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Hydromorphic soils, hydrology and water quality: spatial distribution and functional modelling at different scales

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Abstract

The hydrology and water quality in landscapes with hydromorphic soils depends on the space and time extension of wetland areas and on water pathways within the landscape at different scales. To study the control of nitrate fluxes by these areas, investigations were carried out on a detailed study site - the Coët Dan catchment (1200 ha) in Brittany, France - involving various disciplines: pedology, soil physics, hydrology, geochemistry and agronomy.

An attempt of functional modelling at different hierarchical levels from the horizon level (i - 1) to the region level (i + 3) of soil distribution, extension of saturated areas, horizons physical characteristics, water transfer in a multilayer soil profile and nitrate fluxes was carried out. The soil system, which can be described as a spatial arrangement of a limited number of horizon types with genetic relationships, is tightly controlled by topography. Predictive models of hydromorphic soil distribution using different topographic indexes and DEM were established. Regarding to their hydrodynamic properties, horizons of the soil system have been classified into “building blocks”, which allows to define physically based parameters for a two-dimensional multilayer water transfer model. A four compartment model of flood genesis based on chemical data obtained from different parts of the catena and from the river was coherent with the multilayer hydrodynamic model. The mean nitrate concentrations in several subcatchments were negatively correlated with the percentage of hydromorphic soils. These studies reveal that the hydromorphic zones had an effect on the nitrogen transfer in the catchment, but this effect is limited by the importance of water pathways by-passing the buffer zones. The conclusions of this programme have direct outcomes for designing new landscape management options.

Introduction

The continuous modernisation and development of agriculture in Brittany over the last 30 years have placed it in the first french and european regions for pig, dairy and vegetable productions. The environmental consequences of such a development have been underestimated: this region is also one of the most polluted rural areas in Europe, especially for soils and surface waters. A significant part of the area shows a structural excess of nitrogen due to the density of indoor farming. The problem is so acute that it threatens all the economical assets of the region, such as tourism, seafood production, and even agriculture itself, through the problems of water supply and the increasingly negative public image of the products.

The CORMORAN multidisciplinary programme (a french acronym for characterization, observation and modelling of mass and energy transfers in intensive farmland environments) was launched in 1991 in this context by INRA (national agricultural research institute). The main aim of this programme was to understand the impact of the physiographic structure of an agrosystem on the water pathways and on the control of the surface water quality. The idea was to check whether a short term and cost efficient improvement of the water quality was possible by changing the landscape management and restoring partially the natural buffering capacity of the system. This led to conduct the investigations at a hydrological and landscape unit level, i.e., a catchment, and to focus on the description

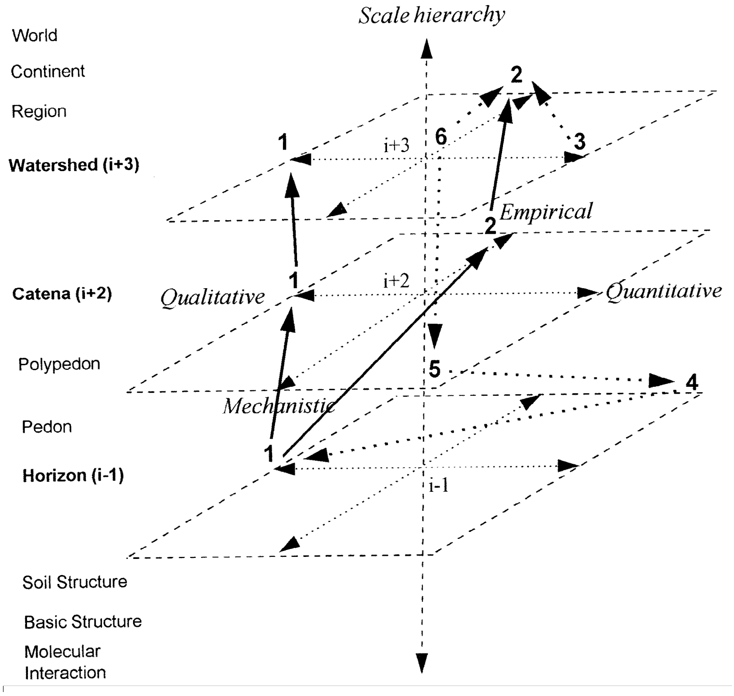

Figure 1. The sequence of knowledge levels at different scales for the Coët Dan study (after [23])

of the spatial structure of the processes governing the water transfers.

The main hierarchical levels of investigation [23] are the soil horizon (i - 1), the catena (i + 2) and the watershed (i + 3) (Fig. 1). A conceptual qualitative pedological approach (1) links by upscaling the different levels of organization. The other semi-quantitative or quantitative approaches are developed at a given level but referred to the pedological approach. Three research chains have been developed. One deals with spatial distribution of hydromorphic soils. It includes: (i) a conceptual qualitative model of soil distribution based on pedology (1) and an empirical semi-quantitative model of spatial distribution of hydromorphic soils using topographic data (2); and (ii) an empirical quantitative hydrological model of the extension of saturated areas (3). An other chain deals with the water transfer in soils. It includes regrouping of pedological horizons according to their hydrodynamic properties (4) and a quantitative mechanistic model of the transfer in the bottom slope catena (5). The third chain deals with the influence of water pathways on water quality (6). It includes an empirical semi-quantitative model of endmember mixing during storm flow referring to previous studies at the horizon and catena levels and an empirical semi-quantitative approach of the influence of the extension of hydromorphic soils on water quality at the catchment level.

The experimental catchment

The Coët Dan catchment, near Naizin (Central Brittany) was chosen because it is fairly typical of the landscape and agriculture of the region, and because both the hydrology and water quality have been monitored since 1978 by CEMAGREF [12]. The catchment is included in the ERB (European Research Basins) network.

The total area of the catchment is 12 km^2. The bedrock is Brioverian (Primary) schists. The soils are developed on a silty material that is a mixture of weathering products and Quaternary eolian deposits. The elevation ranges between 65 and 136 m above sea level. The climate is oceanic. The mean annual rainfall over 22 years is 713.5 ± 125 mm and the mean annual discharge is 305 ± 168 mm. The agriculture is dominated by indoor pig farming and intensive dairy farming. Maize is the most important crop, which has progressively replaced the permanent pastures. The mean annual nitrate concentration at the outlet of the catchment has increased from 1.5 to more than 15 mg

l^{-1} N-NO_3^- in the last two decades. However, the nitrogen losses at the outlet of the catchment account for a minor part (10 to 20%) of the excess of nitrogen resulting from the unbalanced agricultural budget [12].

Identification and organization of the pedological system

In the armorican massif, under oceanic temperate climate and on acid rocks (granite, schists and sandstones) with a silty loam cover, the pedological and micromorphological research, carried out for the last twenty years on detailed study sites (2 - 50 ha) and the 1/100,000 soil survey reveal the association of a few soil types according to the “Référentiel Pédologique” [4]. “Alocrisols” and “Luvisols” occur in a well drained domain on one hand and “Luvisols - Rédoxisols” and “Luvisols - Rédoxisols dégradés” occur in a poorly drained domain on the other hand (Dystrochreps, Hapludalfs and Glossaqualfs [31]). This association results from three dominant processes: leaching of clay particles, hydromorphy and degradation which produce a limited number of horizons (seven) with a determined spatial arrangement (topology) and genetic relationship (chronology) (Fig. 2).

