INTERNATIONAL HYDROLOGICAL PROGRAMME

Ecohydrology

A New Paradigm for the Sustainable Use of Aquatic Resources

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Conceptual Background, Working Hypothesis, Rationale and Scientific Guidelines for the Implementation of the IHP-V Projects 2.3/2.4

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FOREWORD

At the present state of the human population in many areas of the world the freshwater resources are becoming the most limiting factor not only for development but even for persistence of some communities. On the other hand, the exponential growth of human population and aspirations creates and amplifies the various impacts on freshwater ecosystems. For this reason a new solution has been postulated in 1992 during the Dublin International Conference on Water and Environment.

Why has the integration of Ecology and Hydrology a potential to create a new paradigm? Up to now freshwater management dealt mostly with the elimination of threats such as floods, droughts and point source pollution. However, every successful strategy has to contain two elements: elimination of threats and amplification of chances.

One of the chances should be the use of understanding of the evolutionarily established resistance and resilience of freshwater ecosystems to stress. Besides the fundamental assumptions of the new approach , it should be environmentally sound, economically possible and socially acceptable. This goal can be achieved by research focused on integrating the functioning of freshwater ecosystems with large scale hydrological processes. The integration of the dynamics of the three components, catchment, water and biota into a "superorganism" determines the management target - the maintenance of its homeostatic equilibrium measurable by biodiversity, water quantity and quality. The information achieved has to be transferred to the public through education and applied toward creation of a new strategy adjusted to the given economic conditions. The integration of the dynamics of freshwater ecosystems into hydrological processes should create the basis for sustainable development of freshwater resources.

Maciej Zalewski

Warsaw, December 1996

ACKNOWLEDGEMENT

This publication incorporates the results of a Core Group Scientific Committee meeting of IHP-V, Projects 2.3 and 2.4, on Ecohydrology, which was held in Warsaw in October 1996. However, the final shape owes its being to many of our friends and colleagues who share our enthusiasm for the idea of integrating hydrology and ecology toward a sustainable development of the aquatic resources of the world.

We would like to express our special thanks to Fred Fournier, from the headquarters of UNESCO IHP, who was the *spiritus movens* of all the activity. His experience, and that of Phillipe Pypaert from the UNESCO Venice Office, in various forms of UNESCO environmental policies and programmes, were extremely valuable as far as the planning and organisation of such a long term strategic action is concerned.

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M.Zalewski, G.A.Janauer, G.Jolánkai

Preface

When the UNESCO Programme on Man and the Biosphere (MAB) was launched in 1971, aquatic ecosystems immediately become the subject of a special project due to the important changes inflicted by human activities.

Initially attention focused on the consequences of intensification of agriculture. At the end of the first phase a meeting was organised in Toulouse, France, in April 1986, which was devoted to the use of scientific information in understanding the impact of land use on aquatic ecosystems. During this meeting, one topic was identified as crucial: the major role played by interfaces (ecotones) between terrestrial and aquatic ecosystems in the regulation of the biogeochemical cycles and in the structure of landscape mosaics.

Therefore, it was recommended that UNESCO's future work on ecosystems should emphasize the in-depth study of ecotones and at the International Workshop organised by UNESCO at Sopron, Hungary, in May 1988 the International Institute of Applied Systems Analysis and the Hungarian Academy of Sciences prepared the collaborative research project on the role of land/inland water ecotones, to determine the management options for their conservation and restoration, through increased understanding of ecological processes.

During the project's preparation it became clearly apparent that hydrology had to be fully involved as it is shown by such working hypothesis as:

- sequence of flooding events affects the coupling of ecotones to adjacent ecosystems,
- the quantity and direction of water flow through ecotones directly affects the rate of exchange of dissolved and suspended solids between ecotones and adjacent ecosystems,
- material retention is greatest in ecotones where there is a sharp decrease in the kinetic energy of water. These ecotones frequently occur at breaks in topography.

Finally, the project launched by UNESCO in 1988 became a MAB/IHP project based on co-operation between the UNESCO's Divisions of Ecological Sciences and Water Sciences.

After five years of activities, Ecotones project participants gathered in a meeting held in Seattle, USA, in 1994 to analyse project's results. They came to the conclusion, that a considerable amount of information is already known, but there is still an urgent need to help environmental management. Efforts should be made to find out how to promote co-operation between ecology and other sciences and how to evaluate economic and social values of ecotones. Efforts should also be concentrated on specific problems and particularly on priority themes of biodiversity, the filtering capacity of ecotones and their role in maintaining landscape integrity.

Regarding the relation between ecotones and the adjacent ecosystems, the participants recommended that the project should formulate a functional model, test its validity and establish a predictive instrument based upon it.

