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# Exchange between systems: from river catchments to coastal marine waters

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**Abstract** The European Water Framework, promulgated in 2000, proposed a global approach with a precise schedule and a clear objective: the long term protection of aquatic environments and resources and, especially for the rivers, their ecological integrity from the source to the mouth. For a long time, the "ecosystem approach" appeared a good way in terms of research to show, at a landscape level, the reality of a link between the functioning of such different systems as watersheds, rivers, streams, estuaries and marine coastal water systems. Much research on exchange, transfers of energy and materials between these systems have proved that, finally, the water quality in rivers and in the sea as well as and the functioning of aquatic ecosystems (freshwater and marine ecosystems) depend on the evolution of land cover and land use of the watersheds. The development of intensive agriculture that takes no account of the environmental issues, regularly destroys the integrity of biogeochemical and water transfers between land and ocean. It is one of the main causes of the disturbance of the functioning of aquatic ecosystems. In Celtic Countries, at a local scale, the Mont-Saint-Michel bay and its watershed appears as an appropriate model to analyse the multiple consequences of land use changes in the watershed, due to agriculture, on the deterioration of aquatic ecosystem and water quality. Brittany in its entirety seems to be one of the best models to study the same processes at a regional scale.

**Key words** coastal marine water; ecosystems; exchange; freshwater; functions; holistic model; industrial agriculture practice; landscape; river; transfer; watershed

## INTRODUCTION

In 1866, Haeckel understood the strong relationships between organisms and their physico-chemical environments. This was the creation of a new scientific field: ecology which involved interdisciplinary research. Later, this discipline taught how to understand, measure and model the complexity of ecosystems and the effects of forcing factors that interact at different times on spatial scales, and form the indispensable conditions of the expression of biological diversity and persistence of life.

For many people in the hierarchical arrangement of biological studies, ecology occupies more than one level. One of them concerns autoecology: the study of individual species populations. The other one is community studies. In principle, these studies should link the gap between studies of species populations and attempt to understand the functions of ecosystems. Such studies are less reductionist in their methods than the studies on species populations (Pomeroy *et al.*, 1988). The real originality of ecology in the context of biological studies is to use the concept of ecosystem and to promote the ecosystem approach to improve the understanding of ecosystems' complex functioning in time and space with a focus on exchange, transfer interactions, storage ability, etc.

Ecology is indeed a holistic science as Odum (1977) strongly stated. The truly holistic study of the ecosystem brings together ecosystem and population processes as a continuum of functional responses to changing conditions. The "ecosystem approach" enables a link between the functioning of different ecosystems considered at a landscape level in terms of transfer of energy and material between very different systems such as watersheds, rivers, estuaries and marine coastal waters.

## A BRIEF HISTORY: FROM ECOSYSTEM APPROACHES TO COUPLING APPROACHES BETWEEN LAND AND WATER SYSTEMS

"Ecosystem" was defined in 1935 by Tansley as "*the whole system (in the sense of physics), including not only the organism complex, but also the whole complex of physical factors forming what we call the environment of the biome—the habitat factors in the widest sense... It is the systems so formed which, from the point of view of the ecologist, are the basic units of nature on the face of the earth"*. Although Tansley (1935) is credited with the invention of the ecosystem concept, biologists such as Möebius (1877) previously created the term of biocenosis and Forbes (1887) described "the lake as a microcosm". Truly limnologists and hydrobiologists have played an important role in the historical development of ecological theory. As says Rich (1988), while the holological approach is considered as the dominant perspective in modern ecosystem research, a different sense of organization emerges from the ecological survey work conducted by Forel on Lac Léman (1895). Elton (1966) noted that Forel's work was the first survey of a "great ecological system" that presented a broad account of how the features of a lake are "integrated into a whole working system in which the flora and fauna form part of the network of channels for matter and energy".

These theories on energy transfer between and inside ecosystems are a development of the first law on thermodynamics by Lavoisier (1777). Lavoisier showed that living organisms consume energy as food and lose energy in the form of heat, and that a quantitative relationship links the loss of energy of food and the heat produced. More than a century after Lavoisier's discovery, energy flux began to be used in descriptive ecology by aquatic ecologists, culminating in the trophic dynamic principle emphasized by Lindeman (1942), whose paper became one of the most quoted papers in the field of ecological energetics (Wiegert, 1988). McIntosh (1985, in Rich, 1988) even states that Lindeman's paper "*published the actual research upon which the science of ecosystem ecology was founded*". Based on biomass data from three lakes, his paper described the flow of material and energy from the environment through the predatory hierarchy of plants, herbivores, carnivores and decomposers (Lindeman, 1942). Lindeman's ecosystem receives energy from solar radiation captured by plants (photosynthesis). The captured energy is used immediately by plants to transform inorganic matter. Energy and material are returned to the environment via respiration. He synthesized a number of different views of how ecosystems were organized, the main theme being that the dynamic of a system could be represented by a description of the amount, efficiencies and rates of energy transfer and transformation (Wiegert, 1988). Lindeman outlined the trophic dynamics of ecosystems clearly (Rich, 1988).

After Lindeman's death, no useful descriptive studies of ecological energetics can be found before the 1950s. Among the numerous papers on this theme, it is necessary to emphasize the role of the Odum brothers. Indeed following the classic study of both Odums on the energetics of coral reef (Odum & Odum, 1955), total system energetic descriptions were published on Silver Springs (H. T. Odum, 1957). After the book "*Fundamentals of Ecology*" (E. P. Odum, 1959), many papers on trophic structure of ecosystems and energy flow were published by E. P. Odum and his students.

If we pointed out these studies, many of which were produced by the University of Georgia (Odum & Smalley, 1959; Odum *et al*., 1965; Odum & de la Cruz, 1967), most were focused on saltmarsh functioning. These choices have had three major consequences:

– to draw attention to a special transitional zone between continent and sea corresponding exactly to the definition of ecotone: "*zone of transition between adjacent ecological systems, having a set of characteristics uniquely defined by space and time scales, and by the strength of the interaction between adjacent ecological systems*" (Holland, 1988);
– to analyse the role of these original terrestrial ecosystems periodically flooded by the tide;
– to promote the idea that there are exchanges between terrestrial and aquatic ecosystems and that it is necessary to develop research on the mutual benefits of the exchanges for each component (terrestrial and aquatic) of this complex ecosystem.

During this period, Teal (1962) produced one of the famous papers, his well know article "*Energy flow in the salt marsh ecosystem of Georgia*" considered as one of the 40 papers which have founded modern ecology (Real & Brown, 1991).

He showed that the productivity of the salt marsh he studied, dominated by the grass *Spartina alterniflora*, was much higher than any other ecosystem types. Only a small part of the energy captured by the grass halophyte meadows was grazed. From that study came the new perception of the salt marsh ecosystem as one in which microbial transformation of energy and nutrients are quantitatively dominant and are key links in the food web (Wiegert *et al*., 1981). These remarks led Odum & de la Cruz (1967) to say "*the bacteria-rich detritus is nutritionally a better food source for animal than in the Spartina tissue forms the originally base for most of the particulate matter*". The Teal mass balance energy budget of this marsh indicated that primary production was greater than community respiration (P/R>1) and he assumed that the excess was exported along with shrimp and other organisms that use the marsh as a nursery ground. Specifically, he shows that 45% of the salt marsh's production is lost in estuarine water and he thinks that "*since the waters of these estuaries are so turbid and well mixed that the phytoplankton spend most of their time in the dark and their net production is zero, the estuarine animals must be living on the exported marsh production*".

Thomas (1966) using C-14 measurement along the Georgia coast (western USA) reinforced the Teal results in finding that high offshore productivity was associated with nearby marshes rather than with large river plumes.

