice as great as that on the granite catchments, in winter. These contrasting features have been confirmed by different studies [3, 39].

Basically, this leads to attribute a buffering capacity on flows more important for catchments on granite than for catchments on schist. Land development such as removing or setting up bocage network will affect marginally this features. Particularly, the regulating role of bocage is likely to be less noticeable in granitic environments, where superficial flows that could be intercepted by hedgerows are less important.

3. Bocage and soil surface structure

Conceptually, the setting up of a bocage can be presented as the segmentation of an organised space (*figure 2*). Introducing a bank perpendicular to the slope segments the hillslope and has consequences on the soil spatial distribution and on water movements. Introducing a footslope bank enclosing the valley bottom reinforces the contrast between the hillslope and the talweg,

Looking at the surface water pathways, the presence of the bank can either concentrate the runoff or force it to infiltrate, depending on the orientation of the bank relative to the slope [12].

Finally, the whole network of hedges, including the hedges parallel to the slope, can have an influence on the atmospheric phase of the water cycle (precipitation, evaporation, etc.), due to the modification of the microclimatic conditions around the hedges. These points will be detailed successively.

The soil plays a key role in the water cycle: its water retention capacity controls the storage of water in the non-saturated zone and the actual evapotranspiration (AET). Its hydrodynamics control the separation between runoff and infiltration on the surface and the percolation towards the water table and lateral subsurface flows in depth. The soil organisation of Brittany is mainly controlled by topography [17, 62]. Two major domains are distributed depending on their position in the landscape: the soils of the hillslopes, generally well-drained, becoming more differentiated further down slope; and hydromorphic and colluvio-alluvial soils situated in the talwegs. There are of course noteworthy exceptions (plateau hydromorphy, hydromorphy of geological origin).

When the hedge is between hillslope and footslope, there is a reinforcement of the boundary between hydromorphic soils and the hillslope soils.

Although the bocage does not modify the general soil distribution, it introduces noticeable variations because of its role in erosion control (*figure 3*) [13]. On hillslopes, the depth of the organic horizon increases on the upslope side of the bank. This depth can reach one meter close to the hedge. Baffet [6] refers to an accumulation bank (soils with colluvial deposits) corresponding to a non-cultivated strip alongside the hedge. This, added to the erosion downslope the hedge, creates a difference in level between upslope and downslope, even on gentle slope (2–3 %), reaching sometimes up to 2 m [46]. From the topographical point of view, this erosion can lead to the creation of a system of hillslopes in treads and risers, for example on loamy soils of the Rennes basin, in eastern Brittany [52]. This type of differentiation has also been observed in contour hedge systems [1].

As far as mechanisms are concerned, this illustrates two facts:

– the existence of erosion in bocage catchments,

– the limitation of erosion to a local transfert of material, within the fields, without export or with a minimal export out of the catchment considered.

A precise study of the texture of the soil horizons close to the bank [14] demonstrates that the difference in level between upslope and downslope can be reinforced by the deposits related to an anthropogenic mechanical action (downslope discharge of earth during ploughing).

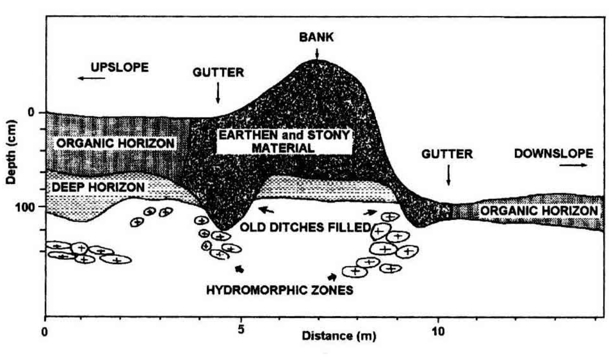

Figure 3. Typical pedological section of a bank (from [13], simplified).

4. Bocage and the atmospheric phase of the water cycle

The effect of hedges on the atmospheric phase of the water cycle in temperate climates has been hypothesized, either by analogy with the unquestionable role of hedges in Mediterranean or arid environments, or by analogy with the role of a forest cover. Different reviews report the effect of the forest cover on annual flow and evapotranspiration [33, 9]. These authors summarise the results of 94 catchment experiments all over the world: the runoff depth increases – and the AET decreases – from 100 to 200 mm, for broad-leaved trees or to 300 mm, for coniferous trees, when the deforestation rate increases from 20 to 100 %. However, Cosandey [16] highlights that these results must be cautiously applied to temperate climates, where the AET is moderate: the effect of partial forestation on the annual flow balance is probably minor, because the difference in AET between forested cover and cultivated land is low [15]. In any case, evaluation of evapotranspiration in a bocage landscape is more complex and its effect not intuitive due to the interaction between the hedges and the fields. Demonstrating the effect of a forest cover on the annual rainfall is even more difficult: increase of the annual rainfall of less than 2 %, mainly due to convective storms in summer time, is estimated for temperate climate [5].