In the well drained domain, acid conditions (pH between 5 and 6) lead to the development of a microgranular structure in the Sal horizon (Fig. 2) of the Alocrisol [3] and the leaching of clay particles occurs in the whole domain. Depending on the thickness of the loamy cover, this clay migration causes clay illuviation in the saprolite down the “Alocrisol” or the development of an illuvial B horizon in the loamy cover when it is thick enough in the “Luvisol” [16].

Micromorphological analyses [30, 16, 37] reveal the relative chronology of the processes taking place in the poorly drained domain. In the “Luvisol Rédoxisol”, iron redistribution due to hydromorphy follows clay particle accumulation. The degradation process in acid and reducing conditions occurs afterwards in the “Luvisol Rédoxisol dégradé”. This phenomenon covers geochemical, mineralogical and morphological aspects simultaneously, resulting in: (i) geochemically, a loss of iron and clay mineral hydrolysis, (ii) mineralogically, a relative increase of quartz in the clay fraction and an aluminisation of clay interlayer spaces, (iii) morphologically, the bleaching and the loss of structure of the reduced volumes [30]. This structure loss leads to an important macroporosity when non degraded volumes are still present and maintain the global architecture. This is the case of the BTgd horizon where the resulting macropores are the centre of preferential flow [19]. On the contrary, when degradation concerns the whole horizon, structure collapse is total and leads to a compact massive structure, as a result of the silty texture of the material. This is the case of the eluvial albic horizon Ea, a horizon of very low permeability that induces hypodermic subsurface flow.

Detailed studies of catenas show that hydromorphy, increasingly accompanied by degradation, appears from upslope to downslope starting at the basis of the silty horizons and gradually reaching the outer surface (Fig 3). Therefore, an increasing development of hydromorphy and degradation in originally well drained horizons seems to be caused by an excess of water of topographical origin. A pedological system from a well drained domain to a poorly drained domain is thus defined.

The detailed survey of the stream banks reveals a second type of colluvio-alluvial system comprising an association of hydromorphic soils, whose organization and relationships with the downslope limit of the previous system are still not well understood. In the case of Coët Dan catchment, as far as the hydrodynamic properties are concerned, this colluvio-alluvial system can be assimilated to the downslope end of the hydromorphic and degraded domain.

The 1/25,000 Coët Dan catchment soil map was established from a free sampling (900 auger holes) completed by extrinsic factors (topography, surface characteristics, vegetation, etc...) [35]. The map exhibits a main structure differentiating the soils of plateaus and slope from the soils of bottomlands. Considering the soil systems previously defined, it appears that the “complete” catenas including the degraded and alluvial soils are observed in the upstream part of the catchment while in its downstream part, where topography is more pronounced, the passage from well drained to alluvial soils is often direct.

Modelling the spatial distribution of hydromorphic soils using topographic data

Since the maps of these pedological systems are scarce at a regional scale, and considering the increasing interest placed on wetlands, a predictive model of their location, based on topography, was developed as an aid for soil survey. The model was built using data collected along topographic transects and validated by

REFERENCE	ALOCRISOL	LUVISOL	LUVISOL REDOXISOL	LUVISOL REDOXISOL DEGRADE
PEDOLOGICAL HORIZONS	Structural aluminique **Sal**	Eluvial **E**	Eluvial rédoxique **Eg**	Eluvial albique **Ea**
		Illuvial **BT**	Illuvial rédoxique **BTg**	Illuvial rédoxique et dégradé **BTgd**
DOMAINS	well drained domain		poorly drained domain	

Figure 2. The pedological horizons of the "Alocrisol - Luvisol/Luvisol - Rédoxisol dégradé" soil system in the silty loam cover. The symbols used were the following: S for cambic horizons, E for eluvial horizons, BT for illuvial horizons, -al for dystric properties, -a for albic properties, -t for evidences of clay accumulation, -d for leaching and tonguing features, -g for pseudogleyic features, according to [4]

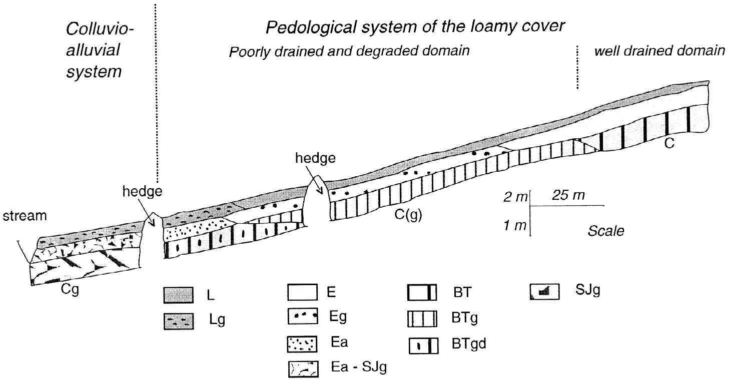

Figure 3. Organization of the horizons along a typical soil transect in the Coët Dan catchment.

an independent data set at the catchment scale. It was then tested in an other catchment.

Model construction

Detailed pedological and topographical data were collected from 15 transects established in various topographic situations from the stream to the hill top. On each transect the different horizons were delimited precisely by auger holing. In each point of a transect, the following parameters were available: (i) hydromorphy intensity (0: absence of hydromorphy to 3: hydromorphy of the whole profile) and (ii) two topographic indexes, the elevation above nearest stream level [15] and an index (log[drained area / slope gradient against stream]) adapted from [6]. This latter index takes into account the converging drainage lines due to the slope shape at each point of the transect. A strong relationship appears between hydromorphy intensity and the two topographic indexes (Fig. 4). The predictive model is based on the splitting of the topography indexes in four classes [34]: for each class the predicted hydromorphy intensity is the one that appears more frequently on the graph.

Model validation

The model validation was carried out over the whole catchment on two data sets collected independently from the one used for the model construction: (i) 487 observation points used for soil mapping and (ii) the pedological map itself which gives an image of hydromorphy intensity, though with some uncertainty, throughout the whole catchment. In both cases, topography indexes were derived from a 30 m-grid Digital Elevation Model (DEM). The percentages of right prediction for both data sets show that the hydromorphic soils are better predicted (58% and 65%) than the overall population of soils (46% and 50% respectively). Figure 5 shows the hydromorphy intensity maps obtained using the DEM and the pedological map. The extension of hydromorphic areas appears very similar in both maps. The main discrepancies concern plateau areas with well drained or weak hydromorphic soils. Prediction errors can be attributed to three causes: (i)

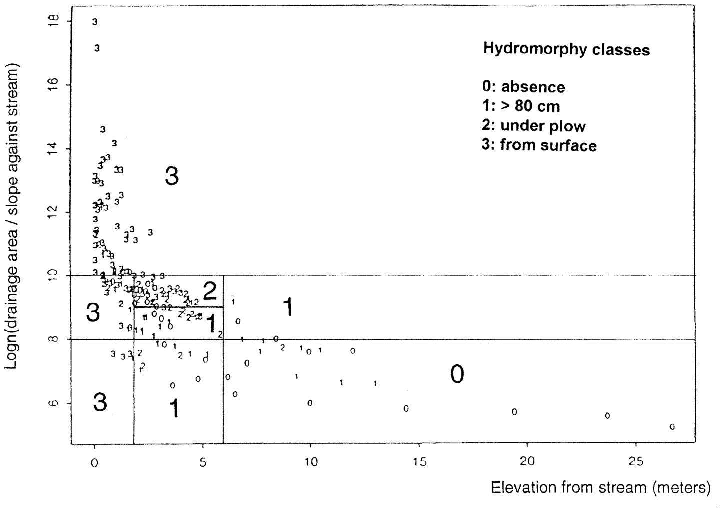

Figure 4. Hydromorphy intensity of the profiles in a plot of Beven Kirkby index versus elevation above the stream