On this basis, Odum (1968) suggested that most fertile zones in coastal areas capable of supporting expanded fisheries result either from "*upwelling*" of nutrients from deep water or from "*outwelling*" *of nutrients and organic detritus* from shallow water hot spots such as reef, banks, seaweed or seagrass beds and salt marshes. Odum (1980) proposes that salt marshes produce more material than can be degraded or stored within the system, and that the excess is exported to coastal waters where it supports ocean productivity. It is at this time that he said "*the salt marshes are the richness of the sea*".

These ideas turned into a dogma and have been used by many authors to save the salt marshes from drainage and reclamation polderization. Extensive research was conducted to test these "outwelling hypothesises". Some of them showed that salt marshes are not always a source for all materials or nutrients. For example, *Spartina* marshes can be sinks, not only for nutrients but also for heavy metals. In this view, the pollutants are removed from the water over the marsh via sedimentation and incorporated into the tissues of plants through normal growth and metabolism (Dame, 1989). Since 1980, many studies have tried to explain this apparent confusion. Indeed a number of factors may be related to this variability, either in primary production or the import/export capacity of salt marshes (Lefeuvre & Dame, 1994). For Dame (1989) this "outwelling hypothesis" has been one of the most dynamic and controversial issues of ecological investigations over the last three decades.

For us, these early investigations involve a holistic approach of complex systems when most ecologists still used sectorial studies and analysed species individually, independently from others. This required a new way of thinking in order to link studies and specialists in a multidisciplinary approach. It is certain that the research difficulties found in salt marshes contributed to creating a greater spirit of cooperation than among most ecologists at this time (except freshwater ecologists). However, while during the period this research was developed on coastal zones, some limnologists and hydrobiologists promoted the idea of coupling land and water systems (Hasler, 1974). The aim was not exactly the same at the beginning: the problem was to explain the concept of the "trophy" lakes. The terms of "oligotrophy", "mesotrophy" and "eutrophy" were based on the degree of biological productivity and therefore on the amount of available nutrients (low, medium, high) (Hasler, 1974). Naumann (1921) was one of the first to realize the importance of the drainage basin as a source of nutrients to lakes. This regional limnology was based mainly on the relation between the "fertility" of lakes and the fertility of soils in the neighbouring lands. But despite this first attempt to link lakes and catchment basins, for many years, many scientists working on rivers have considered these complex environments as linear systems changing in a more or less predictable way from source to mouth. It is probably due to the complexity of this "continuum" (Vannote *et al.*, 1980), which is often divided for convenience into three primary zones: production zone, transfer, and storage zone (Schumm, 1977) (Fig. 1).

The first may be viewed as the source region; here river flow, sediment and solute load are closely coupled to hillslope process. For Burt (1997), in the middle zone, a real transitional zone, the river, is increasingly isolated from adjacent hillslopes as flood plain width increases and the riparian land is gradually becoming a sink rather than a source. For this author, the lowland flood plain river is a depositional or storage zone in which transfers from river to flood plain dominate. However, as Petts (1994)

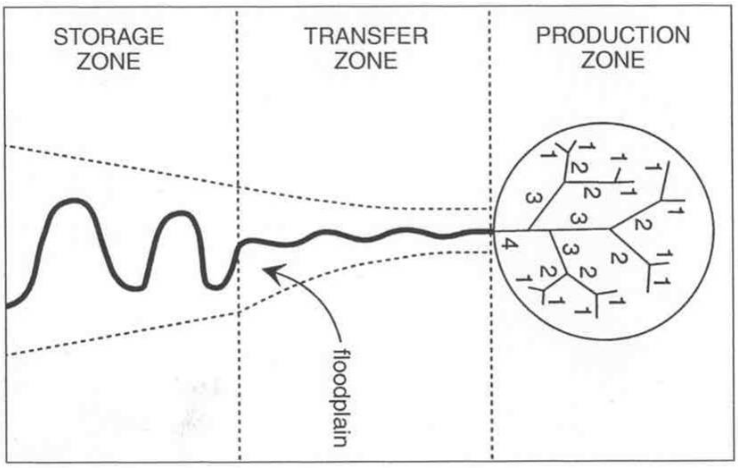


**Fig. 1** Land water interaction within a fluvial system: the three primary zones (after Schumm, 1977).

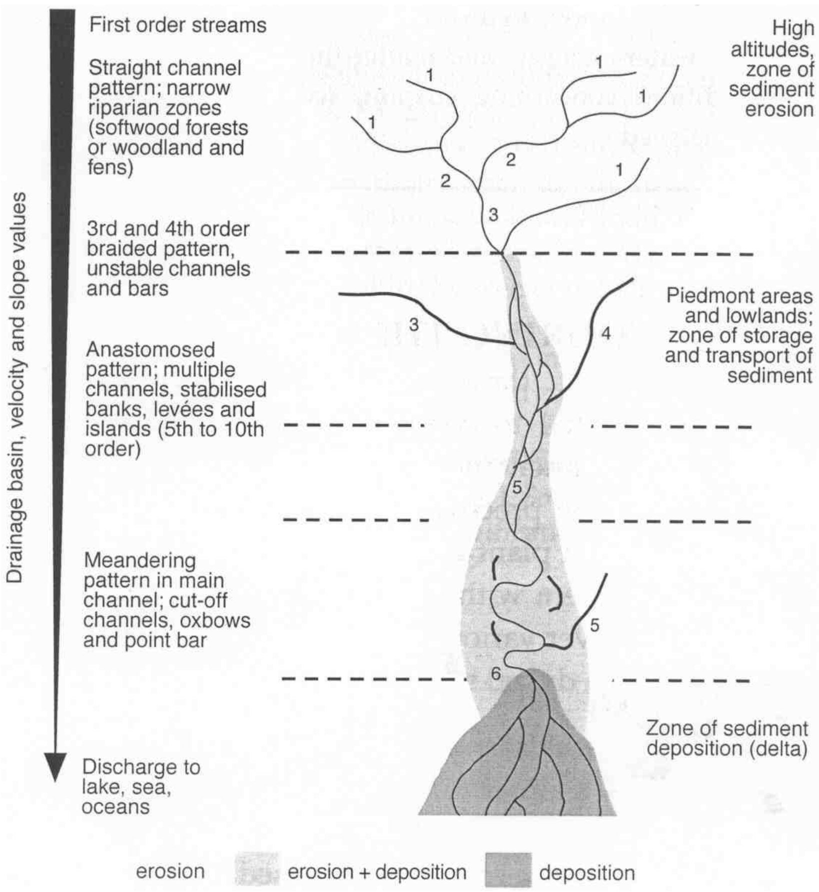


**Fig. 2** Geomorphic zones and flood plain models (from Girel & Pautou, 1997). Note that narrow flood plains border the channel in the prodution or headwater zone. Further down the basin the flood plain becomes wider and hillscope inputs assume less importance relative to runoff production from the flood plain itself. In the lower reaches of the basin, the flood plain receives little water from surrounding land and inputs of flood water from the channel become of major significance to flood plain hydrology.