4.1. Bocage and evapotranspiration

Studies have been conducted essentially on:

Potential evapotranspiration (PET) – a comparative study of the energy balance and PET in zones with varying densities of bocage [19, 21, 30, 32]. The major results have been recapitulated recently by Guyot [29].

Actual evapotranspiration (AET) – a comparative study of the hydrological balance of two catchments, one with bocage and the other without [40].

These two studies showed that neither PET nor AET are seriously affected by the presence or absence of bocage, in the humid temperate context of Brittany. The fact that the PET is independent of the presence of bocage is important as far as hydrology is concerned, since the PET is often the basis for calculating the AET. Nevertheless, since PET is not affected in Brittany by hedgerow systems to a considerable degree, the effect of hedgerow on PET factors (wind, radiation balance, temperature, air humidity) will not be developped here; detailed considerations can be founded in Guyot [29]. In summary, PET depends on the evaporative capacity of the air (contribution of advective energy) and the net radiation. The main effect of bocage is the reduction in the evaporative capacity of the air, the modification of the radiative balance acts as a corrective term only [31]. However, because of the relatively high atmospheric humidity, the contribution of advective energy to PET is small (20 %). The theoretical reduction of the PET, based on Penman formula would be less than 6 % ([29] p. 252), in a bocage field compared to an open field.

4.2. Independence of the AET with regard to the presence or absence of bocage

The annual AET at the catchment scale can be assessed by the hydrological balance. This has been done by Merot [40] when comparing catchments with and without bocage. The author came to the conclusion that AET was equal for the two landscapes during two mean climatic years. Although this conclusion is coherent with the results obtained for PET, it must be qualified by the following remarks: firstly, the hydrological balance method applied by Merot [40] did not take the water content of the soil into account, and secondly the degree of forestation of the catchment without bocage (15 % of the catchment is forested, while the other one is no forested) biased the comparison of the AET of the two catchments, which could lead to underestimating the existing differences.

The local scale studies of a bank give further information. The study by Carnet [13] of the soil water content and the soil water potential profiles below and around the banks shows a significant drying in summer. For example, in the deep soils, the matrix potential reaches 1.5 MPa at 1.80 m depth compared to 0.1 MPa at the same depth 30 m away from the hedge. This indicates that there is locally (close to and under the bank) an increase in the AET in summer. The reason for this is twofold. First, trees have deeper root systems than crops; second, the AET of cultivated plots decreases when the crops reach maturity whereas trees continue to take up water much later in the season. Mette and Sattelmacher [48] and Mette [47] conducted a study on the organisation, hydrology and geochemistry of a wooded bank in Schleswig-Holstein (Germany). They have drawn up a map of the root density of the crops on both sides of a bank showing the competition between trees and crops, depending on the distance from the hedge. They also monitored the soil water potential throughout the year, showing a greater drying at 50 cm in depth – with a difference up to 40 kPa in summer – under the hedge and close to it, comparatively to a 10 m distant site. They came to the same conclusions as Carnet [13]. Moreover, they observed a large di-symmetry of drying depending on the orientation, the hillslope exposed to the north remaining wetter because of the lower climatic demand. Agus et al. [1] have also shown drying close to a hedge. This drying is dissymmetrical depending on the root system of the hedge, which is more developed upslope. In Poland, Ryszkowski [53] has measured an increase of 170 mm of annual AET of hedges comparatively to surrounding plots. He explains this increasing by differences in albedo, root system and also in atmospheric exchanges related to the roughness of the hedges.

Does this local drying affects AET at the catchment scale? This effect depends on the relative volume of soil concerned by the large drying due to the hedge compared to the volume of soil of the enclosed fields. A simple calculation based on a

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bocage model with regular square fields gives a rough estimate. Considering that the hedge affects a 4 m^2 area on both sides, the relative extension of the affected domain, which increases linearly with the density of the bocage, reaches 8 % for a density of 100 m of hedge/ha or 16 % for 200 $m.ha^{-1}$. Farington and Salama [25] report an experiment where the evaporative effect caused by tree rows is used to decrease, by evapotranspiration, the level of a water table which was detrimental to growing crops. However, in this case, the hedges corresponded to 25 to 30 % of the surface area of the hillslopes.

We can therefore consider that in summer AET near the hedges is higher than in surrounding fields and fields in open catchments. This leads to two consequences for a bocage area at a higher level of integration (hillslope and catchment). First, there is a heterogeneity in the distribution of moisture of the soils on the hillslope marked by a decrease in the water content in the vicinity of the hedge in summer, and second, AET increases at the level of the catchment. However, given the accuracy of AET measurements at the scale of the catchment which is at best only 5 to 10 %, differences could only be measured with a density of bocage higher than 60 to 120 $m.ha^{-1}$.

Therefore, although the experimental studies showed that there is no significant difference either in AET or in PET in catchments with or without bocage, more theoretical approaches suggest that in an area with bocage there should be a decrease in the PET and an increase in the AET, of a few percent in each case.