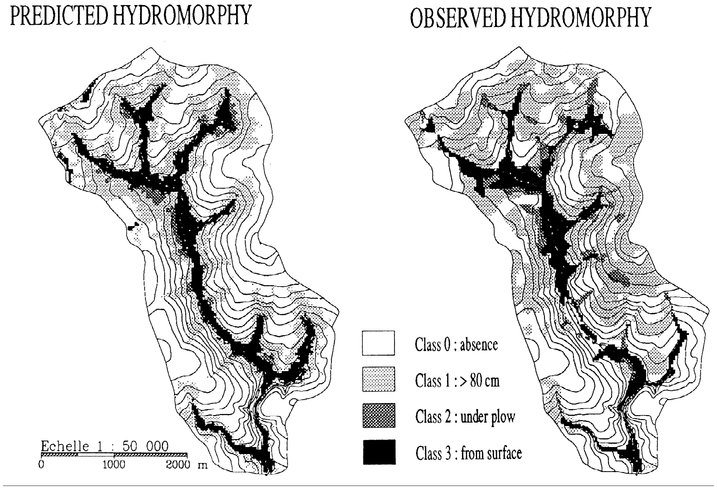

Figure 5. Comparison of hydromorphy intensity predicted by the topographical model and observed on the pedological soil map

the nature of the model itself, which ignores hydromophy of a lithologic origin (variation of the permeability of the bedrock) [17]; (ii) the imprecision of the DEM (elevations, location of the drainage network); (iii) the anthropogenic perturbations (artificial drainage, hedges, ...) which modify the soil characteristics.

In order to check the extrapolation capacity of the model, it was applied to another catchment in Normandy [1] which presents the same pedological systems on a loamy cover overlying a predominantly granitic bedrock. A similar percentage of right prediction of hydromorphic intensity was observed (60%) without any modification to the topographic parameters.

Structure of the bottomland contributing areas: hydrological modelling, temporal and spatial sensitivity of the model

The approach presented above give a static picture of the waterlogged domain. Here are introduced the variations in space and time of this domain. In different geographical contexts, even outside the humid temperate european zone, the contributing area concept is used to explain the hydrology of small catchments

[24]. According to this concept, hydrological processes are assumed to be mainly controlled by the saturated area, also called contributing area, generally connected to the natural drainage network. The extension of this saturated area varies in space and time with the weather variations.

The TOPMODEL [5, 6] is a spatially, semi-distributed and physically based hydrological model. It is based on the variable contributing area concept and the use of a topographic index, the Beven-Kirkby index, calculated from a DEM. The distribution function of this index characterizes the catchment geometry. The hydrological behaviour of a grid node is dependent on the index value in the node. The climatic and water flow time series are required to apply and calibrate the model. The model computes for each time step the extension of the saturated area.

This model was applied on the Coët Dan catchment during a two month winter period to estimate the extension of the saturated areas. Surface runoff due to saturation represents about 9% of the total flow for that period. The influence of space and time resolution on estimation of the total flows, runoff flows and on the temporal variation of saturated areas extension was performed using the following variation range of input data [11]: (i) six DEMs, independently calculated from scanned 1/10,000 contour data, whose grid sizes were respectively 20, 25, 30, 50, 70 and 100 m.; (ii) seven time steps: 30 minutes, 1, 2, 4, 7, 12 and 24 hours.

Saturated area extension

During the study period, the saturated area extension in terms of their relative saturation duration is hardly affected by space and time resolution except for the largest time steps (Fig. 6). The relative saturation duration is validated according to the spatial extension of pedological hydromorphic features: it is assumed that hydromorphy intensity corresponds to a duration of soil saturation. The estimation of the saturated area extension over the period agrees fairly well with the soil survey data: the area of permanent saturation matches with the alluvial and degraded soil area and the area saturated during 10% of the study period matches fairly well with the area of soils hydromorphic up to the surface. In short, the model gives consistent results in terms of saturated areas extension in practically most of the resolution domain studied for a medium spell of time.

Model sensitivity analysis to space and time resolution

The modelling efficiency, defined according to [28] criterium, to predict total flows is higher than 90% inside a domain delimited by pairs of space and time values: (70m; one hour), (50m; two hours), (30m; four hours) [11]. Outside this domain, the efficiency decreases, more rapidly with an increase in time step than in grid size. The predicted contribution of surface runoff increases continuously with time step and grid size, and the contribution of the baseflow becomes inconsistent beyond a time step of four hours. The surface runoff depends directly on the saturated areas estimated by the model.

This hydrological modelling approach shows that: (i) to estimate the relative saturation of the soil during a few months, rough temporal and spatial resolutions are sufficient while (ii) to estimate saturated areas extension or conversely to validate predicted runoff flows, accurate temporal and spatial resolution is required: one hour time step and 30 m grid size.

This approach bears two interesting perspectives concerning the location of the saturated areas. Firstly, the comparison of the observed and simulated saturated areas extension is an additional criterion for the model validation. Secondly, this information on saturated area extension may well become easy to acquire in the near future by radar techniques [10, 25] which will facilitate the model extrapolation to non-research catchments.

Hydrodynamic characteristics of the pedological horizons of the soil system

The conceptual hydrological approach showed the functional validity of the separation in two domains. The soil system study identified a small number of horizons and their topological relationships. The next step was to test the interest of this stratification to predict the hydrodynamical properties of the soil [7, 9]. For this purpose saturated hydraulic conductivity (Ksat) and water retention curves of the seven horizons were studied in detail [37, 38] and an attempt to group these horizons following the “building blocks concept” [7] was done.

Saturated hydraulic conductivity

Ksat was determined on 29 detached cubes (8,000 cm^3) according to [8]. Ksat data were lognormaly distribut-

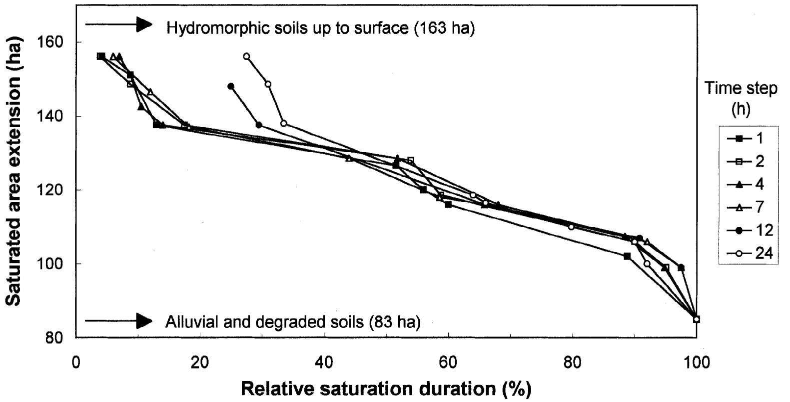

Figure 6. Simulated saturated area extension versus relative saturation duration during a two months period for six time steps.