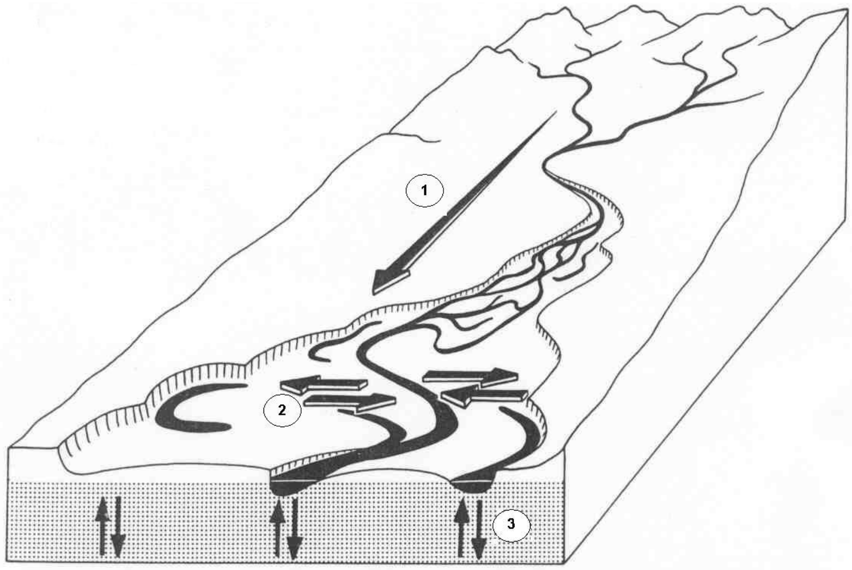


**Fig. 3** Hydrosystem (from Amoros & Pett, 1993) The hydrosystem concept integrates the three primary spatial dimensions: 1, longitudinal flow; 2, transverse flow; 3, vertical flow.

notes, such downstream variations are more than just a structural sequence: this represents a longitudinal continuum dominated by downstream transfer of energy and matter. Moreover it is important to emphasize the storage as well as the transfer taking place within each zone. Indeed for Amoros & Petts (1993) this classic approach based on the idea of unidirectional flow is more complicated: they proposed the concept of "hydrosystem" which combined uni and bi-directional flow.

Indeed, it is possible to distinguish two types of bi-directional flow, one transversal between the river and the flood plain, the other vertical–underground infiltration (Figs 2, 3).

The hydrosystem concept integrates the three primary spatial dimensions but also integrates a fourth dimension: the time. They conclude that the stream functioning is dependent on the flood plain and reciprocally the flood plain is under control of the stream. These conceptual bases explain why many limnologists now pay attention, not only to the river aquatic system, but also to the flood plain and the catchment basin.

The conception of a complex system formed both by the drainage basin and lake or river or estuary, extended after the World War. For example, Horton (1945) considered the network of brooklet, brook, river converging for stream that leads to the sea as a drainage system of catchment basin that is "the basic unit of the landscape". For a better understanding of how the transfer from catchment basin varies in time and space, it is necessary to look at the runoff pathways (Fig. 4). For Burt (1997) most research on hillslope hydrology had been carried out in headwater basins where slopes directly adjoin the channel. Further downstream a flood plain is commonly found, though curiously there has been little field research in such locations. The important point for Burt (1997) is that the hydrology of many flood plains is closely controlled by hillslope inputs.

The hillslope hydrology is strongly influenced by the vegetation of the catchment basin. Likens *et al.* (1970), comparing forested and deforested catchment basins, found

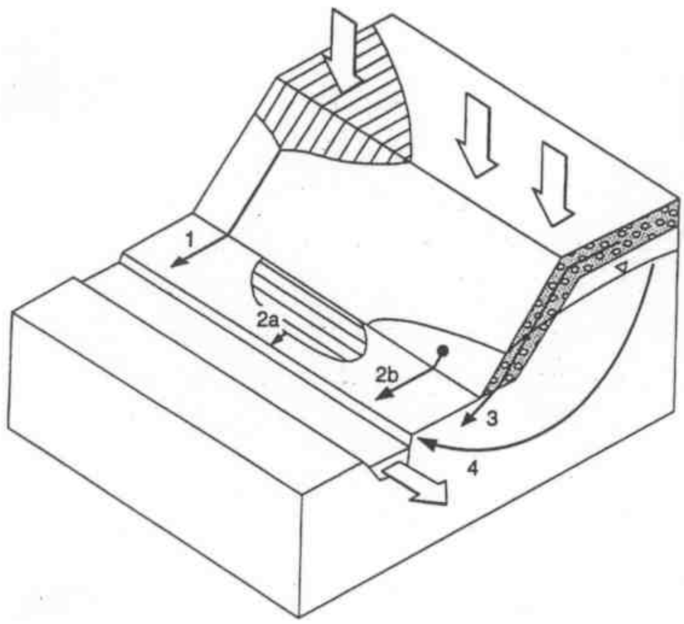


**Fig. 4** Hydrological pathways: 1, infiltration-excess overland flow; 2, status-excess overland flow; 2a, direct runoff; 2b, return flow; 3, subsurface stormflow; 4, groundwater flow.

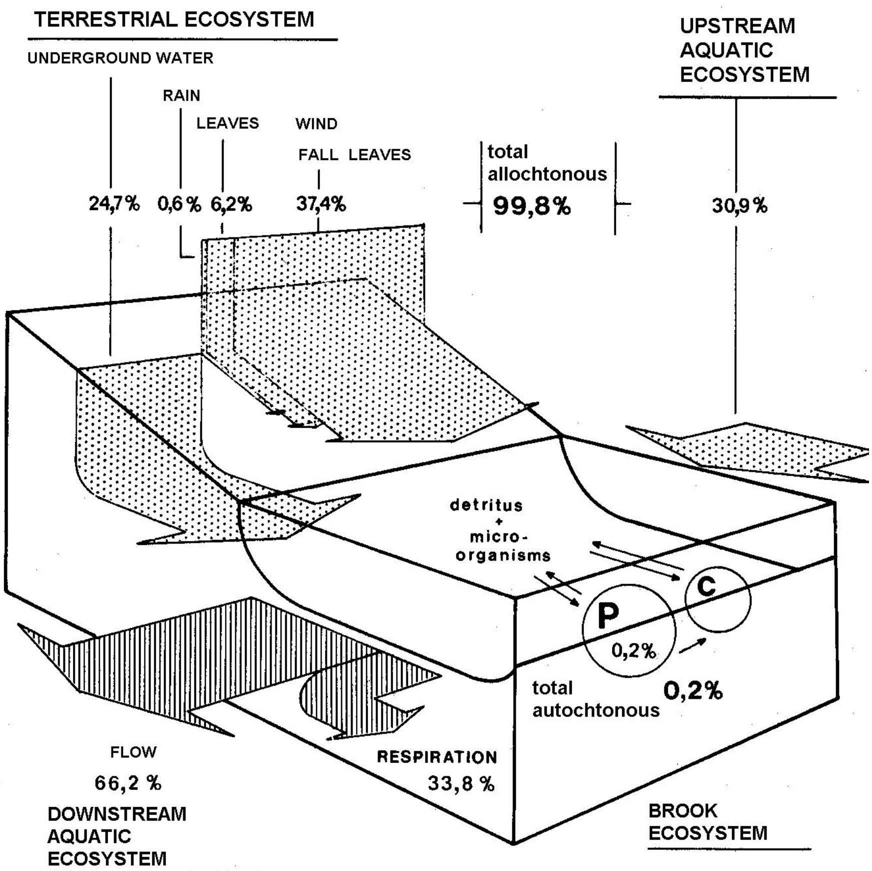


**Fig. 5** Schematic representation of energy flow in a stream in a forested catchment basis (from Fisher & Likens, 1972).

that the annual stream-flow was increased by about 39% in the first year and 28% in the second year above the value expected if the catchment basin was not deforested (Fig. 5). The structure and organization of landscape in a catchment basin is also an important parameter. Merot (1976), looking at the outflow of two elementary catchment areas in a bocage, one with a network of banks with hedgerows (see Fig. 7), the other transformed into open field by removal of the network of forested banks, showed the important damming role of the embankment which brakes the lateral flow and enhances percolation, whence its importance in the recharging of the aquifer. Comparison of storm runoff shows on a typical event that the direct runoff volume and the peak flow was 1.5 to 2 times lower in the bocage catchment than in the open field catchment. The bocage introduces noticeable heterogeneity in soil distribution because of its role in erosion control.