4.3. Bocage and precipitation

The idea that the bocage may influence the overall volume of precipitation is sometimes put forward, although few scientific data can justify this assertion [54]. This needs to be qualified in two cases: first, an effect on occult precipitation (increased fog, dew, etc.) may be considered because of microclimatic modifications caused by the bocage, in particular the decrease in wind speed close to the ground; and second, storms seem to be more frequent on areas with bocage (Hubert-Moy, personal communication, 1995).

The effect of a hedge on the spatial distribution of snow and rain has been reported several times in literature [22, 51, 56]. The effect on rain depends on where the winds come from with respect to the bocage and the local topography. There is an increase in the heterogeneity of precipitation on the ground due to an increase upwind and a decrease downwind. The variation can reach 5 mm for a 10 to 25 mm precipitation depth [40]. In hilly areas, the effect can be more complex. Narrow bottom land enclosed by a bocage bank may receive less rainfall because of the synergy between the orographic effect and the protective effect of the hedge. This effect should be taken into account, because of the important role of this area in the flow generation.

5. Bocage and the rewetting of soils

A recent study conducted on the local scale makes it possible to illustrate infiltration dynamics close to the hedge [26]. A series of tensiometers placed perpendicularly to a bank with trees enclosing bottom land (at 1, 3 and 5 m far from the hedge, and at every 10 cm from -20 cm to -155 cm depth) and monitored from the beginning of the dry period make it possible to describe the sequence of infiltration over time. The scheme presented in *figure 4* is the interpretation of these data. The initial situation at the end of summer is a dry zone, shaped like a bulb, centred on the bank and a groundwater level which is lower upslope of the bank than downslope. Rewetting occurs gradually, keeping a dry dome, which becomes skewed because of a more rapid rewetting downslope. The influence of the hedge remains visible until the complete rewetting of the soil, and reappears at the end of the rainy period. This study confirms and clarifies the results of Carnet [13].

6. Bocage and quick flow during storm runoff

Storm runoff is generated by different internal processes within the catchment: surface runoff