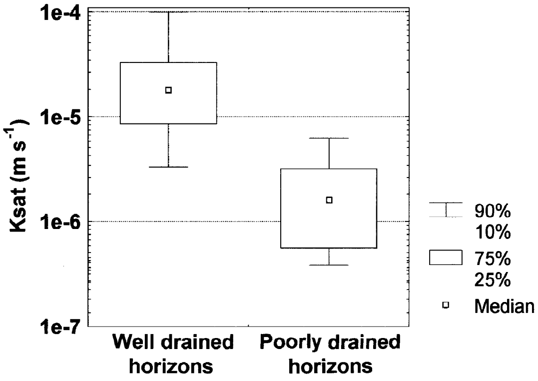

Figure 7. Saturated hydraulic conductivity of the well drained and poorly drained horizons.

ed. Ksat of the well drained horizons (Sal, E, BT) were significantly higher and more scattered than Ksat of the poorly drained horizons (Eg, Ea, BTg, BTgd) (Fig. 7) which led to define two “building blocks”.

Water retention properties

The water retention was determined on undisturbed cores at six potentials using a suction table down to -24.6 kPa [32] on 250 cm^3 cores and a Richards’ apparatus down to -1550 kPa on 10 cm^3 clods. For each horizon, three to ten measurements were carried out on samples coming from a 50 ha reference zone. Statistical analyses involving mean comparisons and discriminant factor analysis (DFA) allowed to group these horizons. These groups are significantly different from each other and the intra-group variability is lower than the overall variability [37].

The DFA on the measurements of the retention curves led to create three building blocks, each block being defined by the mean values and standard deviations of the water contents at six potentials. Block I comprises the Sal and E horizons, block II, the Eg, BT, BTg and BTgd horizons and block III the Ea horizon (Fig. 8A).

Further investigations were done on the water retention curves [36] to validate the previous stratification in three building blocks, to test their stability and to evaluate the prediction errors.

A new data set has been realized using a sampling strategy based on the existing soil map. For each horizon, five sites were chosen randomly among the mapping units where the horizon was theoretically present. If the horizon was not effectively present, the site was rejected and a complementary site was chosen. In each site, two cores, a least one meter apart, were sampled. On each of the ten samples of a given horizon, the water retention was measured as previously.

The data from the validation set (Fig. 8B) were grouped in the same way as the original one. The order between the three blocks is conserved, block I showing higher moistures than block II and III. Within a given block, no significant differences appeared between the original and the validation set, except for block I, where the validation set gives lower means (Student t test at 0.05) for 0.25 and 25 kPa.

Stability of the building blocks was then tested using the discriminant functions estimated by DFA on the initial set which were applied to the horizons of the validation set to identify the block in which that individual fall. Their attachment to one of the three building blocks is so based on their measured water content at the six potentials. The comparison between the blocks predicted by this DFA and the one deduced from the morphology is given in Table 1. The two pre-

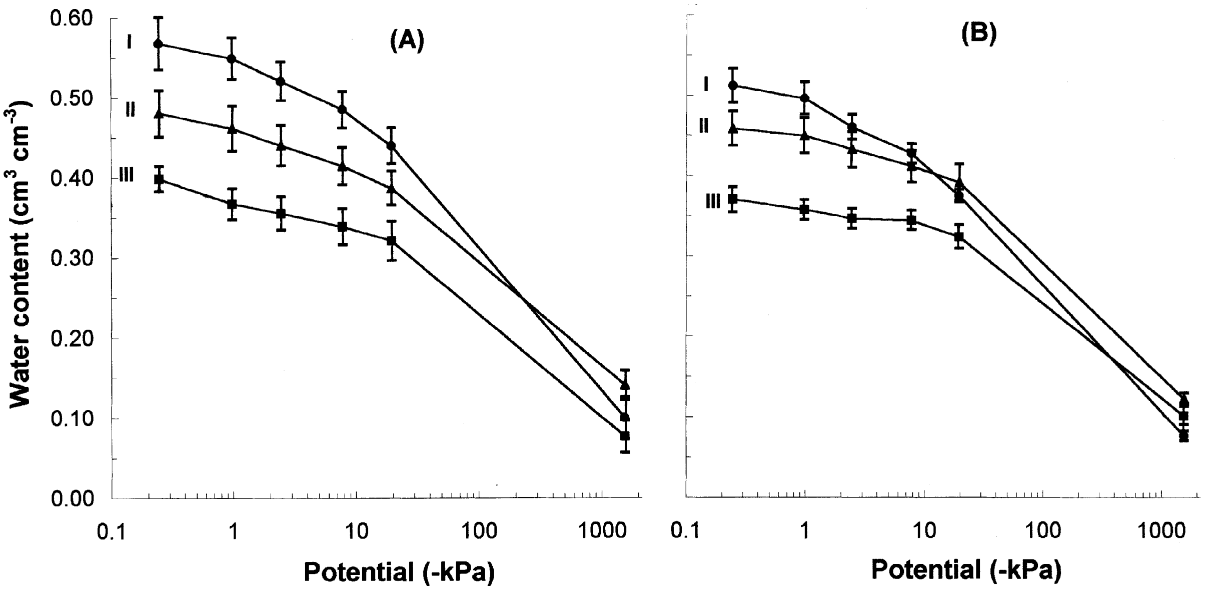

Figure 8. Comparison of the retention curves of the three building blocks in the initial (A) and the validation (B) data sets. For each potential, mean and confidence interval ($t_{0.95}$) of the water contents.

Table 1. Matching table of the horizon types (i.e., building blocks) deduced from morphology and from Discriminant Factor Analysis, for the validation dataset.

DFA types ⟶ morphological ↓	I	II	III	*Total*
I	**14**	1	4	*19*
II	0	**15**	**14**	*29*
III	0	0	**9**	*9*
Total	14	16	27	**57**

dictions are identical in 65% of the cases. The main discrepancies are found for block II, where some individuals showed very low moistures leading to rank them in block III. However, the significant differences of the mean values observed for block I had no incidence: The E and Sal horizons showed high water retention and steep retention curves which are typical of block one.

The errors induced by the use of mean block values to estimate the retention properties of a given horizon are given in Table 2. The mean deviation between estimated and measured values is always positive: a slight overestimation of the soil moisture is obtained. The relative deviation generally ranked from 10 to 15%, except for -1550 kPa (25%). When considering a soil with a water retention capacity of 250 mm (calculated between -7.8 kPa and -1550 kPa), this corresponds to an error of about 6 mm. These first results obtained on a reference site and validated at the catchment scale show that the soil horizons can be grouped in a smaller number of building blocks, depending on the parameter considered: two blocks for Ksat and three blocks for the retention curves. These groupings illustrate that in soils relatively homogeneous in texture, the structure variations induced by the pedological processes are dominant. The hydrodynamic properties of the horizons worsen when soil formation progresses, due to silty texture: when iron and clay are lost, the structure collapses.

A two dimensional multilayer water transfer model

The development of temporary shallow perched water tables (vadose saturated zone) at the interface between the upper horizon Lg and Ea horizon, in the poorly drained domain, was observed from tensiometric measurements [39]. To test the hydrological behaviour of the poorly drained soils in the valley bottoms and to separate the specific contributions of the different soil layers, a mechanistic model making full use of the study at the soil horizon level was used. This mod-

Table 2. Deviation between measured soil moisture and soil moisture estimated by the mean building block values. θ^* and θ stand for the estimated and measured soil moisture, respectively.