Due to a change in its priorities, the MAB Programme now is not in a position to continue to fully support the Ecotones project. However, the International Hydrological Programme with respect to Theme 2 of its fifth phase (1996-2001), devoted to ecohydrological processes in the surficial environment, is able to link with the Ecotones project in a new framework of two projects:

- Interactions between river systems, flood plains and wetlands,
- Comprehensive assessment of surficial ecohydrological processes.

As a conclusion, we hope this publication can be used to launch a new challenging concept, the Ecohydrology.

We look forward to the full support of the IHP National Committees, the MAB participants in the first phase of the Ecotones project, and the IHP Council and its Bureau, for the success of our challenge.

Frederic Fournier

1. Conceptual background

1.1. Ecohydrology as a tool for sustainable management of freshwater resources

Water, soil and plant cover are fundamental components which determine the productivity of the land. Large scale deforestation, urbanisation and infrastructure development resulting from rapid population growth, and aspirations of the people, have generated major impacts on aquatic ecosystems (Zalewski, 1992, 1995a), often beyond the buffering capacity of the environment. This is the result of cumulative synergetic effects on global (climate changes) and regional (e.g. acid rains) processes with various local impacts (pollution, excessive water extraction). These various forms of environmental perturbations affect quality and acceptable quantity of inland waters by increasing runoff, erosion, sedimentation and pollution. In parallel, modifications of land use affect the residence time and partitioning into which precipitation is transformed: surface runoff, soil moisture, evaporation and ground water. The channelisation of rivers, reduction of floodplain areas and wetland drainage cause serious modifications in patterns of water flow, nutrients, sediments and pollutants. These processes reduce the biodiversity and biotic integrity of many flood plain ecosystems.

These phenomena are of increasing concern because they are likely to inflict irreversible damage on the sustainable use of freshwater resources in many regions. For example, even in developed countries where the public are generally environmentally conscious, there still is a lack of any integrated conservation strategy that considers entire freshwater ecosystems including their catchments. Consequently, decisions concerning freshwater resources management are too often taken without sufficient scientific and empirical background, addressing only short term and single goals, and ignoring the complexity of processes in aquatic ecosystems (Naiman *et al.* 1995). Consequently, low environmental and economic efficiency of activities have usually been observed. To solve complex environmental problems, such as sustainable use of freshwater resources, it is necessary to apply a new multidimensional approach.

An efficient and realistic strategy for the management of aquatic resources was developed by the UNESCO MAB Program *Role of land/inland water ecotones in water management and restoration* (Naiman, Decamps, Fournier 1989). The fundamental assumption was that in most situations it is impossible to stop catchment development which often degrades aquatic ecosystems. Thus, the solution should be the creation, management and restoration of ecotone buffering zones between land and water. The ecotones are boundaries between resource patches in the landscape. These patches regulate energy, nutrient and mineral sediment flow between adjacent patches. Five years of scientific activities have provided important progress in understanding the role of ecotones in the landscape (Naiman *et al.* 1995, Schiemer *et al.* 1995). However, ecotone projects deal mostly with small scale and short time processes. Besides the ecotone programme highlighted the lack of activity orientated towards the socioeconomic aspects of aquatic management. The sustainable development of freshwater resources of a given region is not a spontaneous process, but needs a strategy based on profound understanding of hydrology, biotic mechanisms and the economics of the region (catchment), which in most regions of the world is usually talked about but never implemented. Therefore in future should be created a programme concerned with the integration of large scale, long term hydrological processes with biota dynamics - ecohydrology (EH).

Why is ecohydrology the appropriate tool? The amount of water, its quality, and some processes in the aquatic environment are guided mostly by climate, but also to a great extent by biotic factors. The evolution of ecosystems after the glaciation period progressed as a series of successional stages. Every stage depended on climatic/hydrologic conditions and, as a factor triggering primary productivity, on nutrient availability. Subsequent phases were characterised by the unique composition of plants and animals which determined the ability to retain water and nutrients within the system. Thus, the biota possess the potential to regulate water and matter flow through the landscape. Consequently, the evaluation of how and to what extent biotic processes might modify flow of water, nutrients, sediments, and pollutants in aquatic ecosystems and the surrounding landscape is a logical step further in both hydrological and ecological development.
Such a new knowledge-intensive, integrated approach has been urgently needed in recent freshwater management practices e.g. river restoration (Hansen 1996).
Freshwater resources are endangered to a greater degree than ever before in human history. That is why the integration of the most recent knowledge from two branches of science - hydrology and ecology - must provide new insight into the interrelation between water and biota. Only this can generate the new solutions postulated at the International Conference on Water and Environment (ICWE) held in Dublin in 1992, and at the ICSU Conference Agenda of Science for Environment and Development into the 21st Century (ASCEND 21) held in Vienna in 1991.