The first demonstration that the land use and the land cover of a drainage basin control a large part of transfers of energy and matter to the river is due to Likens *et al.* (1970). They compared a forested and deforested catchment basin, considered as an ecosystem, where the vegetation regrowth was inhibited by periodic application of pesticides. One of the important conclusions was that a schematic view of energy flow in a river in a forested catchment basin shows that 99.8% of diverse inputs are allochthonous. Only 0.2% is autochthonous production.

Large increases in stream water concentration were observed for all major ions except $NH^{4+}$, $SO^{4-}$ and $HCO^{3-}$ five months after the deforestation. Nitrate concentrations were 41-fold higher than the undisturbed condition in the first year and 56-fold higher the second (Fig. 6). The nitrate concentration in stream water has exceeded, almost continuously, the health threshold recommended for drinking water. Sulphate was the only major ion in stream water that decreased in concentration after deforestation. Total gross export of dissolved solids, exclusive of organic matter was about 6–8 times greater than would be expected for an undisturbed watershed. The greatly increased export of dissolved nutrients from the deforested ecosystem was due to an alteration of the nitrogen cycle within the ecosystem. The results of these experimental research projects developed by Likens *et al*. (1970) led to consideration of the consequences of changes in land cover and land use of the catchment basin on the importance of transfer of nutrients, pollutants, matter and energy. Indeed at that time (1970s), the real agriculture revolution, marked by the enlargement of crop fields and the increase of production by hectares, as well as the expansion of cities, were considered as the major sources of pollution for rivers and lakes.

The link between changes in agricultural practices and the nitrate load in water was rapidly understood in France. As early as 1970, a team of the INRA (National Institute for Research in Agronomy) drew the attention of the public authorities to the increase of authorized nitrate loads in 24 drinking water reservoirs in the Yonne region area, in which the Yonne River flows. This increase was sudden, simultaneous and persistant in the whole county (Chrétien *et al*., 1974; Concaret *et al*., 1976) (Fig. 6).

In the regions where agriculture is most intensive, nitrate loads increased the most (Concaret *et al*., 1976). Among the principal causes, we may outline “clearing”, the extension of maize culture associated with nitrate fertilization and bare soils in winter. We criticised such practices in 1970 (Lefeuvre, 1970) when, after a few years, nitrates increased from traces to over 10 mg $L^{-1}$ in the rivers of Brittany. In some parts of this catchment, the traditional bocage landscape was turned into an open field system by cutting down thousands of kilometres of hedgerows, which all contributed to the retention of runoff water. Moreover, meadows were converted to maize cultures that were created to feed cattle in intensive batteries (Fig. 7).

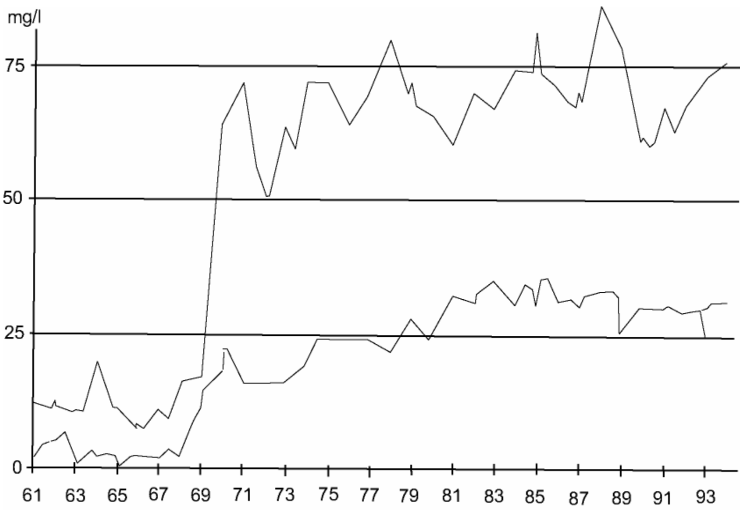


**Fig. 6** Nitrate load evolution in water catchment since 1962 (Yonne country, France) (from Chrétien *et al*., 1974).

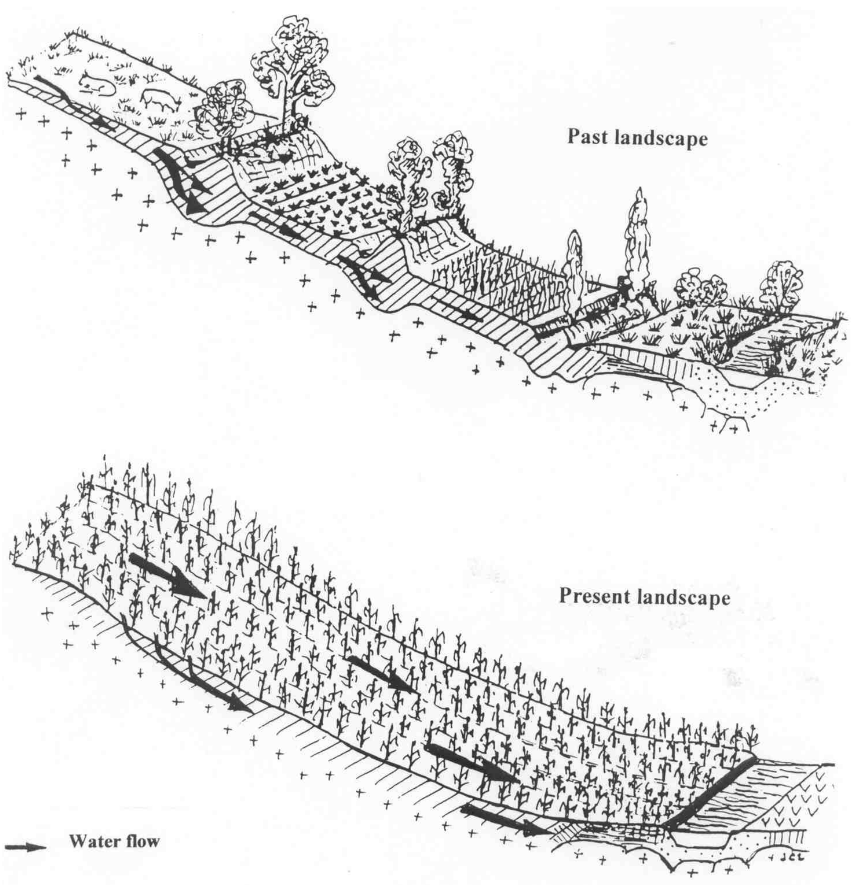


**Fig. 7** Change in Brittany landscape (from Lefeuvre).

Because of this state, ecologists are now used to pay attention to the flood plain and riparian vegetation of rivers that are considered as efficient buffer zones. The use of natural buffer zones to protect freshwater from pollution has attracted considerable interest within the European Union and elsewhere (Haycock *et al.*, 1997). However, the factors accounting for the pollution retention capacity of buffer zones are diverse and, therefore, the performance of these ecotones within a catchment is always difficult to predict. Nevertheless, these land–water ecotones were considered as membranes between ecological systems, but the barrier functions were examined thoroughly. Conversely, other researches focused on their capacity to control the intensity and quality of exchanges between systems, in other terms, their selective permeability (Amoros *et al.*, 1993). These authors thus distinguish fluxes under the influence of these buffer zones, and especially the direct transfer and a filter effect that has various expressions: gradient effect, zonation effect, accumulation effect and barrier effect (Fig. 8).

