

Ecohydrology: a new paradigm for bioengineers ?

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Worried about the future of freshwater resources, UNESCO launched in 1996 a new worldwide programme called "Ecohydrology, a New Paradigm". As a first step, the paper defines the term "ecohydrology" more widely. Five practical cases, in Europe and Africa, synthesize the large domain that ecohydrology embraces. The concept is then discussed on three points: topicality, involved actors and innovative research axes. The latest briefly present phytoremediation and biomanipulation.

Keywords. Biomanipulation, ecohydrology, phytoremediation.

Écohydrologie : un nouveau paradigme pour les bio-ingénieurs ? Soucieux du devenir des ressources d'eaux douces, l'UNESCO lançait en 1996 un nouveau projet mondial intitulé "Écohydrologie, un nouveau paradigme". Dans un premier temps, l'article définit plus amplement le terme d'écohydrologie. Cinq applications pratiques, en Europe et en Afrique, synthétisent la large gamme d'activités qu'englobe l'écohydrologie. Le concept est ensuite discuté sous trois points : son actualité, les acteurs impliqués, les axes de recherche innovateurs. Ces derniers présentent brièvement la phytoremédiation et la biomanipulation.

Mots-clés. Biomanipulation, écohydrologie, phytoremédiation.

1. INTRODUCTION

The *Brundtland* report (WCED) edited in 1987 and the International Conference of Rio in 1992 (UNCED, 1993), both organized by the *United Nation Commission for Environment and Development*, obviously showed the endless damage to environment and the unconditional report of application of draconian solutions towards the coming generations. Both manifesti plead for a *sustainable development* able to assume, simultaneously and at long term, economic growth, improvement of environment and protection of natural resources.

Among the latest, a crucial importance must be dedicated to fresh, drinking water. The management of this resource will be one of the major challenges for the new Millennium, as well as the allowance for the whole population to reach fair conditions of nourishment and hygiene.

Since 1970, UNESCO has launched studies of integrated management of watershed throughout the world, through the development of two programs: *Man and Biosphere*, followed by the *International Hydrological Programme* in 1975. The *Fifth Phase* of the latest program began in 1996 with ecohydrology as a major theme.

As part of this project, UNESCO invited forty scientists of various nationalities at an itinerant course in Poland, Austria, Hungary, Croatia and Italy (8–22 September 1999). This scientific training, called *Advanced Study Course in Ecohydrology*, presented the particularity of being established upon two major goals:

- to offer a real opportunity to young research scientists to improve their first knowledge in ecohydrology by practical and targeted field cases as well as to share the experience of senior scientists;
- to promote the birth of a dynamic group of young scientists through a joint experience, the development of a network of exchange and the share of knowledge on a worldwide scale.

The present paper is a continuation of this theoretical and applied education. It suggests to identify new developments by the re-definition of the "ecohydrology" concept and the application of bioengineer technology.

2. ECOHYDROLOGY

Ecohydrology, considered as a new paradigm, is a neologism arising from the coalescence of both terms "hydrology" and "ecology". It was first postulated in

Dublin in 1992 at the International Conference on Water and Environment (Zalewski et al., 1997) and suggests a new watershed approach methodology. Scientists wished to bind biological and physical sciences together with the goal of a better understanding of the studied ecosystems (Viville, Littlewood, 1997).

The concept “ecohydrology” is aimed at scientists working in the water domain. It tries to heighten the awareness of engineers in hydrology to more ecological methods and *vice versa*. Indeed up to now, many scientists and industrialists take into consideration solutions from their own skills, whilst a co-operation between hydrologists and ecologists would result in more adapted solutions for the aquatic environment (Jolankai, pers. com., 1999).

Figure 1, taken from the Fifth Phase booklet, sets ecohydrology as a link between past and future in water management. Ecohydrology is a current phase which will allow at middle term a development and a management of aquatic environments. Up to now, water management is limited to the reduction or even to the elimination of periodical phenomenons such as catastrophic floods, droughts, pollution or erosion. The future must go beyond this concept and “amplify the chance” through ecohydrology. Indeed, biological methods allow to strengthen technical methods for an equivalent price and moreover rise their efficiency (Zalewski, pers. com., 1999). Unfortunately this amplification of opportunities is, nowadays, still too often neglected (Zalewski, Mc Clain, 1998).