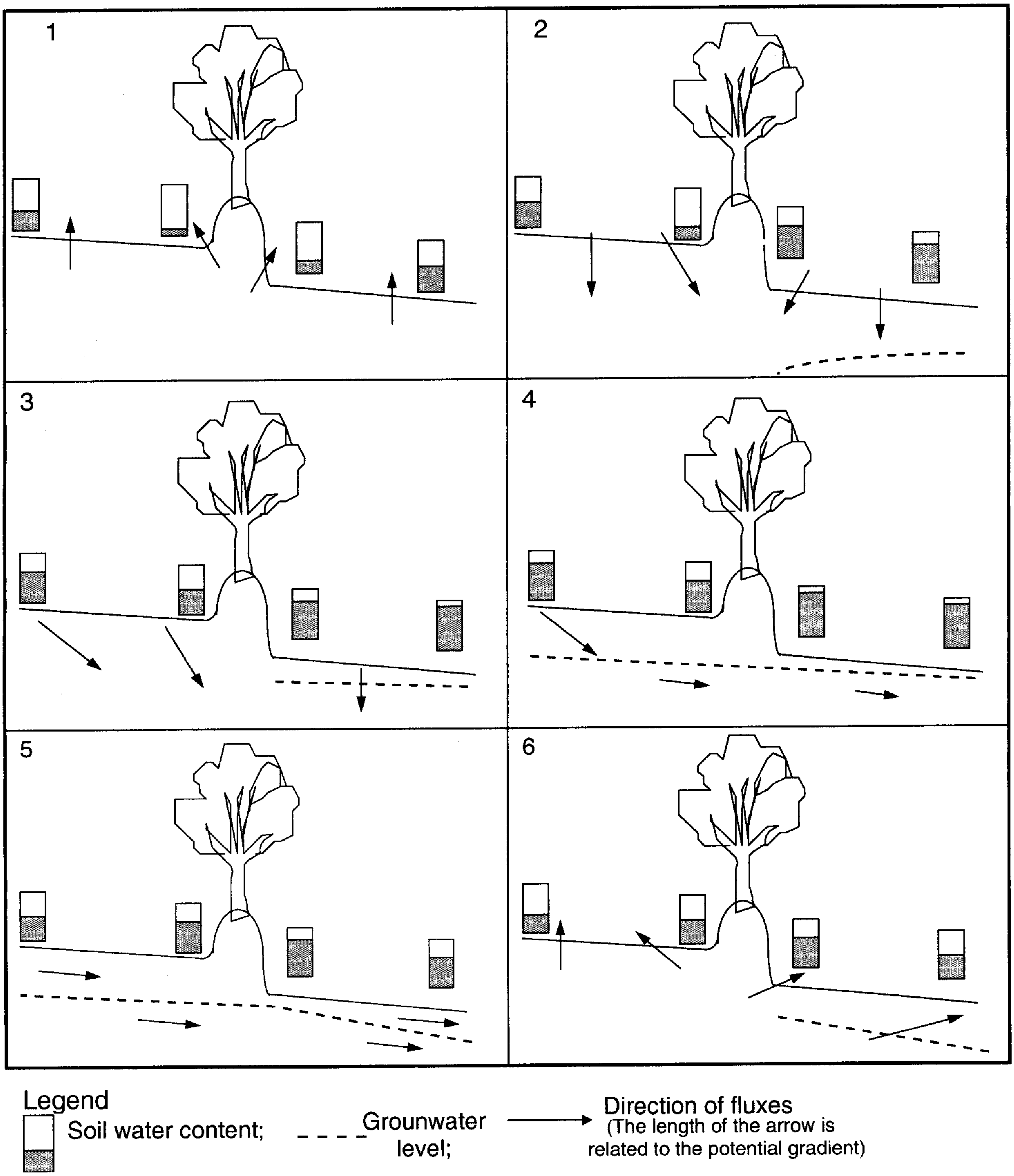

Figure 4. Effect of a bank enclosing valley bottom land on water movement in the soil; interpretation of the measurement of the water potential: 1) end of summer period. 2) and 3) beginning of the wet period. 4) winter period. 5) and 6) spring period and beginning of evaporation (from Forget, [26] modified).

(Hortonian flow), groundwater ridge formation, contribution of the saturated zone of bottom land (contributive zone runoff, [36]). It is now clearly established that the hydrology of the catchment in Brittany is determined by the interaction of 4 compartments: groundwater, saturated zone, which seems to correspond to the hydromorphic soils of bottom land, runoff and hillslope subsurface flow [24, 43]. The hydrology is therefore very much controlled by soil distribution, which is in turn controlled by the topography.

The influence of bocage on quick flow will be considered here at three levels:

– at the catchment outlet, where the storm runoff hydrograph represents a synthesis of the different processes involved in the catchment,

– in the saturated zone at the talweg bottom (contributive zone runoff),

– on the hillslopes (Hortonian flow).

6.1. Quick flow at the outlet of a catchment

6.1.1. Comparison of two catchments

The studies conducted by Merot [40] are based on the comparison of the hydrology of two small (32 ha) catchments, one with and the other without bocage. The bocage network consists of hedges on a bank, with a hedge density of 106 m.ha^{-1} including 64 m.ha^{-1} perpendicular to the slope and, in particular, a continuous bank enclosing the valley bottom. Precipitation and water level flow were continuously recorded on each catchment. The conclusions from this study are the following:

Comparison of storm runoff on a typical event shows that the direct runoff volume and the peak flow [60] was 1.5 to 2 times lower in the bocage catchment than in the non bocage catchment. The statistical analysis of a series of approximately 30 storm runoffs shows that the runoff coefficient, Cr (Cr = storm flow volume/volume of associated precipitation), is stable around 5 %, whatever the winter storm runoff on the bocage catchment, whereas it varies from a few percent up to 15 % on the open catchment (figure 5). In summer, the number of storm runoffs is too small to conclude, but it seems

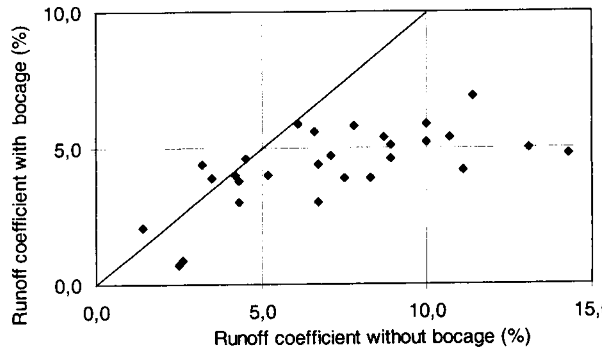

Figure 5. Comparison of the runoff coefficients on 2 catchments, with and without bocage during 2 hydrological years. Each dot corresponds to the same rainfall event and expresses the corresponding runoff coefficient on each catchment.

that the role of bocage on summer storm runoffs is not significant or that it can be reversed (Cann, oral communication) for small storm runoffs.

A deeper analysis can be undertaken (*figure 6*) by looking for explanatory factors which usually involve a factor expressing the state of saturation of the catchment (antecedent rainfall, soil moisture, initial flow of the river, etc.), factors linked to the rainfall event (rainfall intensity, rainfall amount, etc.) and factors linked to the state of the surface (vegetation, soil roughness, etc.). A step by step identification of the main factors gives different results for the bocage catchment and the open catchment. For the bocage catchment, the volume of runoff water depends only on the rainfall amount (*figure 6B*). For the open catchment (*figure 6A*), the volume of runoff water depends on a complex factor (on the x axis) which integrates rainfall depth, Pu (mm) and intensity, Iu (mm.h^{-1}).

$$f(\mathrm{Pu}, \mathrm{Iu}) = \frac{\mathrm{Pu}^{1.2} \,.\, \mathrm{Iu}^{0.6}}{47.2} \qquad (1)$$

Moreover, for this open catchment, two sets can be distinguished, depending on the wetness of the catchment prevailing before the rainfall-runoff event: isolated storms, with the initial soil moisture at field capacity, and successive storms, occurring less than 48 hours after another storm and with an initial soil moisture above field capacity.