	θ-0.25	*θ-7.8*	*θ-1550*	*θ-7.8-θ-1550*
mean deviation (cm^3 cm^{-3}) $\theta^* - \theta$	0.033	0.019	0.012	0.006
mean square deviation (cm^3 cm^{-3}): $\sqrt{(\theta^* - \theta))^2}$	0.062	0.053	0.028	0.044
relative deviation (%) $\frac{(\theta^* - \theta)}{\theta}$	12	12	25	13

el, the Hillslope mechanistic model (HM Model) [21, 33] simulates the two dimensional hydrodynamics of a layered section of hillslope. To describe a typical bottomslope of the area, three horizons have been distinguished: Lg, an old ploughed horizon with pseudogleyic features which now supports a grassland; Ea and BTgd.

The HM-Model uses the classical equation of mass transfer, using only in this first stage the measured saturated hydraulic conductivity of the horizons. The model uses the finite difference method to solve the two dimensional transient saturated-unsaturated flow equation [29]. The application of the model was only a simulation exercise, with no calibration nor validation against real data in this first work. The aim was merely to have an idea on the hydrological behaviour of the soil system described. However, the general trends obtained agreed well with in situ observations and with the shape of the hydrographs at the outlet of the catchment.

Different rainfall events have been tested, showing that the contribution of the upper layer rises rapidly after the beginning of the shower and stops relatively quickly after the end of it (Fig. 9). These results suggest that the importance and dynamics of the stormflow response depend strongly on the development of the shallow perched water table in the upper layer Lg. At least, two compartments corresponding to two different flow paths contribute to streamflow in Coët Dan catchment.

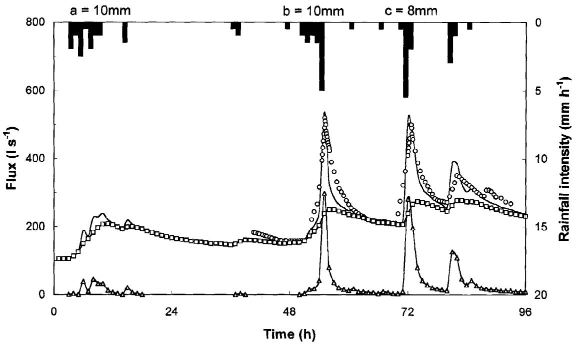

Figure 9. Simulated contribution by application of the HM-model of the perched water table (△) and the deep groundwater (☐) to the total hydrograph (–), (observed hydrograph = ○)

The influence of water pathways on water quality

The potential of bottomland hydromorphic zones to decrease the nitrogen fluxes to the surface water via denitrification and biological uptake is well documented (e.g., [22]). In the Coët Dan catchment, detailed hydrogeochemical studies and denitrification measurements at the local scale have demonstrated that this potential should be high enough to keep the nitrate concentrations well bellow their actual level [18]. Given the results of the soil and hydrology studies in the catchment, it was assumed that these potentially highly denitrifying zones did not fully act as buffer zones because of the water pathways. This can be due, firstly, to the hydrodynamics of the bottomland that do not allow the transfer of nitrate through the denitrifying sites; secondly, to the "by-passes" existing in this intensively cultivated landscape. The study of the first process requires local measurements: the results are briefly summarised here; the study of the second process is necessarily carried out at the catchment scale: this will be described in more details.

Water and solute transfer in hydromorphic zones

The chemistry of free soil water was monitored at the transition between a cultivated, hydromorphic field and a non cultivated zone with hydromorphic and degraded soils. Additionally, the solute transfer was studied by coupling infiltrometry and experimental tracing (especially after [14]). Both studies showed that water transfer in the saturated zone was mostly lateral, with a contrasted behaviour of the surface horizon (L or Lg) compared to the deeper horizon (BTg or BTgd). In the upper horizon, water flows quickly during and shortly after the rainfall events. This water, diluted by the rainwater, exhibits relatively low nitrate concentrations except just after fertilizer applications. In the lower horizon the transfer is slow but the nitrate concentrations are generally higher: it concerns the slowly percolating water from the cultivated zone. The results of both studies are far too limited, both in terms of spatial representativity and number of observations, to allow generalization and quantification at the catchment scale, but they helped completing the conceptual framework of the mixing model analysis performed at the catchment scale.

Mixing model

The hydrochemical variations in streamwater at the outlet of a 4.9 km^2 subcatchment during storm events were explained using a four endmember conservative mixing model to separate the hydrograph [20, 27]. The hypotheses on which this approach is based, and its applicability in agricultural catchment are discussed in detail in [20]. In summary, the main hypotheses are: the solutes are conserved during mixing and subsequent transfer; the endmembers (= water types) have contrasted, and constant, chemical fingerprints during the events. Three solutes were used to solve the equation system and the other solutes were used to validate the model. The solutes chosen for the computation were not the same for all the events: nitrate, chloride, silica, magnesium, alkalinity, ^{18}O and sulphate were alternatively used, depending on their variations during the event. A sensitivity analysis was performed for the uncertainty on the endmember compositions. The model was applied on six storm events in different seasons and with contrasted hydrological features.

The four endmembers were defined following the converging conclusions of the studies in hydrology, pedology and biogeochemistry. The pedological studies described above helped to delineate the domains where the different fluxes could occur and to locate the sampling points. The hydrological studies were used to define these fluxes and to provide a cross check of their dynamics. The biogeochemical studies, not described here because they are not explicitly included in the research chains exposed, were used to define the chemical fingerprints of the endmembers.

The first endmember has a chemistry close to those of the streamwater before the flood event: it was identified as the groundwater located in the weathered bedrock and the deep soil horizons. The deeper aquifer, located in the fissures of the non weathered bedrock, has a specific chemical fingerprint that was not detectable in the streamwater. The second endmember is the overland flow, whose composition was assimilated to that of the rainwater. Actually, analyses performed on overland flow water collected in a cultivated field showed that it is very diluted and close to the rainwater [13]. This overland flow is located on the poorly permeable areas of the catchment: farmyards, roads, and bare, crusted soils. The third endmember is the perched aquifer located in the upper horizon (Lg) of the bottomland soils. It is composed of denitrified waters seeping in the stream mainly during the storm events, due to piston flow. Its chemical fingerprint was defined according to the results of the monitoring of the free waters in the hydromophic soils. Originally, a three component separation using these three endmembers was performed. This model failed to explain the hydrochemical variations of the streamwater, especially during the falling branch of the hydrograph, when nitrate concentrations higher than in the pre-storm streamwater are often observed. A fourth component must be added to explain this observation. Free soil water collected in the upper horizons of cultivated fields proved to have an adequate composition to play this role. This quickly circulating water can reach the stream without flowing through the bottom land saturated zone because, firstly, there is an important ditch network around the fields and along the roads and secondly, a lot of riparian areas have been artificially drained. Although this ditch network collects a mixture of water types, it can be assumed that the

Table 3. Relative contributions of the four endmembers to the stormflow for the six studied events.

	EM1 (groundwater) %	EM2 (overland flow) %	EM3 (riparian seepage) %	EM4 (cultivated zone water) %
event 1	31.3	13.2	34.8	20.7
event 2	11.3	13.4	33.7	41.6
event 3	23.8	25.7	32.0	18.5
event 4	42.9	10.5	10.2	36.3
event 5	42.9	10.5	10.2	36.3
event 6	26.8	12.6	25.9	33.8

fingerprint of this fourth component will be conserved down to the outlet of the catchment.