The postulate of ecohydrology considers the watershed as a “super-organism” (ecological macro-system) where an action in a local ecosystem generates

a reaction in an another one, through the hydrographical network, which is equivalent to both a receiving and transmitting system. The environment “physiology” (functioning) and its water dynamics must be understood above all. Three main objectives are described by Zalewski and Mc Clain (1998):

- the knowledge of “hydrosystems” (aquatic ecosystems) and comprehension of their relations with climatology, hydrology, water chemistry, toxicology, biology, geology, physical as well as biological processes, and mankind;
- integration of computerized models based on this knowledge;
- prediction of changes in the hydrosystem – simulations, scenarii – with random variations of hydroclimatological, chemical and biological data, or variations due to management politics.

Let’s notice with Janauer (pers. com., 1999) that GIS tools are probably amongst the best ones to make a link between hydrology and ecology: valuable ecohydrological results are provided without the scale differences generally used in both specific domains.

Through the analysis of ecological and hydrological components, ecohydrology takes place in various and interconnected sectors, i.e. water storage, denitrification, water self-purification, biofiltration. The paradigm is applicable to natural as well as to artificial aquatic ecosystems (Zalewski, pers. com., 1999). The itinerant course provided practical applications in ecohydrology through four cases described below. A last case will be discussed as a recent appraisal conducted by the Ecology Laboratory.

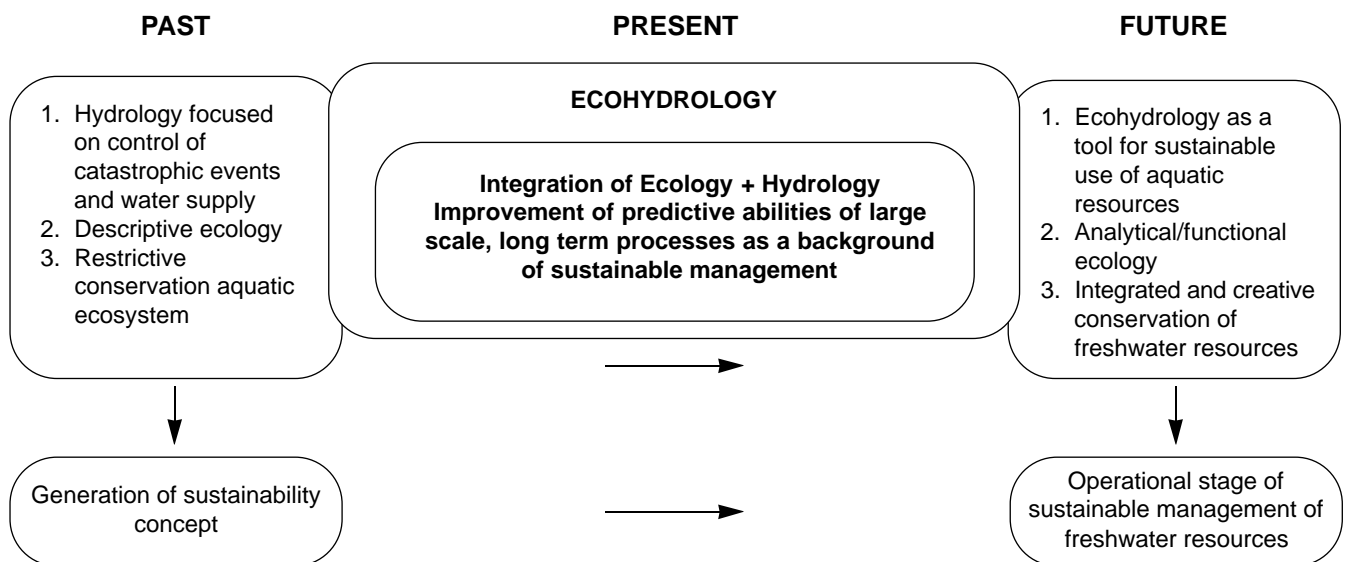


Figure 1. Evolution of ecological and hydrological sciences (from Zalewski, 1996) — *Évolution des sciences écologiques et hydrologiques (d’après Zalewski, 1996).*