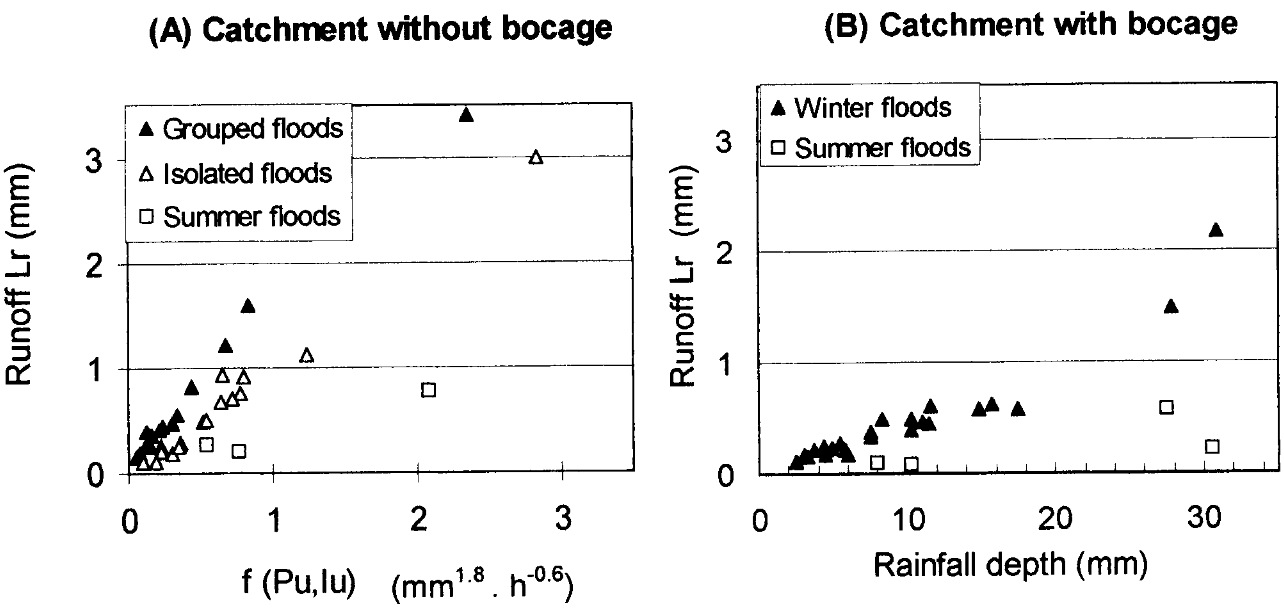

Figure 6. Relation between characteristics of the net rainfall and the runoff depth for the different rainfall-runoff events during 2 hydrological years, for the two catchments.

Unpublished studies of Merot and the study by Blavoux et al. [8] on the hydrochemical monitoring of storm runoff provide interesting information on the water pathways during the stormflow. In an open catchment, the variations of different parameters (Na^+, K^+, SO_4^{--}, NO_3^{--}, Cl^-, O^{18}) are approximately synchronous with the hydrograph, which is not the case in the bocage catchment. In particular, a persistence of dilution after the end of the storm runoff is observed in the bocage, which suggests that water pathways are longer and more complex.

6.1.2 Storm runoff of rare frequency

The preceding conclusions concern a set of frequent storm runoffs and do not apply necessarily to extreme events. It is generally considered that beyond a rainfall amount, all the rainfall runs off (i.e., the gradex method) after a first phase of soil saturation. Whatever the type of surface (bocage, open, urban), there will be the same runoff yield, because the infiltration capacity is exceeded. However, the transfer function [60], which characterises the form of the storm runoff hydrograph, remains specific to each type of catchment. The evacuation time of the storm runoff will be longer in the bocage catchment and the discharge peak will be reduced. However, for the large catchments where the smoothing out of the storm hydrograph occurs essentially in the river, this effect is probably secondary.

6.2. Influence of bocage on the processes generating quick flow

6.2.1. In the saturated zone of the talweg bottom (contributive area flow)

The contributive area flow (saturation and/or exfiltration runoff) is independent of rainfall intensity [36]. All rainfall, whatever its intensity, which falls on saturated soil runs off or penetrates the soil by driving out the same amount of water. This explains the independence of the volume of quick flow with regard to the intensity of rainfall observed on a bocage catchment. The quick flow of a bocage catchment originates mainly from this type of flow for storm runoffs of frequent occurence (*figure 6B*).