Ecohydrology creates a new background for the assessment and management of freshwater resources and accelerates the implementation of an idea relating to sustainable development, because it fulfils the two fundamental conditions of successful strategic action according to decision-making theory: elimination of threats and amplification of chances (Fig. 1). If the action is focused only on one of those components it never leads to success (Kołodziejski 1995).

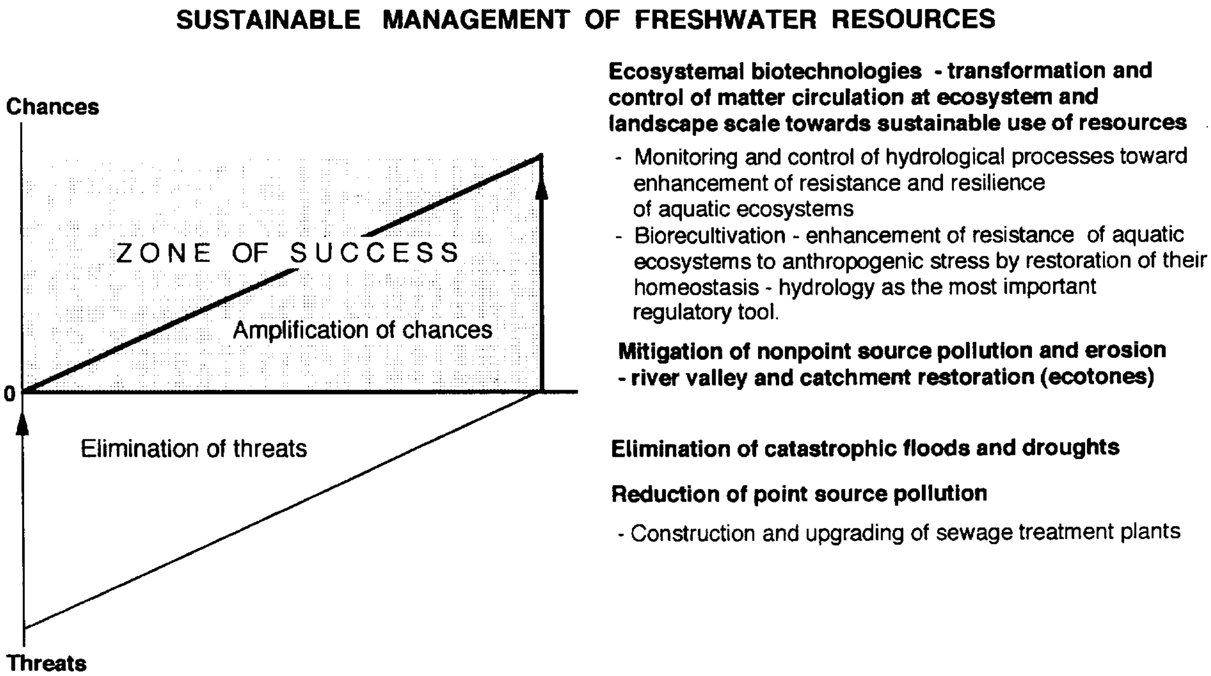


Fig. 1. An example of the application ecohydrology as a factor maximising chances in the successful strategic scenario of freshwater management (Zalewski 1996).

To date, water management and consequently the spending of societal taxes has concentrated on the elimination of threats, such as: (1) catastrophic floods and droughts, mostly by building dams and levées; (2) pollution, by construction of sewage treatment plants; and (3) erosion, by planting trees or reduction of slope of river valleys by terraces. However, most of these measures often do not provide the improvements expected, despite heavy expenditure. The lack of positive results may be attributed to neglecting the second component of successful strategic action - amplification of chances.

What does amplification of chances mean in the case of conservation of freshwater resources? The key should be using ecosystem properties created by evolutionary processes as the management tool; i.e. the integration of the resistance/robustness and resilience of ecosystems against various forms of abiotic/ stochastic stress.

However, some biologists have considered the importance of abiotic hydrologic processes in regulation of biotic community structure and dynamics (e.g. Ward and Stanford 1979, Roux 1982, Zalewski and Naiman 1985, Higler 1986, Schiemer and Zalewski 1992, Boon *et al.* 1992, Leclerc *et al.* 1996).

Also hydrologists had recognised very early the effect of the vegetation cover on hydrological processes such as erosion, sedimentation, and runoff generation, which appear by interception and evapotranspiration (eg. Johansson 1991). Another important aspect has been that for the maintenance of freshwater ecosystem biotic structure, a certain amount of water has to be provided. Thus, in many countries this esential quantity of water has been expressed by law as obligatory release flow or minimum permeable flow.