Case 1. The Sulejów Reservoir, Poland (Figure 2)

This lake illustrates an example of eutrophication studied by Prof. M. Zalewski's team of University of Łódź (Zalewski *et al.*, 1990a, 1990b; Zalewski *et al.*, 1998; Zalewski, Wagner, 1998). With an area of 22 km², this lake supplies one million people with drinking water. For some years, various problems have been emerging. Algal blooms appear during summer because of favourable climatic conditions coupled to a natural release of nutrients useful to their development. This release is caused by the sediment bioturbation resulting from the grazing of submerged macrophytes by herbivorous fishes. Moreover its recreation function is no more assumed. An effective restoration of this eutrophicated reservoir is considered through a better comprehension of the hydrological and biological phenomena. The monitoring and the stabilization of the water level should allow the development of a riparian vegetation, able to trap the excess of nutrients. Microbiological tests of water quality (traditional kits) are currently carried out in order to measure effectively the scheduled reductions of cyanobacteria biomass. As stated above, social, economic and environmental aspects are considered and match perfectly the ecohydrological concept.



Figure 2. Cyanobacteria sampling in the Sulejów Reservoir, Poland — *Prélèvement de cyanobactéries dans le bassin de retenue de Sulejów, Pologne.*

Case 2. The New Danube, Austria (Figure 3). About 80% of the Danube and its tributaries are influenced by human activities – a recent example is found in the dumping of toxic waste issued from a Romanian gold mine last January 2000 – and by hydrological factors such as floods. Our example concerns the neighbourhood of Vienna where part of the river waters have been canalized for 125 years. Upstream from this city, the artificial conditions of the Danube lead to a progressive disappearance of meanders and arms. Sandbanks become more confined and the



Figure 3. The New Danube, Austria — *Le Nouveau Danube, Autriche.*

gravel zones, useful for fishes, nearly disappear. Tools and practical solutions are discussed:

- survey and quantification of flood impacts through GIS cartography of spatial and temporal dynamics of various aquatic macrophyte communities (Gutknecht, Stephan, 1996; Janauer, 1999; Janauer, Wychera, 1999; Weigluni *et al.*, 1999). Indeed, an evolution of aquatic community plants is observed during time in synergy with the hydrology of the environment;
- monitoring of ichthyological populations as biological indicators (Schiemer *et al.*, 1995). Diversity and abundance of rheophile species (living in torrents) are inversely correlated to the limitation and disappearance of spawning zones due to bank constructions.

The two taxa, chosen as biological indicators, belong to different trophic levels and provide a useful information for the follow-up of the ecosystem evolution. Thereby they must be considered in priority.

Case 3. The Kis-Balaton Water Protection System, Hungary (Figure 4).

The water quality of Lake Balaton has been deteriorating since 1950–1960 by the discharge of waste waters due to a rapid urban development, the use in agriculture of chemical products and industrialization (Magyarics, 1999) as a response to Budapest's vicinity. In order to purify the incoming waters of the River Zala, the Kis-Balaton Water Protection System (KBWPS) was set up by a progressive inundation of arable lands. The KBWPS is a gigantic artificial basin of 70 km² and of about 1.1 m depth. It is shaped like a maze of small and large basins separated by constructed banks. Its major functions concern ecology and hydrology:



Figure 4. The Kis-Balaton water protection system, Hungary — *Le système de protection des eaux du Kis-Balaton, Hongrie.*

- reduction of nutrient loads from the River Zala by sedimentation, adsorption and consumption by algae and by emerged and submerged macrophytes (Istvanovics, 1999; Pomogyi, 1993);
- reduction of eutrophication and algal blooms in sheltered parts (measurements of chlorophyll a concentrations);
- improvement of water quality: incoming black waters are charged in humic and fulvic acids. The green colour of the outgoing waters shows waters abundantly charged in algae;
- rise of purification rate through the introduction of omnivorous fishes (Tatrai, 1999);
- rise of biodiversity (abundance of birds, diversified flora) by creation of a “natural” environment;
- ecological and recreational approach for the surrounding population (use of artificial basins for extensive fishing by tourists).