The contributive area flow, by its very definition, depends on the extension of the saturated zone. The role of the bank on the extension of the saturated zone connected to the stream was modelled by Merot and Bruneau [41], using a topographic index. The topographic index I_t, is defined as:

$$I_t = \log a/\tan b \qquad (2)$$

where a is the upland drainage area per unit contour length and tan b the local slope angle. It expresses the local potential saturation [7]. High index values correspond to high saturation frequency. This index was calculated for two catchments, distinct only by the presence of a bank, parallel to contour lines, enclosing valley bottom land. In the catchment with the bank, the distribution of the index shows a marked discontinuity between the high and the low values (*figure 7*): For a high saturation probability (index > 12), no difference in distribution occurs. For mean saturation probability (9 < index < 12), the depletion of the dot scattering for the catchment 2 expresses the extension of the saturation is limited upslope by the bank. Consequently, the extension of the contributive saturated zone is limited upslope by the presence of this bank. Its extension varies little during the wet season. The contributive zone flow will therefore vary little with time.

This explains the consistency in the runoff coefficients in a bocage catchment previously reported.

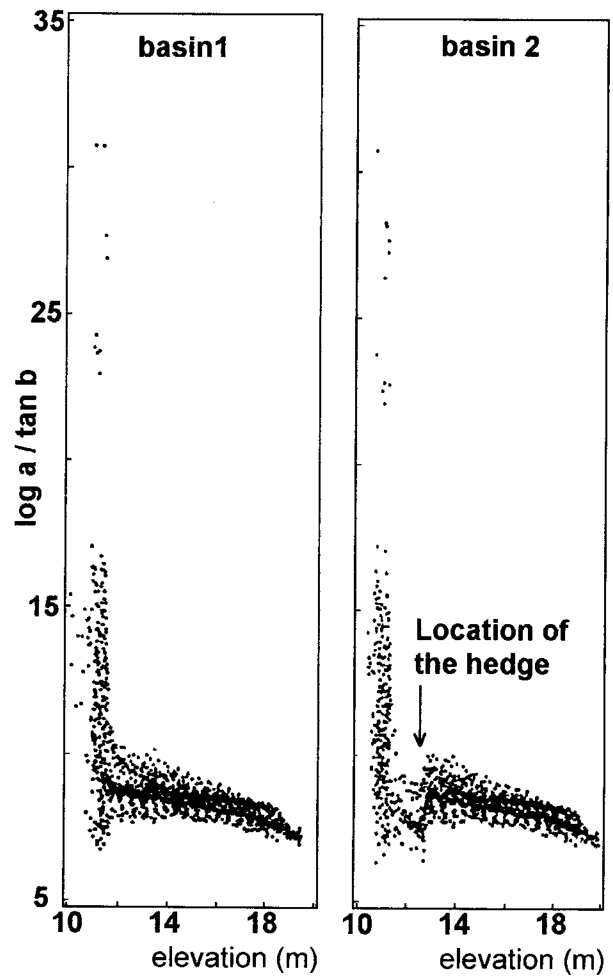

Figure 7. Distribution of the topographic index versus elevation for catchment 1 without bocage and catchment 2 with a bank following the 12.5 m contour line.

6.2.2. On the hillslopes (Hortonian overland flow)

Hortonian overland flow occurs when rainfall intensity is greater than the permeability of the soil surface. Although formerly rare in the western part of France, it is becoming more common, particularly due to intensive agricultural practices and maize cultivation, which leaves the soil bare and leads to surface sealing [27].

The role of banks perpendicular to the slope as a barrier to Hortonian overland flow is immediately perceptible. The upper side of the bank being both, higher and more level because of the accumulation of eroded particles, and more permeable because of the roots, reinforces this role.

The bank, when it is not perpendicular to the slope, and allows water to reach the river can act as an element of the anthropogenic drainage network, by modifying the surface water pathways. It extends the length of transfer to the outlet and therefore the transfer time.

On the other hand, the absence of bocage should make it possible to observe an Hortonian overland flow with larger surface flows than on a comparable bocage catchment. The observations made on a catchment without bocage (*figure 6A*) can be explained mainly by hortonian overland flow, as the flow depends on rainfall intensity and on the wetness of the catchment.

These considerations have led Zhang [65] and Merot et al. [44] to analyse the modification of surface water pathways by actual bocage networks, characterised by the most varied discontinuities and orientations as regard to the slope. It involves spatial modelling combining the digital elevation model of a catchment and the map describing the network of hedges. The objective was to model the superficial drainage network (that is, all the flow lines onto the catchment) as it is modified by the presence of hedges. *Figure 8* presents a scheme of the modification of the drainage network by a hedge. The authors compared the effect of bocage on three parameters: the slope of hedges, pixel, the length of flow lines and the number of pixels disconnected from the river (*figure 9*) for five situations: the Coët-Dan catchment (south of Brittanny) in 1948 (known maximum of the network density on this site) with 71 m.ha^{-1}, and 1992 with 39 m.ha^{-1}, and three other sites with contrasted densities of bocage (69, 160, 196 m.ha^{-1}) in the Mont Saint Michel region.