The results of the hydrograph separation performed on the six storm events (Fig 10 and Table 3) show that overland flow and riparian zone seepage are responsible for the beginning of water level rising, while water from the cultivated zone comes generally later. The groundwater contribution decreases during the rising limb of the hydrograph, as if it was replaced by more superficial water. The nitrate dilution observed during the flood is nearly equally due to the overland flow and to the seepage of denitrified water. The latter accounts for a maximum of 30% of the streamflow. The relative contribution of each endmember varies between the events due to the antecedent conditions of the catchment and to the rainfall pattern.

This result was tested using the data on the chemical parameters not used in the separation computation. The model was able to reproduce the variations of most of the parameters. The root mean square error between the observed and simulated concentrations was less than 15%. However, for nearly each event, one or two parameters (not always the same) did not seem to follow the same pattern. This suggest either particular behaviour of these parameters (reactivity within the stream channel, for example) or the existence of a local source, insignificant for most of the solutes and not taken into account in the separation.

The chemical composition of the endmembers was not determined from a systematic sampling of the whole catchment. It was then necessary to test the sensitivity of the results to the uncertainty on this composition. This was done using a Monte Carlo procedure: the concentrations of the solutes were allowed to vary ramdomly within an interval of ± 5, 10 and 20% around the value actually used. A hundred realizations were compared in terms of total relative contribution during the flood and root mean squared error between the simulated and observed concentrations of an independent solute. The results showed that the separation is sensitive to the uncertainty of the endmembers whose composition is close to the observed stream water composition (event 1, Table 4). Therefore, although the separation results seemed consistent with the observed behaviour of the catchment, a reliable quantification of the contribution of the endmembers would require an important investment in data collection. This approach must be taken as a step towards the building of a coupled hydrological/hydrochemical model taking into account the spatial arrangement of the soil horizons.

A spatial approach of the control of streamwater chemistry by the riparian areas

The endmember mixing approach provided valuable information on the catchment behaviour during the flood events, especially concerning the role of the denitrifying riparian areas. However, it cannot apply to the non stormflow periods because the temporal variations of the chemical fingerprints of the endmembers are not precisely known. It is likely that during such periods, a partial mixing occur between the groundwater, the riparian zone water and the cultivated zone water, together with chemical and biological transformations. These complex processes cannot be accounted for by a simple conservative mixing model. Nonetheless, the spatial and temporal hydrochemical variations in the drainage network of the catchment were used to qualitatively assess the role of the riparian areas during non stormflow periods.

The streamwater chemistry at the outlet of the main subcatchments of the Coët Dan catchment was monitored fortnightly during two years. The geomorphology, soil distribution and agricultural practices of each subcatchment were described. The aim was to select

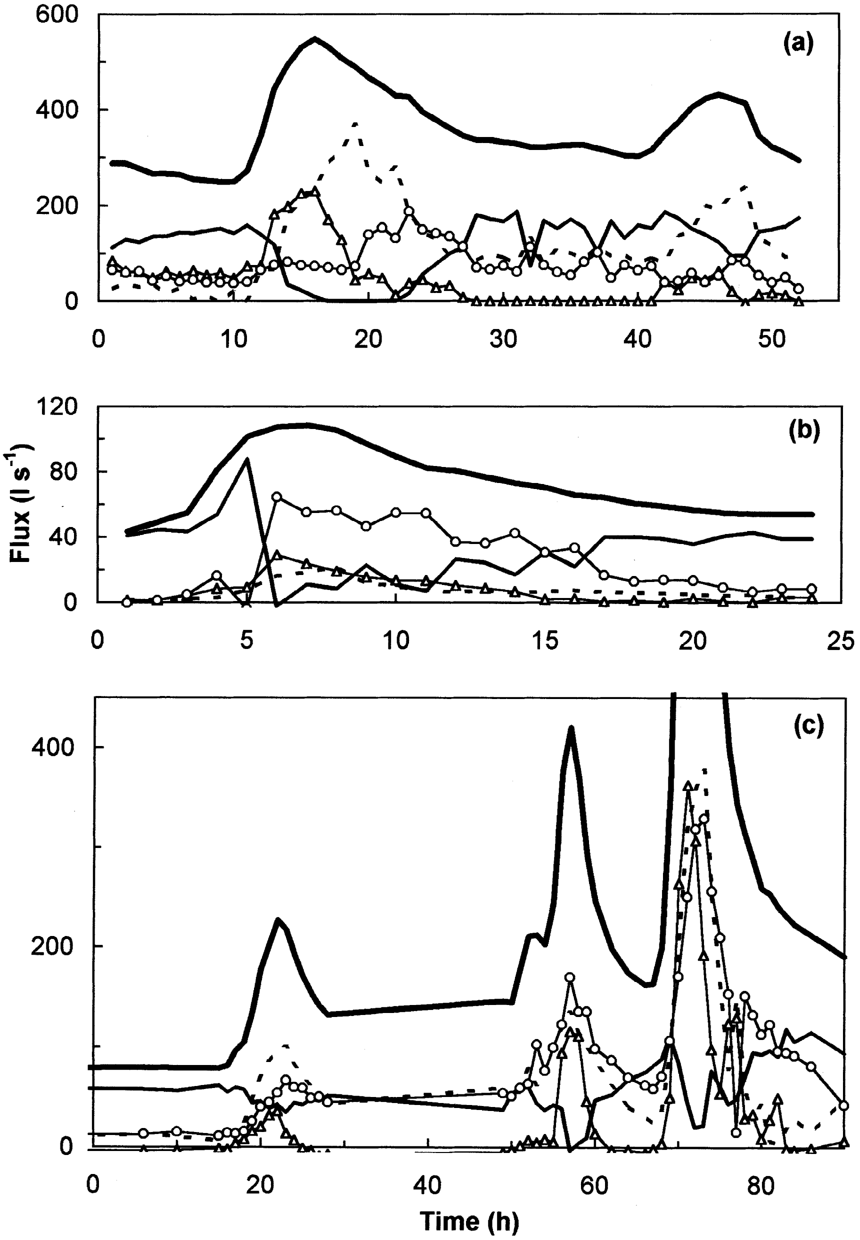

Figure 10. Hydrograph separation obtained by application of a four endmember mixing model for three storm events (a, b; c) (total flow = —; groundwater = —; overland flow =△; perched aquifer = - - -; cultivated zone water = ○)

the features that could account for the significant chemical differences observed between the subcatchments. The geomorphological parameters (mean slope, hillslope shape and length...) did not seem to be related to the hydrochemistry. The differences in agricultural practices, especially through the excess nitrogen load, were not consistent with the difference in nitrate concentration at the outlets of the subcatchments. The proportion of the area occupied by the hydromorphic soil was very variable for the smallest subcatchments but tended to stabilize around 20% for the largest (> 2 km^2) subcatchments (Fig. 11). The nitrate concentrations were negatively correlated with this proportion. The chloride concentrations followed the same

Table 4. Sensitivity analysis: statistics on the relative contributions of the endmembers and on the root mean squared error between simulated and observed Cl^- concentrations for event 1 and event 2. The composition of the endmember varied ramdomly within ±k/2 (100 runs).