Even if at first sight the suggested system seems a simple diversion and storage basin, its multifunctional role brings an ecohydrological dimension.

Case 4. Lake of Njivice, Krk Island, Croatia (Figure 5). Water is a crucial factor on this island, even if it is located nearby the continent. Up to 1999, the lake of Njivice has been the main drinking water source for the insular population. Awrong management of its watershed (i.e. intensive grazing, draining network connected to the lake) led to the degradation of water quality. The watershed problems were diagnosed by Torres (1999) in order to valorize the water resource. Four ecohydrological components were studied:

- evolution of meteorological data as well as main physical and chemical parameters of the lake in the past few years;
- study of underground water streams by the installation of piezometers;



Figure 5. Lake of Njivice, Krk Island, Croatia — *Lac de Njivice, île de Krk, Croatie.*

- identification of the vegetation located in the whole basin and its potential for phytoremediation;
- physical, chemical and microbiological analysis of draining water.

From these results, a map was drawn by GIS and set for the watershed. It allows to delimit risky zones and defines an appropriate management for each of them. The concrete application of such guidelines represents for the watershed the first step of a sustainable management and rehabilitation of the lacustrine water. Since then, other research has been started and allow the local bioengineers to develop other long-term techniques such as biomanipulation or phytoremediation on the lake of Njivice.

Case 5. The Lower Senegal River Management (Figure 6). With about 1,800 km length, the Senegal River takes its spring in the Fouta Djallon massif. Its catchment area is about 290,000 km². The flow presented strong seasonality. From 1968, severe decreases in flow were observed, which had led to the construction of two dams: the Diama Dam in 1986 and the Manantali Dam in 1988 at about 1,100 km from the mouth. Purposes of the Diama dam were to act as an “against-salt barrier”, in order to establish a freshwater reservoir for irrigation of some 70,000 ha of rice. A dyke completed the man-made reservoir. Ecological impacts of the dam are summarized:

- Hydrological changes: salt content of water decreases from 2 to values comprised between 1–0.2%; whilst main water depth values became stable, without important variations, with values between 1.5 and 2.1 m.
- Several systemic changes in the vegetation were observed: regression of the *Tamarix senegalensis* DC. thickets, which formerly provided firewood for the local population; explosion of bulrush and to a lesser degree of reed carpets; increase of two types



Figure 6. Aerial view of the Senegal River — *Vue aérienne de la rivière Sénégal.*

of aquatic meadows, according to water depth, with the development of aquatic pests such as *Salvinia molesta* D.S. Mitchell; loss of natural brackish water communities in adjacent areas such as Djoudj Bird National Park and Guiers Lake; decline of mangroves, downstream the dam, in response to occasional releases of freshwater; encroachment of flooded *Aeschynomene elaphroxylon* (Guill. & Perr.) Taub. thickets.

Those changes induce fine values of rice production, but also public health issues, mainly regarding paludism and bilharziasis in response to development of *Biomphalaria pfeifferi* (Krauss) and *Bulinus* spp. populations, decrease of diversity in fish communities, decrease of bird biodiversity (this area was known as a bird sanctuary). Major of these disadvantages are due to the non-consideration of risks foreshadowed by ecologists (Anon., s.d.). An ecohydrological approach would have minimized these regrettable consequences. We are presently looking about the feasibility of using this tremendous bulrush biomass (Malaisse, Matera, 2001). Values are included between 1.3 and 3.0 kg·m⁻² dry weight, with a mean useful dry biomass of 18 tons·ha⁻¹ and at least 120,000 tons for the area under study. Local uses of bulrush are restricted to thatch roofs, fences, mats, mattresses and baskets. Uses could be extended to charcoal by using a newly-constructed engine.

The five cases treated as examples above represent a glimpse of the wide theme that ecohydrology embraces. Many other examples could be evoked – management of tropical freshwater (Harper, 1998), environmental impacts on Lake Kinneret and its watershed (Berman, 1998), phytoremediation for polluted highway waters (Gouder de Beauregard, 1996, 2000, **figure 7**) – but their exhaustive enumeration goes beyond the limits of the present paper.