The major results are the following. The drainage network modified by the hedgerow system was very different from the one derived from the topography: the contributing area of up to 90 % of the pixels has changed, in the sense that they drain either more or fewer pixels upslope. This modification in the network is correlated to the overall density of the hedges. However, the most important effect is the disconnection of certain branches of the drainage network, which was previously continuous down to the outlet. Certain hedges play the role of sinks, where the water can only infiltrate (hedges parallel to the contour lines). These sinks, by blocking the runoff, control an area that can reach up to 40 % of the total catchment area (*figure 10B*), since the hedges are located on major flow lines on the slope. The whole density of hedges (*figure 10A*) is a poor indicator of the efficiency of the hedge network, because it does not take into account the location of the hedges on flowlines. Modifications are also observed for the length of the runoff: without hedges, the potential length of runoff is equal to the length of each hillslope. With a hedge parallel to the contour lines, this length is segmented on each hillslope. The bocage reduces on average this length of runoff, but in small proportions (10 to 20 %). A change in the distribution of these lengths is also observed, with an increase in the category of runoff lengths

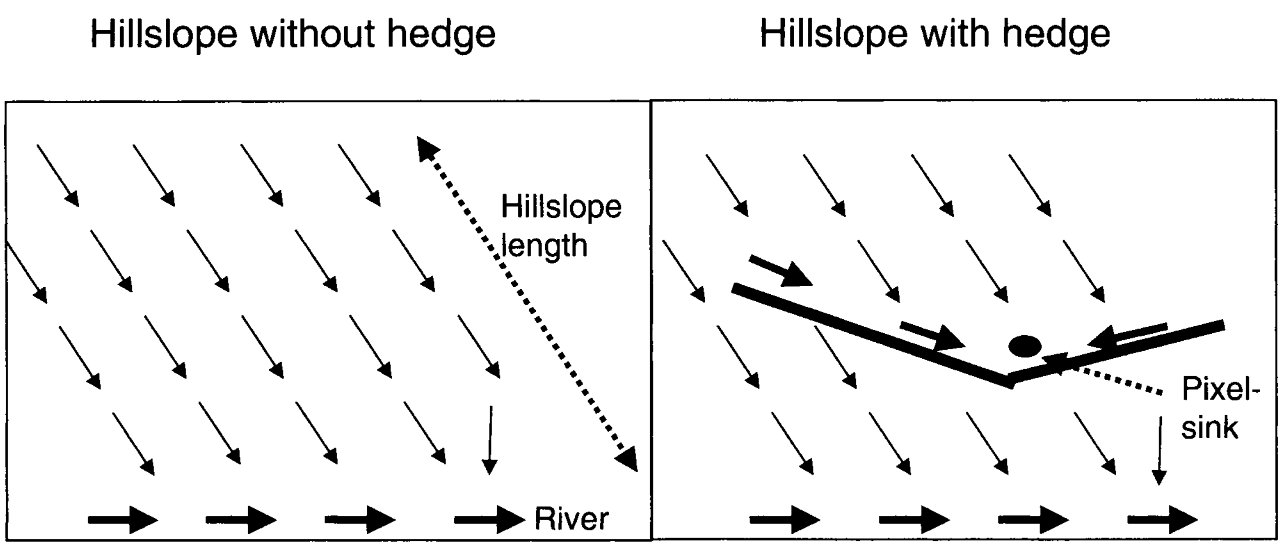

Figure 8. Modification of the drainage directions by a hedge.

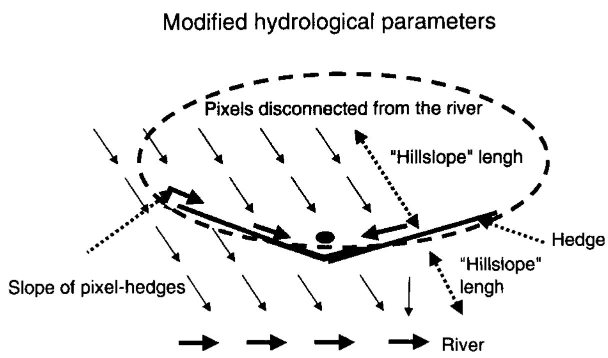

Figure 9. Hydrometric parameters modified by a hedge.

lower than 250 m and a decrease in the runoff lengths higher than 500 m. The mean slope of the hedge-pixels, calculated according to the modified flow direction, also decreased by approximately 50 %.

7. Conclusion and future directions

The presence of bocage leads to a segmentation of the landscape within catchments. This segmentation increases the heterogeneity of the environment at a local scale, around the hedges (distribution of soils, rainfall, soil moisture, radiative balance, etc.). Whereas the distribution of many of these variables in open areas is most often determined by the topography which creates gradients along the hillslopes, in bocage landscapes there is a variation of smaller wavelength, determined by the distance from the hedge, but presenting a dissymmetry related to the topography.