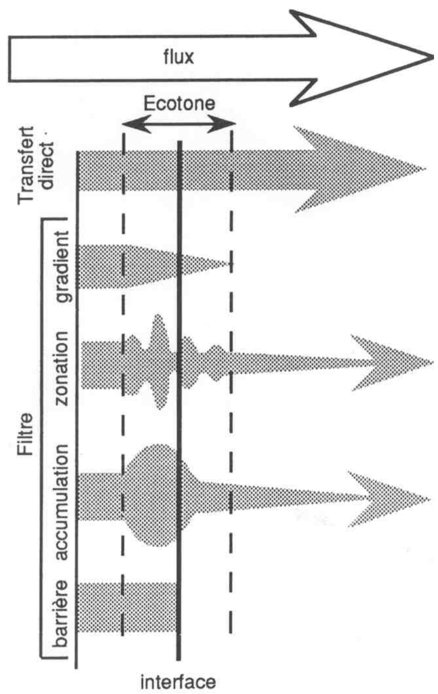


**Fig. 8** Energy fluxx through an ecotone (from Amoros & Petts, 1993). Direct transfer, filter, gradient, zonation, storage, barrier.

The natural systems (riparian forests, wetlands) and developed systems (wet meadows) represent efficient filters for nutrients and contaminants transported by surface and runoff waters towards rivers. Thus the retention rates of nitrogen compounds reach up to 80% in an alluvial forest whereas they are only 8% in neighbouring cultivated meadows (Peterjohn & Corell, 1984) (Fig. 9).

Pinay (1986) assessed that the denitrification capacity of alluvial forests of the Garonne River was 50 mg $m^2$ $day^{-1}$ of nitrogen. This mineralization capacity varies in time and space. It is very sensitive to environmental conditions. In general, riparian vegetation stores nitrogen during the growing season and releases it as litter which will

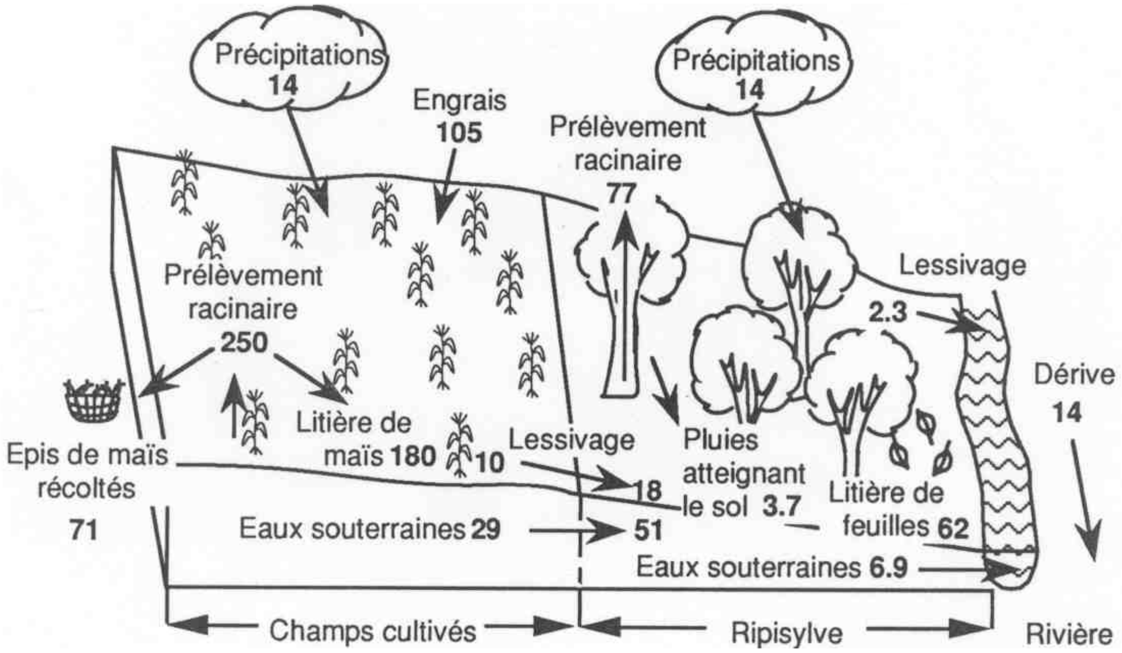


**Fig. 9** Diagram of flow and total nitrogen cycle in a catchment basin of the Rhode River (Maryland) (from Perterjohn & Correll, 1984).

then be mineralized. Nitrates produced in such a way are then available for denitrifying micro-organisms during high water periods at the end of the winter or beginning of spring.

Recent research on the bocage landscape has shown that the bank separating cultivated areas and the transition zone are essential in the transfer of water and nitrates through the landscape. Caubel (2001) showed a direct effect of the trees on the bank on the uptake of nitrates by the rhizosphere from the water table. Up to 75% of the nitrates are used by such bank tree hedges. These buffer zones are also essential to maintain a certain quality of the surface water transported by the rivers. Indeed, during floods, water is transferred sideways towards wetlands and flood plains, and finally seeps into the water table where a number of physico-chemical process occur, reducing, or even stopping, transfer of pollutants towards subterranean water.

All this area of research focusing on the interactions between catchment areas, buffer zones, rivers and estuaries, was initiated in the 1970s at the beginning of the agricultural revolution in all industrial countries. The aim was to understand the effects of the transformation of landscapes on the degradation of the quality of the water. It is regrettable that the agricultural and public policies were unable to take into account this holistic research on interactions between watershed and water bodies. Indeed, they provided essential comprehensive knowledge to support the elaboration and implementation of sustainable development policies at regional levels. Agriculture was identified as the primary source of pollution in rivers and lakes and the main source of sediments in all water bodies (Dillaha & Inandar, 1997). Non-point source (NSP) pollution essentially from agricultural areas, is now recognized as one of the most significant water quality problems facing the world.

## TWENTY YEARS OF A MULTIDISCIPLINARY RESEARCH ON THE MONT SAINT MICHEL BAY AND ITS CATCHMENT BASIN

In 1985 we used the new international knowledge on intersystem exchanges, to define the aims of a research project on salt marsh estuarine systems. The main target was to understand the functioning of a bay in relation with the inputs from continental river discharge. Mont Saint Michel Bay appeared to be interesting for such a fundamental approach. Firstly, the surface of the bay extends 500 km$^2$, including 250 km$^2$ of mudflats and sand, 150 km$^2$ of polders, and 50 km$^2$ of salt marshes, which is one of the largest salt marshes in Europe. This bay receives the waters of three main river systems covering a total of nearly 3000 km$^2$. Mont Saint Michel and its bay have been part of the world heritage of UNESCO since 1979, both for cultural and natural reasons. The bay is listed as a site of international interest for water birds that are hosted during wintering and migration stops. It also has a remarkable *Sabellaria alveolata* (Polychaete) reef that hosts a number of species usually present on rocky shores. The salt marsh communities are composed of 67 halophytic plants. The bay is also characterized by the turbidity of the water, which stops the penetration of light and the development of phytoplankton. It was therefore difficult to understand how this bay could sustain the food resources for 50 000 water birds and 18 000 tons of shellfish per year.

We focused on the role of salt marshes as producers and exporters of organic matter, as stated by the outwelling paradigm (Teal, 1962; Odum, 1968). In this context, considerable scientific research was initiated by us at the European level. In 1990, scientific teams from The Netherlands, the United Kingdom, Portugal and France started working together, using standardised methodologies to understand how these “salt marshes ecotones”, located at the interface between land and estuaries or open sea, contribute to the ecological functioning of adjacent coastal areas (Fig. 10).

The main results obtained over 10 years present a large variability between sites. This variability is due *pro parte*: (1) to tide amplitude (<3 m in The Netherlands, almost 15 m in Mont Saint Michel Bay); (2) to the location of marshes in relation to the mean sea levels; (3) to plant competition.