Figure 7. Cédrogne's storm water basin, Belgium — *Bassin d'orage de Cédrogne, Belgique.*

3. DISCUSSION

As previously explained, the definition of ecohydrology was specified in 1992 by an academic organizing committee in co-ordination with UNESCO. It gathers both sciences of hydrology and ecology. Examples above illustrate the variety of domains of ecohydrology. All concern the water resources and their management, quality, preservation and sustainability, sometimes on large scale areas. The environmental studies are various and may be highly specialized; among them, ecotones – or buffer zones – are often tackled through the macrophytic vegetation. For many years various themes have been frequently developed. Why is therefore ecohydrology presented as a “new” paradigm? Has it really to be considered as a new thought process? Our answer will be organized in three reflections: concept topicality, involved actors in ecohydrology and innovative research axes.

3.1. Concept topicality

As far as we know, Pedroli (1990) first used the term “eco hydrology” in an underground water study. However the correlation of both domains was evoked one year before by Falkenmark and Chapman (1989), as well as by Dussart in 1966. References to this concept are increasing ever since (**Figure 8**), even if sometimes papers which belong indisputably to it do not evoke the term. Only two papers will be quoted as an example, Grootjans *et al.* (1996) and Hobma *et al.* (1997). They tackle respectively the hydrological impacts on vegetation ecology, and the use of ecological ranges of plant communities to estimate the quality of surface and underground waters. The term remains relatively discreet and we do recommend a larger use in both international journals and in search engines of websites specialized in hydrology.

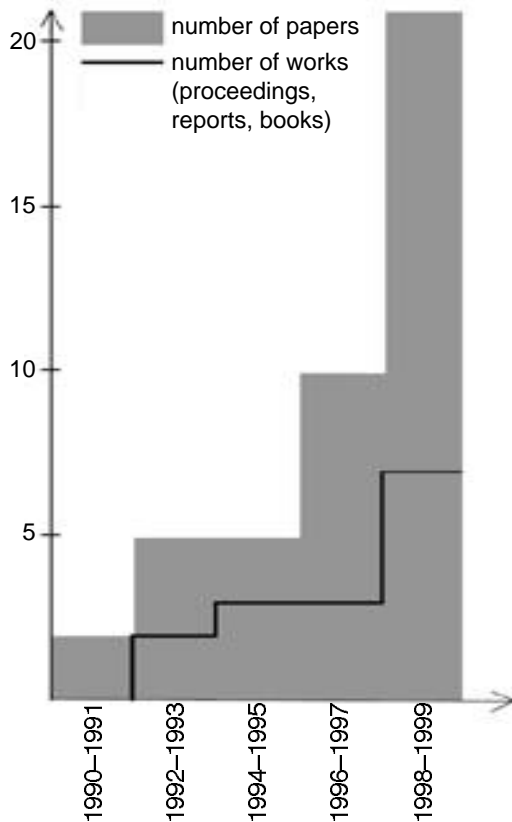


Figure 8. Increasing references of the ecohydrology concept in international publications — *Références croissantes du concept de l'écohydrologie dans les publications internationales.*

3.2. Involved actors in ecohydrology

Ecohydrology brings an additional dimension to water management. The paradigm consists in a thought process which allows a synergy through the complementarity of various research sectors. The concept was first dedicated to civil engineers and to hydrologists *sensu stricto*. According to Jolankai (pers. com., 1999), hydrology has neglected the natural environment for too long. Ecohydrology is a way to open up to this green wave, to apply methodologies in association with environmental solutions and co-operate with other scientists, ecologists in particular.

The above examples show that bioengineers co-operate with other actors such as civil engineers, physicists, meteorologists, chemists. A multidisciplinary reflection rallies all scientists in such a way that each of them is able to step into his own domain. Similarly, ecohydrology represents a way to share knowledge for a better identification of adapted solutions for the aquatic environment. A large network is thereby constituted by actors involved in water management, linking international specialists of various disciplines.