The effect of bocage on AET and PET at the catchment scale, depending on the density of the whole hedge network, is not very apparent considering the low densities of the present bocage networks. Although the experimental studies found no significant difference neither in AET nor in PET in catchments with or without bocage, more theoretical approaches suggest that in an area with bocage there should be a decrease in PET and an increase in AET, of a few percent in each case.

Others variables, characterising surface processes (runoff, erosion) depend on the structure of this network. The effect of a few hedges located in key situations – hedges parallel to the contour lines and crossing flow lines controlling a important part of the drainage network – can affect significantly

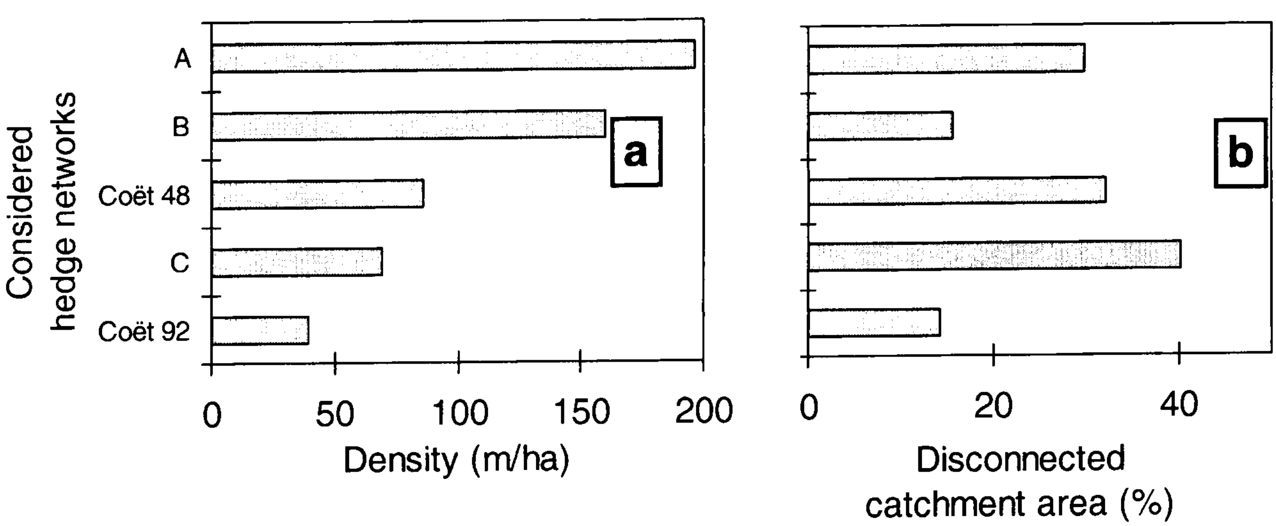

Figure 10. Influence of a hedge network on the connection of the drainage network: a) density of the hedge network on 5 sites, b) percentage of the catchment area disconnected from the hydrographic network (from Merot et al. [44]). The five sites are presented in the same order on *figures 10A* and *10B*.

runoff and erosion, even when the overall density of the bocage is low. In a case study, the direct runoff volume and the peak flow was 1.5 to 2 times lower in the bocage catchment than in the other. This role could be important, because the occurrence of Hortonian runoff increases on intensively cultivated fields. The hedges enclosing valley bottom land play a determining role, because they can also limit the extension of saturated areas connected to the hydrologic network. They can limit the surface runoff on contributing zone, which is the major process for surface flow in this region, for flood of high frequency.

While the main features of the effect of bocage on hydrology are established, further work is needed in the following directions:

• the relative role of bocage depending on the context, particularly the geological context, or how hydrological impact of bocage depends on the relative volume of superficial flow and deep flow.

• the role of bocage depending on the nature of the hedge: this entails knowing to what extent the results obtained in bocage landscapes with hedges on banks are applicable to systems with hedges without banks.

• upscaling: the influence of the bocage can be measured on the local scale and on small catchments, but it has not yet been integrated at larger scales.

On the methodological point of view, the contribution of new techniques in hydrology, such as distributed hydrological modelling and geographic information systems, should make it possible to quantify the effect of bocage, but the results presently available are partial and often qualitative. New approaches, such as landscape ecology, should also bring a new vision of the relationships between landscape structures and flows [58].

Finally, the effect of bocage on water quality, either on its own or in synergy with other landscape structures (riparian forests, wet bottom land areas) is a new and important concern.

It has been demonstrated that bocage landscapes in the Western France [34], unlike other wooded linear systems encouraged elsewhere in the world, have lost their relevance for agricultural production in the present intensive agricultural context of this region. On the other hand, it still plays an important role in regulating water resources and conserving water and soil resources. These collective functions, as well as its ecological role, must lead us to reconsider this type of landscape.

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