	event 1					event 2				
	%EM1	%EM2	%EM3	%EM4	%RMSE	%EM1	%EM2	%EM3	%EM4	%RMSE
k=20%										
Mean	30.8	13.4	33.9	21.9	10.8	17.7	27.6	34.0	20.7	8.2
min	13.9	3.2	13.1	10.1	7.8	9.3	22.4	26.2	15.6	5.7
max	50.7	24.9	50.1	35.4	16.7	22.8	32.7	40.7	26.4	13.6
%Std. dev.	26.6	34.8	23.7	24.7	17.5	14.9	7.6	10.0	9.7	21.2
k=10%										
Mean	30.7	13.9	33.5	21.9	9.7	17.3	27.4	34.5	20.9	7.0
min	21.5	7.4	22.8	16.0	8.3	14.2	24.6	30.1	18.7	5.9
max	41.0	20.2	44.9	28.9	12.9	19.7	29.8	38.4	23.5	9.2
%Std. dev.	12.7	19.7	13.9	11.4	9.4	7.4	4.0	4.8	4.4	10.5
k=5%										
Mean	30.5	13.8	33.7	22.0	9.3	17.4	27.4	34.3	20.9	6.6
min	25.2	11.0	28.2	19.2	8.6	16.1	26.1	32.6	19.5	6.1
max	35.8	17.0	39.9	24.2	10.3	18.7	28.5	36.9	22.0	7.4
% Std. dev.	7.0	8.6	7.4	4.8	3.7	3.3	1.8	2.4	2.3	4.7

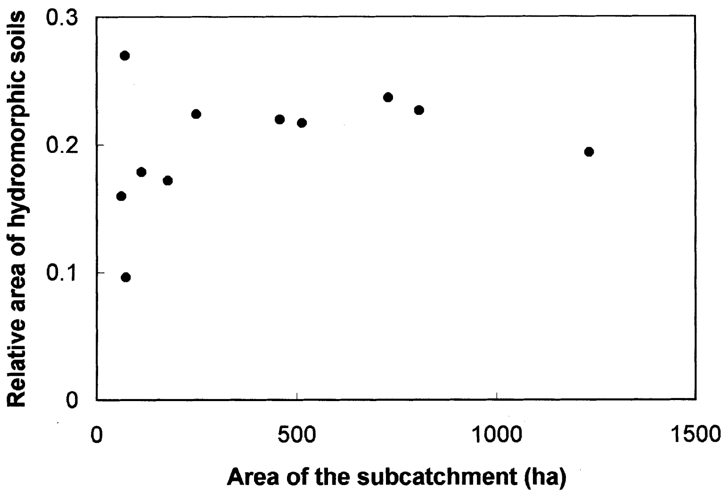

Figure 11. Evolution of relative area of hydromorphic soils according to subcatchment size.

trend, although with smaller variations (Fig. 12). This shows that the hydromorphic zones have a significant effect on the streamwater chemistry. The decrease of Cl^- concentrations suggests that the control of hydromorphic zone over the hydrological functioning of the catchment may well play a part in their effect on water quality. However, the control of nitrate concentration can be mainly attributed to denitrification, for three reasons: first, the NO_3^-/Cl^- ratio decreases also when the proportion of hydromorphic soil increases; second, the variations of NO_3^- and Cl^- concentrations are not synchronous: Cl^- concentrations are highest in late spring and NO_3^- concentrations are highest in February; third, a scale effect is observed in the relationship between nitrate and chloride concentrations: they are

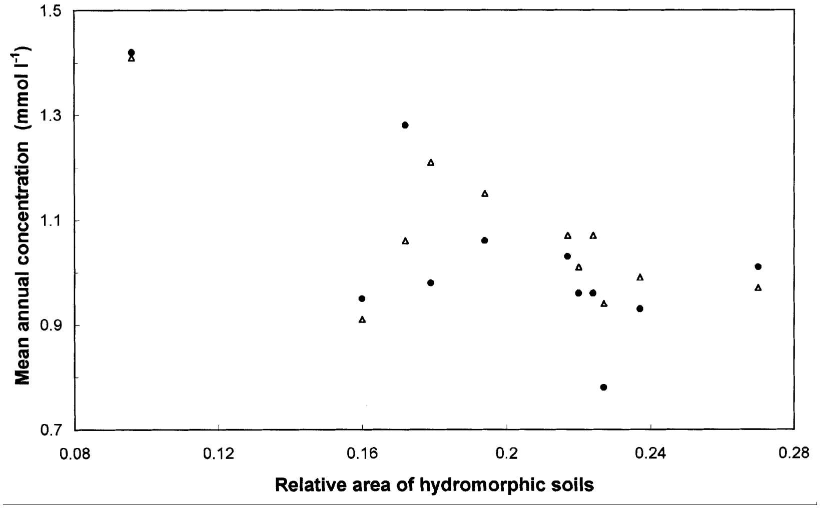

Figure 12. Mean annual concentrations of nitrate (*) and chloride (△) at the outlet of the subcatchments vs. relative area of hydromorphic soils.

correlated in large catchments (above 2 kmFD) and independent in small catchments [26].

Conclusions

The hydrology and biogeochemistry of the Coët Dan catchment are strongly controlled by the topography and the separation in two domains, the hillslopes and the bottom lands. This determines: (i) the soil distribution, comprising well drained soil on one hand and hydromorphic and degraded soils on the other hand, separated by a transition zone whose extension depends on the slope shape; (ii) the soil moisture distribution, that can be modelled using easily accessible topography variables; (iii) the hydrodynamic properties of the soils. The overland flow and erosion processes are also partially controlled by the topography, as showed by another study that is not presented here. However, this scheme is too simple to describe the variety of the water pathways. For example, the anthropogenic networks (field limits, ditches, roads...) play an important part that is currently investigated in this site. Also, the water transfer in the soils is strongly affected by macropore flow.

The hydromorphic soils are essential to regulate the nitrate concentration in streamwater, although their potential is not fully used, due to by-passes. Although 80% of the excess nitrogen coming from over-fertilization does not reach the stream, the water quality is very poor. This suggests that the relatively small decrease of the nitrogen loads that can be achieved by better agricultural practices, without a drastic change in the production system, may well show to be insufficient to recover acceptable nitrate level in the stream. A well designed management of the landscape can increase the buffer capacity of the system. The results of this study have allowed to precise considerably the principles of such a management, based essentially on restoring a temporal and spatial continuity of the buffer zones between the cultivated fields and the surface waters. This involves, for example, the diversion of the ditches so that they would not reach directly the river but instead irrigate wet meadows or woodlots. Real-size experiments are currently carried out to test the efficiency of such hydraulic engineering. Future investigations will also focused on the development of hydrological and water quality models making full use of the methodological and cognitive advances presented here.