Let's emphasize that the perception of the problem will be different according to the involved specialist – hydrologist, ecologist or bioengineer – and therefore, distinct processes will succeed. For instance, the hydrologist will consider the paradigm as a growing awareness for a “more ecological” hydrology in partnership with actors working in the environment. In particular, this was the case during the itinerant course above quoted, where hydrologists represented the majority. On the contrary, the ecologist will discover applied hydrological methods, which will bring him a relevant information for the management of biotic systems. Through his multidisciplinary education, the bioengineer has a thorough knowledge of hydrology and ecology which allows him to build up complementary ecohydrological solutions in partnership with other actors. Ecohydrology will be valorized by a better knowledge of this science and the spread of the concept. It is important to link partners between them and promote exchanges of knowledge, experiences, solutions. Each actor, working in his own domain, will provide, according to his sensibility, elements adapted to the aquatic environment. The joint examination of sector-related propositions should come out on an optimal collegial proposition (**Figure 9**).

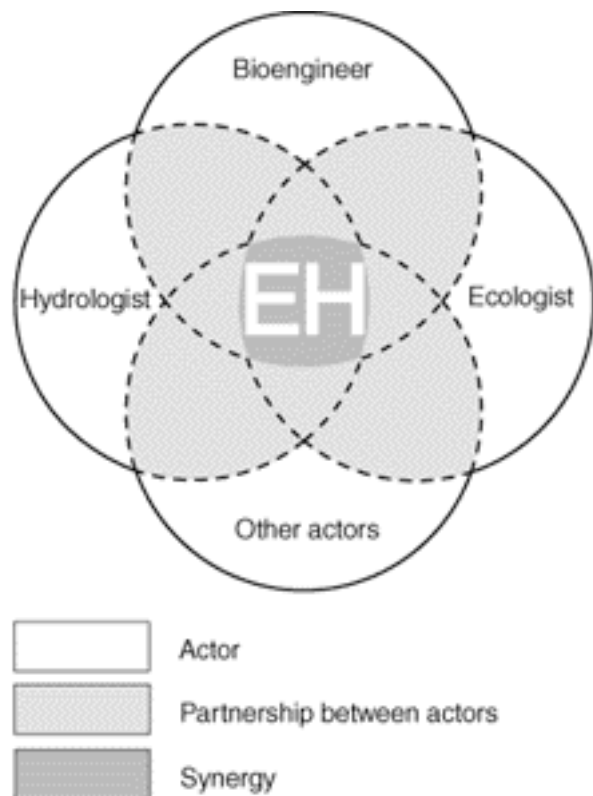


Figure 9. Multidisciplinary approach of ecohydrology — *Approche multidisciplinaire de l'écohydrologie.*

3.3. Innovative research axes

Ecohydrology objectives show by themselves the framework for the methodology (summarized on **figure 10**) to apply. This is based on three steps:

- The preliminary study of a catchment starts with an in-depth ecological understanding of the environment (climate, soil science, vegetation, human occupation).
- The prevention of pollution, basement of a sustainable development, represents the second step. This implies to establish a catchment model in view to precise sources and to assess pollutants fluxes. From this model, a sustainable land-use management programme will be constituted for the catchment.
- Bio-engineers implement several technologies to strengthen the ecosystems, like phytoremediation and biomanipulation. They consider long-term management scenarii, in particular through the model previously established.

It is advisable to insist on phytoremediation and biomanipulation, both important innovative research axes for ecohydrology.

Importance of the ecotones in the phytoremediation.

Phytoremediation consists of using vegetation for *in situ* treatment of polluted ecosystems (Schnoor, 2000). When two biotic communities overlap without defined limits we are in presence of a continuum. But when there is, between these two ecosystems, a tight zone with its own characteristics and species, we have an ecotone (Fischesser, Dupuis-Tate, 1996). Several