Nevertheless, in a natural situation such as the Mont Saint Michel bay, it was shown that immature marshes have a low productivity in the pioneer zone, which is developing and extending. But higher productivity occurs in the more mature communities located at higher levels (about 20 T ha$^{-1}$ year$^{-1}$ produced by *Atriplex portulacoïdes*, with 36 T ha$^{-1}$ year$^{-1}$ as peak at some time in middle marshes, Bouchard & Lefeuvre, 2000). The young immature marshes are a flood dominated system and net importers of sediments and organic matter, while exporting mineral nutrients. Mature marshes on the other hand are ebb dominated and are net exporters of sediments, organic matter (DOC and POC) and nutrients. The use of stable isotopes and biomolecular markers such as fatty acids or osmolytes show that the organic matter can be consumed directly by marine invertebrates.

This organic matter also contributes indirectly to the primary productivity, considering the exported nutrients are a source of enrichment for mud flats. This enrichment allows the development at low tide of microphytobenthos (diatoms) that are used by deposit feeders. At the flow, the superficial zone of mudflats and diatoms are removed, dispersed in the water column and used by filter-feeders such as mussels.

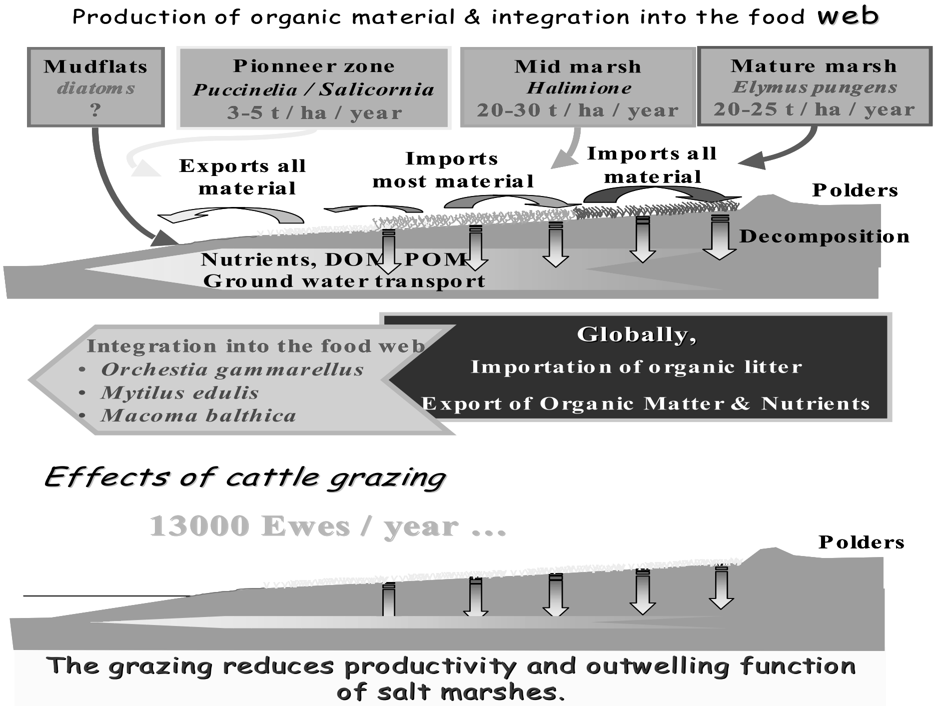


**Fig. 10** Schematic presentation of the compartment model to study the salt marsh functioning and exchanges between salt marsh and marine coastal system (from Lefeuvre *et al*., 2000).

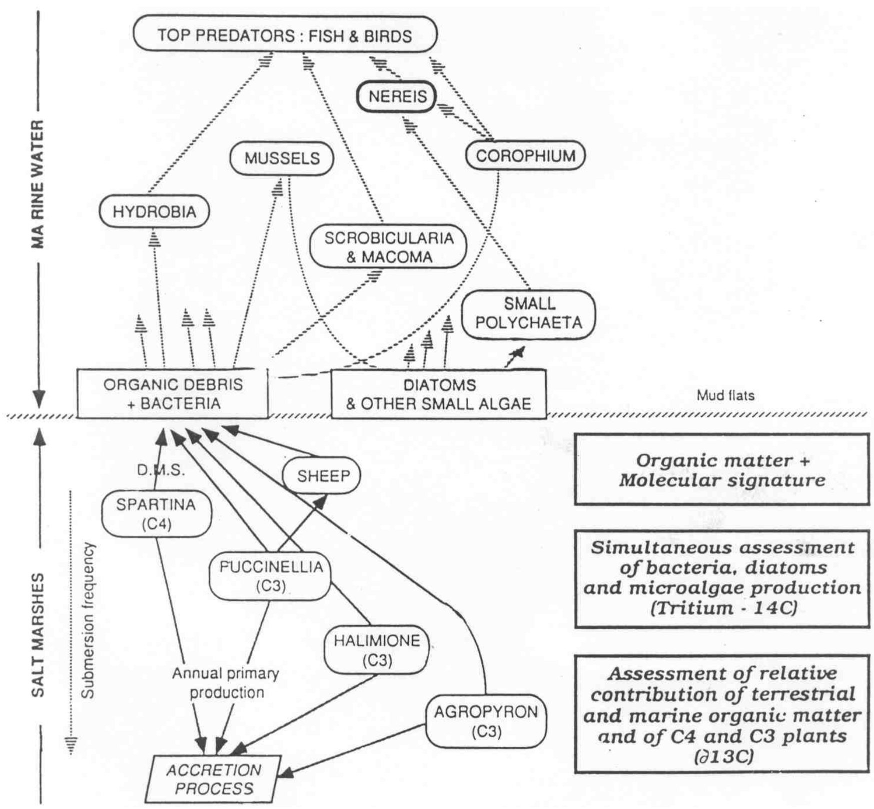


**Fig. 11** Some of the organic matter exchange processes studied in the Bay of Mont Saint Michel (from Lefeuvre).

This important direct service due to salt marshes (production of organic matter–transformation–enrichment of mudflat–diatom production) is completed by transfer of organic matter by fish. Indeed, during the flow, mullets invade the creeks that naturally drain salt marshes. At each tide, mullets swallow a quantity of sediments in the creek, representing at least 48% of their bodyweight. The stomach content is mainly composed of sediment, phytobenthos, halophytic and organic detritus and microzoobenthos. Numerically, diatoms are very largely dominant. Sea bass juveniles also invade creeks and salt marshes at the flow. At this time, many of them have an empty stomach. Nearly all the sea bass have a full stomach as they leave the salt marshes. *Orchestia gammarellus*, a crustacean which helps the *Atriplex* litter decomposition is always the main food item. Lafaille (2000) thinks that the fish communities (mullets, sea-bass and 2 gobies) export several tons DW of OM per year from the salt marshes toward the sea.

Otherwise, Laffaille (2000) shows that between 50 and 100% of the growth of young of the one year sea-bass is supported by the items preyed in the salt marshes. Through the example of this species, he argues that salt marshes play significant nursery roles for over 20 fish species that have a fundamental commercial importance such as soles, clupeids, mullets, etc. Moreover, the fish community in salt marshes and associated marine water contains over 100 fish species that are resident dwellers or transient freshwater, diadromous or marine species.

Fishermen, oyster and mussel producers ignore the economic value of the natural salt marshes. It is not the same for farmers. They traditionally mow hay in the high salt marshes and they breed about 20 000 sheep on a large part of salt marshes. The sheep by grazing and trampling strongly modify the vegetation: they facilitate the domination of one species, *Puccinellia maritima,* which covers large parts of the saltmarsh, replacing the natural *Atriplex* communities. This is valued by some conservationists because during winter a protected bird, the barnacle goose *Branta branta*, grazes these types of pasture (the diet of the barnacle goose is composed of about 80% *Puccinellia*). Hunters also value these grazed salt marshes because they are attractive for widgeons (a highly rated game bird) which also feed on *Puccinellia*.