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References

1. Antoni V (1995) Organisation spatiale des sols hydromorphes de fonds de vallée et modélisation prédictive de leur distribution. DEA Géosciences, filière Pédologie, Univ. Nancy I, 77 p.
2. Aurousseau P, Curmi P, Bouille S and Charpentier S (1983) Les vermiculites hydroxy-alumineuses du Massif Armoricain (France). Approches minéralogique, microanalytique et thermodynamique. Geoderma, 31, 17–40.
3. Aurousseau P, Curmi P and Bresson LM (1985) Microscopy of the cambic horizon. In: L.A. Douglas & M.L.Thompson (Eds), Soil Micromorphology and Soil Classification. Etats Unis. SSSA Spec. Pub. n° 15, 49–61.
4. Baize D and Girard MC (1995) Référentiel Pédologique 1995, Institut National de la Recherche Agronomique, Paris, France.
5. Beven KJ (1986) Hillslope runoff processes and flood frequency characteristics. In: Hillslope processes, Abrahams (Ed), Allen and Unwin, Boston, 187–202.
6. Beven JK and Kirkby MJ (1979) A physically based, variable contributing area model of catchment hydrology. Hydrol. Sci., 24, 43–69.
7. Bouma J (1989) Using soil survey data for quantitative land evaluation. Advances in Soil Science, Vol. 9, 177–213.
8. Bouma J and Dekker LW (1981) A method for measuring the vertical and horizontal Ksat of clay soils with macropores. Soil Sci. Soc. Am. J. 45: 662–663.
9. Bruand A (1990) Improved prediction of water-retention properties of clayey soils by pedological stratification. J. of Soil Science, 41, 491–497.
10. Brun C, Bernard D, Vidal-Madjar D, Gascuel-Odoux C, Mérot P, Duchesne J and Nicolas H (1990) Mapping saturated areas with an helicopter borne C band scatterometer. Water Resour. Res., 26, 945–955.
11. Bruneau P, Gascuel-odoux C, Robin P, Mérot P and Beven KJ (1995) Sensitivity analysis to time and space resolution on an hydrological modelling based on Digital Elevation Model. Hydrol. processes, 69–81.
12. Cann C (1990) Transfer of nutrients in a region of intensive farming. in Hydrological Research Basins and the Environment, Proceedings and Information / TNO committee on Hydrological Research No 44, The Hague, NL: 311–318.
13. Cros-Cayot S (1996) Distribution spatiales des transferts de surface à l échelle du versant. Contexte armoricain. Thèse ENSA-INRA Rennes. 223p.
14. Clothier BE, Kirkham MB and McClean JE (1992) In situ measurements of the effective transport volume for solute moving through soil. Soil Sci. Soc. Am. J., 56, 733–736.
15. Crave A and Gascuel-Odoux C (1996) The influence of topography on space and time distribution of soil water content. Hydrol. processes, 11, 203–210.
16. Curmi P (1993) Analyse structurale et dynamique actuelle des systèmes pédologiques. Mém. Habilitation à Diriger des Recherches, Univ. Rennes I, 83 p. + annexes.
17. Curmi P, Widiatmaka, Pellerin J and Ruellan A (1994) Saprolite influence on formation of well-drained and hydromorphic horizons in an acid soil system as determined by structural analysis. In: A.J. Ringrose-Voase and G.S. Humphreys (Editors), Soil Micromorphology: Studies in Management and Genesis, Developments in Soil Science 22, Elsevier, Amsterdam, 133–140.
18. Curmi P, Durand P, Gascuel-Odoux C, Hallaire V, Mérot P, Robin P, Trolard F, Walter C and Bourrié G (1995) Le programme CORMORAN-INRA: de l'importance du milieu physique dans la régulation biogéochimique de la teneur en nitrate des eaux superficielles. Journal Européen d'Hydrologie, 26, 37–56.
19. Diab M, Mérot P, and Curmi P (1988) Water Movement in a Glossaqualf as Measured by two Tracers. Geoderma, 43, 143–161.
20. Durand P and Juan Torres JL (1996) Solute transfer in agricultural catchments: the interest and limits of mixing models. J. Hydrol, 181, 1–22.
21. Gresillon JM (1994) Contribution à l'étude de la formation des écoulements de crue sur les petits bassins versants. Approches numériques et expérimentales à différentes échelles. Diplome d'habilitation à Diriger des Recherches.
22. Haycock NE, Pinay G and Walker C (1993) Nitrogen retention in river corridors: a european perpspective. Ambio, XXII (6), 340–346
23. Hoosbeek MR and Bryant R (1992) Towards the quantitative modelling of pedogenesis - A review. Geoderma, 55: 183–210.
24. Mérot P (1988) Les zones de sources surface variable et la question de leur localisation. Hydrol. continent., 3, 105–115
25. Mérot P, Crave A, Gascuel-Odoux C and Louhala S (1994) Effect of saturated areas on backscaterring coefficient of the ERS1 SAR: first results. Water Res. Res., 30,2, 175–179.
26. Mérot P and Durand P (1995) Assessing the representativity of catchments according to their size from hydrochemical observations. IAHS Publication, 226, 105–112.
27. Mérot P, Durand P and Morisson C (1995) Four-component hydrograph separation using isotopic and chemical determinations in an agricultural catchment in Western France. Phys. Chem. Earth, vol. 20, n 3-4: 415–425.
28. Nash JE and Sutcliffe JV (1979) River flow forcasting through conceptual models, 1. A discussion of principles. J. Hydrol, 10, 282–290.
29. Richards LA (1931) Capillary conduction of liquids through porous mediums. Physics 1, 318–333.
30. Roussel F (1982) Horizons and microscopic organisations characteristic of degraded soils on cambrian schists in central Brittany. In: Soil micromorphology, Volume 2: Soil Genesis P. Bullock & C.P. Murphy (Editors), AB Academic Publishers, 559–565.
31. Soil Survey Staff (1975) Soil Taxonomy: a Basic System of Soil Classification for Making and Interpreting Soil Survey. U.S. Dept. Agric. Handbook 436, 754 p.
32. Stackman WP, Valk GA and Van der Harst CG (1969) Apparature for determination of pF-curves (range pF0- 2.7) Wageningen, Doc. interne, 19 p.
33. Taha A and Gresillon JM (1994) Modeling the link between hillslope water movement and river flow: application to a small Mediterranean catchment. In: Oceans, Atmosphere, Hydrosphere & Non-Linear Geophysics (Proc. XIX EGS General Assembly, Annales Geophysicae, Grenoble), part II, suppl. II to vol. 12.
34. Thiersault N and Rodriguez Lado L (1994) Un modèle de prédiction de la distribution spatiale des sols hydromorphes à partir des critères topographiques. Mémoire DAA Génie de l'Environnement, Option Sol et Aménagement. ENSA-INRA Rennes & Facultade de Bioloxia, Univ. Santiago de Compostela, 64 p.
35. Walter C, Gourru M and Nicolas JM (1993) Carte des sols du bassin versant de Naizin à l'échelle du 1/10000. Document ENSA-INRA.
36. Walter C, Curmi P and Gascuel-Odoux C (1996) Pertinence du découpage pédologique pour l'estimation spatiale des pro-

priétés physiques du sol. Validation à l'échelle d'un bassin versant. In: C. Christophe, S. Lardon & P. Monestiez (Editeurs) Etudes des Phénomènes Spatiaux en Agriculture , La Rochelle, 6-8 Déc. 1995, Les Colloques, n 78, Inra, Paris, 97–110.

37. Widiatmaka (1994) Analyse structurale et fonctionnement hydrique d'un système pédologique limoneux acide sur granite et sur schiste du Massif Armoricain, France. Thèse ENSA, Rennes, Sciences de l'Environnement, 260 p. + Annexes
38. Widiatmaka and Curmi P (1994) Soil horizons hydrodynamic characteristics of an acid soil system. Interest of their grouping according to functional properties for spatial transposition. 15th World Congress of Soil Science, Acapulco, Mexico, July 10-16, 1994. Transactions, vol 2b, 151–152.
39. Zida M, Curmi P, Hallaire V and Grimaldi M (1996) Fonctionnement d'un système pédologique armoricain (bassin versant du Coët Dan): II Variations saisonnières et au cours des averses de l état hydrique du sol. In: C Walter & Cheverry C (Eds), 5ièmes Journées Nationales de l'Etude des Sols, Sols et transferts des polluants dans les paysages . AFES, ENSA-INRA Rennes, 22-25 Avril 1996, 263-264