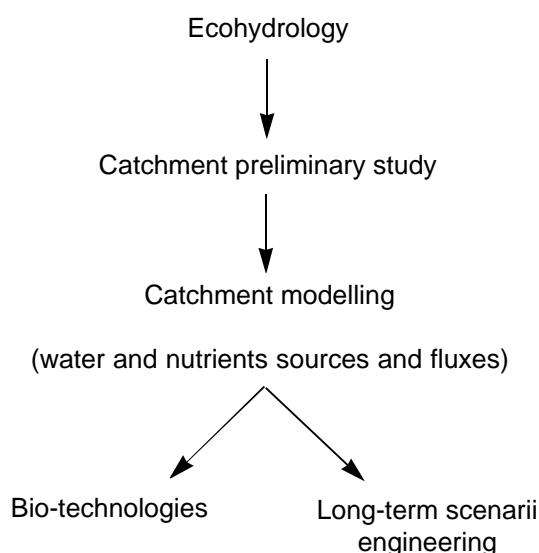


Figure 10. Methodology for ecohydrological research — *Méthodologie pour la recherche en écohydrologie.*

different ecotones exist, depending on whether they are located between two terrestrial ecosystems, two aquatic ecosystems or a terrestrial and an aquatic ecosystem (Piecynska, 1990). They play an important role in the landscape structure, in the biogeochemical cycles (Zalewski *et al.*, 1997) and by their large biodiversity (Fischesser, Dupuis-Tate, 1996). Ecotones studies have been for a long time the subject of numerous researches, in ecohydrology particularly.

In an aquatic ecosystem the purification function of the aquatic vegetation is an important measure for the water biological treatment (Massacci *et al.*, 2000). Many plants use a tight network of roots and rhizomes – like *Typha* spp. and *Phragmites communis* Trin. (Massacci *et al.*, 2000; Naiman, 1990) – which acts as a biological filter, a trapping system for nutrients, a buffer against eutrophication (Torres, 2000; Zalewski *et al.*, 1997).

Conservation and management of ecotones by phytoremediation studies are called to play an important role at long-term in freshwater quality.

Biomanipulation. The “trophic cascade theory”, postulated for the first time by Carpenter and Kitchell (1992), must be understood before suggesting a definition of biomanipulation and assessing its importance.

The trophic cascade is a theory in which the manipulation of a trophic pyramid level induces modifications in the immediate upper and (or) lower levels. These modifications will further create, by a cascade phenomenon, changes in upper or lower levels and so on (Benndorf, 1995). When these changes go up the trophic pyramid, the manipulation is called “bottom-up”. On the contrary, when they go down, it's called “top-down” (Lampert, 1988). Both models are complementary and non-contradictory (Carpenter, Kitchell, 1992).

The control of the trophic pyramid by “top-down” is biomanipulation (Benndorf, 1995). Moss (1988) provided a good example of a strategy for the control of internal lake processes through a deliberated ichtyologic community modification. On the other hand, the “bottom-up” strategy will consist of a reduction of external nutrients, pollutants and organic matter supplies (Benndorf, 1988; Koschel, 1995; Moss *et al.*, 1986, 1996; Olofsson *et al.*, 1988). The **figure 11** shows these manipulations.

The concept was first formulated in 1975 by Shapiro. He suggested an alternative approach to chemical and physical treatments for lake restoration. Although, the process had been already used before. Indeed Caird, already in 1940 (Benndorf, 1995), described a situation in a pond of the Connecticut (United States of America): the pond suffered from algal blooms and needed a copper sulphate treatment

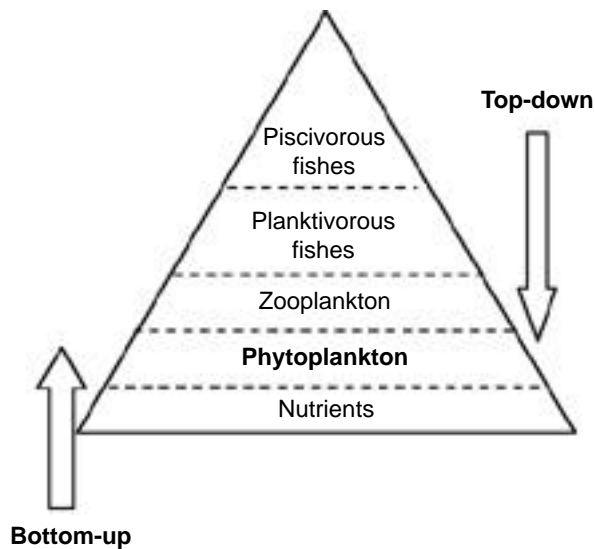


Figure 11. Trophic cascade theory applied to aquatic ecosystems — *Théorie de la cascade trophique appliquée aux écosystèmes aquatiques.*

many times a year. The need of this chemical treatment became useless by the introduction of *Perca fluviatilis* L. He observed an eutrophication reduction without understanding how the perch controlled the algal bloom (the trophic cascade theory was established later!).