Unfortunately, all these people ignore the fact that the production of these transformed salt marshes is about 3 tons DW by hectare (over 20 tons DW in the middle and high natural marshes) and because litter is poor there is no *Orchestia*, and the nursery role for fish species, the organic matter export service is also reduced. So it is necessary to find a compromise between natural and grazed marshes to maintain all diverse activities in this bay.

But during the past 10 years, a new problem appeared: the spread of the native clonal grass *Elymus aethericus*. Formerly confined to the high marsh, this species is progressively invading the middle and low salt marshes where it often forms a dense mono-specific stand. This invasion is more effective in natural salt marshes than in grazed ones where monospecific communities of *Puccinellia* occur. This invasion mainly leads to the replacement of *Atriplex portulacoïdes* communities, which initially covered about 1/3 of the marsh in 1991–1992. The higher Carbon Accumulation Index of the litter under *E. aethericus* than under control plant communities indirectly revealed the slower decay of organic matter and the fact that the high production of *E. aethericus* might be trapped inside the marsh. This slow decay of *Elymus aethericus*

# A CENTRAL SCIENTIFIC ISSUE ?
# Outwelling concept : in Mont Saint-Michel Bay

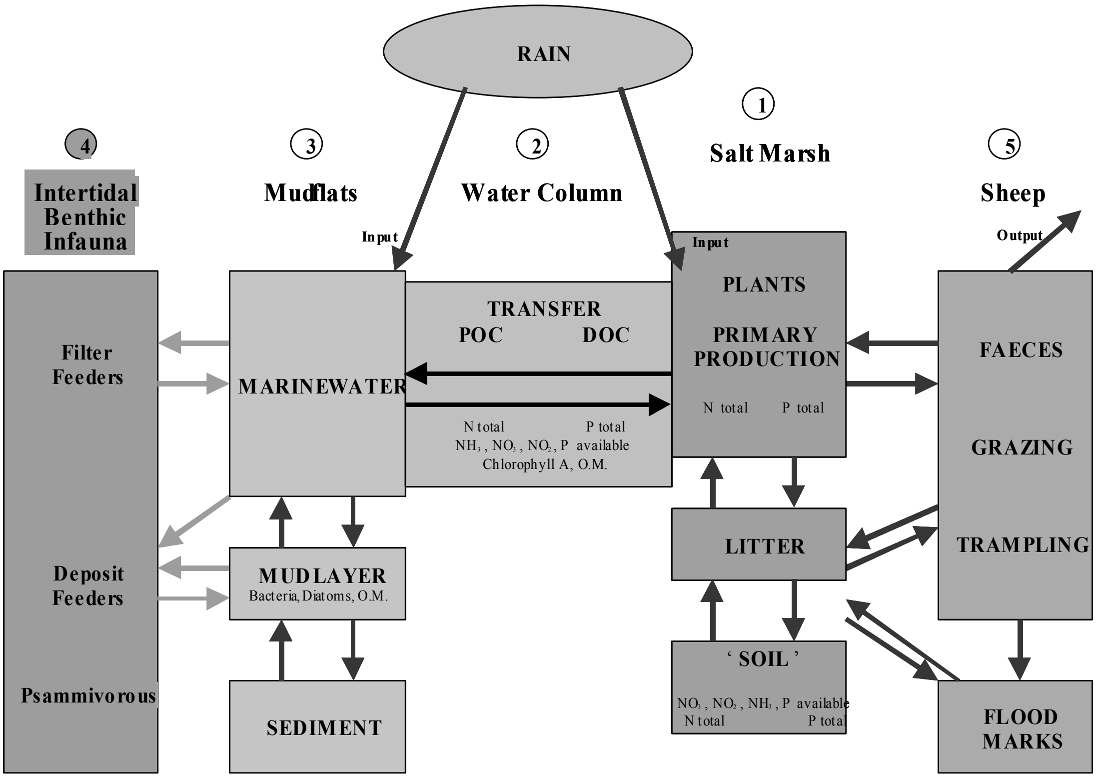


**Fig. 12** Primary production of natural and grazed salt marshes and exchanges with mudflats and marine coastal water (from Lefeuvre *et al.*, 1994.

litter can be explained by its greater lignin content (Valéry, 2006). The low C/N ratio of *E. aethericus* litter also suggested that N might be trapped in the litter, thus limiting the release of this molecule to the environment. In faster decaying litter of *A. portulacoïdes*, Bouchard & Lefeuvre (2000) showed that N was not retained in the litter but, instead, was rapidly redistributed to the system. This supports the idea that the substitution of *A. portulacoïdes* by *E. aethericus* in a large area has a very important negative impact on the land–sea exchange. For example, several functions of the salt marshes may be modified by such an invasion: the exportation capacity of the salt marshes may be modified, and in turn, affect mussel and oyster culture with linked economic consequences. The habitat value for ducks and geese could be changed as well as the nursery function for the fish species. Thus *Elymus* invasion can be considered as responsible for a reduction of the availability and accessibility for the main *Orchestia gammarellus* which probably explained the lower food consumption observed in the sea-bass juveniles that use the modified salt marshes.

Laboratory experiments (Leport *et al.*, 2006) have shown that the amount of osmolyte molecules produced by *Elymus* increased proportionally to the load of nitrates and the frequency of tide floods. The causes of this invasion are mainly due to eutrophication of the coastal water, mostly due to the transport of freshwater from the rivers to the salt marshes. The loads of nitrates have increased regularly since the 1970s and loads of over 50 mg $L^{-1}$ have been regularly recorded since the 1990s. This is related to the intensification of agricultural practices in the catchments. This is supported by the increase of other nitrophilic species as *Suaeda maritima* and *Aster maritima*. Moreover, the first toxic algae (*Pseudonitszchia* sp.) and *Ulvae* blooms were recorded in the late 1990s in the northeastern part of Mont Saint Michel bay.

## Water in a Celtic country: Brittany – a regional model of transfer from continent to ocean

All of this research shows how the ecosystem balance of a littoral system can be disturbed or even compromised by the increase of one category of usage supported by lobbies. The littoral economy is based upon the direct or indirect exploitation (fishery, shell culture, tourism, cattle breeding, hunting, etc) of the primary productivity of the salt marshes and related mudflats (Fig. 12). The development of intensive agriculture that takes no account of the environmental issues regularly destroy the integrity of the land–ocean biogeochemical and water transfers. Many key role systems as wetlands, hedgerows, permanent meadows are destroyed, and cannot play any role in the control of part of the excess of nutrients produced by cattle, pig and chicken intensive breeding and intensive agriculture. These findings were largely demonstrated in a region like Brittany by considerable research on landscape ecology of bocage systems.

It is disappointing, if not tragic, to realise that despite such a considerable research effort and knowledge production to explain how and why our freshwater and marine resources are continuously changing, the behaviour of politicians, decision makers, food industries, and farmers has not changed during the last 30 years. Brittany is now considered at the international level as the model of what one must not do in terms of environmental management.

Indeed, among Celtic countries, Brittany has experienced the most considerable agricultural mutation. In 1989, the regional director of Agriculture, P. Guyomard, stated that "*Since the last world war, this region has acquired industrial agricultural practices and totally turned to market economy ... Nowadays, Brittany is the first region in France for pigs, milk, chicken and some vegetable production*". This analysis is balanced by Canevet (1992) who added that "*this dynamism is also weak and fragile*". This agro-alimentary complex has mainly favoured mass production but is disappointing in terms of income. But overall, Canevet states that "*this uncontrolled productivism is disturbing for the environment and its resources*", therefore compromising other activities such as fisheries, shell culture and tourism.

This deep mutation can be summed up thus:

- 730 000 pigs in 1950, over 13 million in 2004;
- 5 million poultry in 1950, 100 000 million in 2000;
- in 2002 maize covered over 1/4 of arable lands;
- continuous regression of permanent meadows; from 1988 to 2000, 43% of permanent meadows were converted to ploughed fields ;
- over 300 000 km of woody hedges and talus were cut down since 1955.

Tens of kilometres of upstream brooks and rivers were straightened and thousands of hectares of bordering wet meadows were drained and turned to culture.

This global evolution provoked increasing input of nutrients, pesticides, but also of "structural excedents" from pig, cattle or poultry slurry. The whole of Brittany is listed as an area "prone to eutrophication" but has nevertheless seen the nitrate levels increase from 10 mg $L^{-1}$ in 1972 to 40 mg $L^{-1}$ in 1998. By this date, over half the maximal nitrate concentration ranged between 50 and 100 mg $L^{-1}$. In 2003, the region estimated that there was an excess of 44 000 t of organic nitrogen. About ¾ of the Breton population consume tap water with nitrate concentrations over 25 mg $L^{-1}$. In 2000, 25% of the water sources contained over 50 mg $L^{-1}$ of nitrates.

The control of phosphorous matters is also a major concern for the region. Although domestic and industrial activities are sources of phosphorous, most of the loads are due to agriculture. In Brittany, the loss of phosphorous from fields to rivers ranges from 0.5 to 3 kg P $ha^{-1}$ $year^{-1}$, mostly because of soil erosion. Transfers mainly occur during rainy periods and floods over very short periods. Once they arrive in the water, P is partly stored in sediments.

In Brittany, 64 of 118 water points exceed legal thresholds for human health, with levels of oxydability over 10 mg $L^{-1}$. The most polluted water points are concentrated in the northeast of the Brittany area. Record concentrations of dissolved organic carbon (up to 12 mg $L^{-1}$) indicate a highly degraded water quality from the organic matter point of view. Molecular analysis showed high concentrations of coprostanol produced by pig urine. To reduce this pollution, high concentrations of chlorine are used to treat water for human consumption. This procedure in turn provokes the formation of SPC chlorine products that are toxic for people.

To enforce the description of the problem, the data of the "Académie de l'Eau" (2003) are useful: agricultural pollution is expressed in terms of habitant-equivalent. This academy considers that the pollution produced by one pig is equivalent to 3 habitant-equivalent, a cow to 10, a sheep to 2 and one chicken to 1. Combining this with official data of the agricultural census of 2000: the following figures are calculated (Table 1).

**Table 1**

| Domestic animals | Total numbers | Habitant equivalent |
|---|---|---|
| Pig | 8 160 524 | 24 481 572 |
| Cattle | 2 261 780 | 22 617 800 |
| Sheep | 99 978 | 199 956 |
| Poultry | 1 001 307 000 | 10 013 070 |
| TOTAL | | 57 312 398 |

In other words, it represents over 60 million habitant equivalent, which is the human population of five of the largest cities in the world: Sao Paulo, Mexico, New York, Delhi and Beijing, and with wastewaters flowing directly to water bodies, without any treatment.

The contamination of the water by pesticides remains a major concern. In 2004, of 130 molecules analysed, 41 had concentrations greater than 0.1 µg $L^{-1}$. None of the surveyed rivers was without pollution. The cumulating concentrations even reach 19 µg $L^{-1}$. The most often used herbicide, Glyphosate, or its metabolite (AMPA) are detected at concentrations exceeding the European threshold of 0.1 µg $L^{-1}$. Atrazine and related metabolites are still detected in some rivers. It reached 11.1 µg $L^{-1}$ in 2000 while the alachlore concentration was of 6.9 µg $L^{-1}$ in a river of Brittany near Rennes (the Flume). This degradation of water quality is increased by the numerous dams which are built for drinking water supply or hydroelectricity. They are real sediment and nutrient traps and are highly eutrophicated. In over 75% of them, severe cyanobacteria blooms occur, most of which produce mycrocystin, a hepatotoxin. The recent discovery of the ability of most cyanobacteria to produce *B*-*N*-méthylamino-*L*-alanine (BMAA), a neurotoxic amino acid potentially involved in the development of neuro-degenerative diseases (multiple sclerosis, Parkinson disease, Alzeimers) (Cox *et al*., 2005), shows the problem of the reservoirs of hyper eutrophicated waters, some of them cannot be used.

Because the Breton rivers are short, the pollutants transferred from the catchment to the rivers rapidly arrive in estuaries and favour the degradation of coastal marine waters quality. Over one third of the Breton estuaries have experienced some alteration of the oxygen loads during summers. This phenomenon is due to excess of organic matter inputs. Most sites are subjected to ammonium contamination. All the estuaries present bacterial contamination due to urban waste waters. The most spectacular effect of eutrophication is the "green tides" due to the proliferation of *Ulva* sp. in the bays distributed throughout Brittany. A total of 65 littoral towns are currently concerned by this problem. In 2000, 66 000 $m^3$ of ulvae were removed from the beaches. Therefore the agriculture directly effects not only tourism, but also oyster production. Due to the proliferation of toxic algae there are direct consequences on tourism, as *Dinophysis* produces diarrhoeic toxins, while *Pseudonitzschia* sp. and *Alexandrium minutum* sp. produce neurotoxins (Menesguen, 2001). The collection of shells on beaches, the fishing of scallops, and commercialization of mussels and oysters are forbidden during massive blooms, and result in unemployment.

Consumers recently took international companies "Générale des Eaux" and "Suez Lyonnaise des Eaux" to court over. They where convicted of distribution of undrinkable water. The Suez Lyonnaise des Eaux then took the French State to court because of the poor quality of the natural water they had to process. The State was then sentenced to pay back the entire amount of money that the consumers have paid to buy bottled drinking water. Moreover, the "Audit Office" considered in 2002 that the important expenses of money spent in Brittany to restore the quality of the water were wasted as the results were insignificant. This institution denounced the lack of objectives of the State and the absence of "a firm policy leading to a reduction of the size of the domestic cattle". It insisted on the fact that all the problems leading to a degradation of the water quality in Brittany had been identified for more than 30 years and that nothing had really been done to correct the environmental effects of agricultural development. The Court of European Communities also sentenced France for "pollution by nitrates of superficial waters for drinkable water production".

The Ministry of Ecology and Sustainable development considers that part of the evolution of the quality of water and all the consequences, is due to the fact that, to date, there is no global vision of the problems. Researchers are of course bound to agree with this statement: the incapacity of moral people in charge of the management of water, to reason at the level of the river system, from the sources to the estuary and marine boundaries, to take into account intersystem exchanges. This situation made global diagnosis impossible and did not allow implementation of efficient policies.

The European Water Framework promulgated of 23 October 2000, proposed a global approach with a precise schedule and a clear objective: the long term protection of the aquatic environment and resources. This directive insists on the necessity to implement an integrated policy on water management at the catchment level. It is the first time that the worries expressed by researchers appears in an official recommendation. Among the main key words we may emphasize:

– a combined approach to reduce pollution at the source by the implementation of threshold outputs and of norms for environmental quality;
– decisions taken at the closest proximity to the sites of utilization or of degradation of the water;
– the implementation of essential principles such as precautionary principle, correction principle with a priority to the source of degradation of water quality, pollutant–payer principle.

The only hope for the future of freshwater and coastal waters is that this directive remains clearly enforced and results in the implementation of realistic "nature" restoration plans as described for years and years by journals such as *Ecological Engineering and Biological Conservation* as watershed landscape restoration, rehabilitation of wetlands and meandering rivers.

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