Many scientists (Davidowicz *et al.*, 1988; Lampert, 1988; Mc Queen *et al.*, 1992; Zalewski, 1996) have experimentally shown that a maximisation of the filtrating capacity of the phytoplanktivorous zooplankton can be reached by the control of its mortality through the predation of the upper trophic levels. The first step of these interventions consists to favour a weak density in zooplanktivorous fishes. This will increase phytoplanktivorous zooplankton and thus decrease the abundance of phytoplankton.

A lot of techniques are presently used in biomanipulation to increase populations of zooplankton and try to diminish predators, i.e. zooplanktivorous fishes (**Figure 11**).

The first one is the total elimination of planktivorous fishes by the use of rotenone. This is a piscicide used to structure or to eliminate some well-defined fish populations. All fishes are sensitive to its action but the zooplanktivorous and benthivorous fishes are the first targets. A dose of $1.0 \text{ mg}\cdot\text{l}^{-1}$ is lethal for all fishes but the dose can be adjusted to eliminate the desired species (Moss, 1988).

The second method is the use of nets or electrical fisheries to remove zooplanktivorous fishes (Benndorf, 1988; Frankiewicz *et al.*, 1996a, 1996b; Moss *et al.*, 1996; Zalewski, Cowx, 1990).

The third method is the most common. It aims to increase zooplankton by the introduction of

piscivorous fishes. In the literature, *Perca fluviatilis* L. (Benndorf, 1988; Mc Queen *et al.*, 1992; Zalewski *et al.*, 1990a, 1990b) and *Stizostedion lucioperca* L. (Frankiewicz *et al.*, 1996a, 1996b; Moss, 1998) are the most suggested species.

Lastly, water level fluctuations of reservoirs represent another biomanipulation technique. An increase of the level will flood the grassy banks, which are spawn zones for perches (Zalewski *et al.*, 1990a, 1990b).

All these techniques need a large knowledge of the equilibrium between trophic levels of biomanipulated lakes. Introduction as well as removal of fishes suggest to respect a maximum and minimum thresholds. As a matter of fact, a minimal quantity of zooplanktivorous fishes is necessary to control the invertebrate predators that would reduce or eliminate the phytoplanktivorous zooplankton (Benndorf, 1995; Moss *et al.*, 1996). On the other hand, a superior limit in quantity of these fishes can not be exceeded. Benndorf (1995) suggests a maximum of 30–45% of piscivorous fishes on the totality of the fish community.

Biomanipulation is typically used in small and shallow lakes. Its low cost (Zalewski *et al.*, 1997) and long-term remanence (Moss, 1998) allow being financially realisable.

4. CONCLUSION

Nowadays, ecology is a well-considered value in the scientific world. Particularly, the complementary effect between ecological solutions to hydrological problems constitutes a paradigm in the search of sustainable projects. Ecohydrology could be related to the integrated fight in agriculture: the ecohydrological approach does not solve all hydrological imponderables but contributes in getting new solutions. The originality of ecohydrology consists of using well-known concepts (e.g. ecotone, biomanipulation) and gathers them in an innovative, integrated and intellectual network leading to a synergy for the aquatic ecosystems management (Gérard, in litt.). The paradigm, new for some scientists, should be diffused and spread among all as a modern transdisciplinary approach. Such regrouping is presently sought for phytoremediation (Zalewski, pers. com., 2000), the phyto-engineers having an applicable expertise for large-scale aquatic ecosystems. Contacts between different scientific groups will serve to build a proactive ecohydrological network, at the catchment scale, which ultimate goal is the management and the perennality of freshwater, essential for life and the economy of territories.

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