A new era with much more concern about surficial ecohydrological processes came with the recognition that eutrophication was one of the major problems of the aquatic environment, strongly dependent on the runoff-induced export of nutrients from an intensively used catchment. In order to control these excess loads through the filtering and nutrient uptake capacities of terrestrial and aquatic ecosystems, hydrologists became involved in the planning of ecologically-orientated measures, such as vegetation strips, grassed channels, vegetation catch-basins, small artificial reservoirs and macrophyte ponds. The numerical quantification of these retention/uptake processes is still in a very early phase, which hinders the efficiency of the planning/ decision making process of controlling nutrient and pollutant fluxes along their transport pathways. Even less is known about the interactive-cumulative effects; namely how these control zones and buffering strips/ponds react to the prolonged and lasting higher nutrient loads, that is how their growth and uptake/ retention properties change and finally how they affect the water and sediment carrying capacity. As a basic tool for such research, geographical information systems should be applied for identification and quantification of the manageable points and factors with accuracies which permit prediction of effects of such control measures.

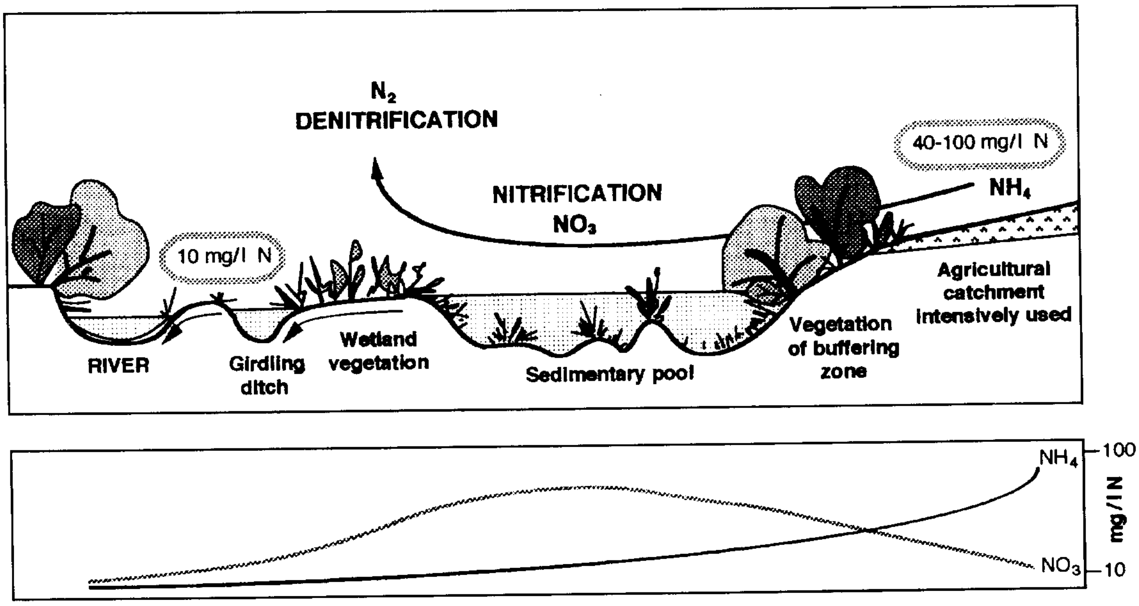
In many highly populated areas human activity in the catchment is elevated to such a level that from an economic point of view, the costs of impact reduction with traditional approaches are impossibly high. According to the IIASA the cost of water protection in countries undergoing development (e.g. Eastern Europe) has been US$ 7 per capita per year; Thus, cost in some highly developed countries approaches US$ 2 000. *The question is it really necessary to spend so much*? The IIASA analysis concluded it was not. The high cost of freshwater resource management and conservation is the result of applying high cost, high technology. However, the potential for development of low costs, high technologies exists. The above idea is implicitly based on the assumption that sustainable use of freshwater resources should be economically possible and socially acceptable.

According to Popper (1980) the predictive planning of the future cannot be generated by extrapolating recently used solutions. This is why the integration of ecology and hydrology should create not only a new solution for sustainable freshwater management but also the background for other, new scientific disciplines, e.g. Ecosystem Biotechnology (Zalewski 1995) .

Biotechnology has traditionally been defined as the application of enzymatic, and immunological processes that convert matter, e.g. use of yeast to produce beer from barley. Analogous processes, on larger scale include conversion and control of biomatter circulation, at a higher level of biotic organisation - the ecosystem and landscape. Thus, monitoring and control of hydrological processes should provide new solutions for freshwater management.

Biogenic flow through the landscape has been regulated by abiotic processes which can be controlled to a certain extent by regulation of hydrological processes, and by biotic structures and interactions which might be regulated greatly. The quality of inland waters is directly dependent on the intensity of catchment use. Thus, for efficient management it is necessary to control biogeochemical processes in the catchment and biotic interactions in the aquatic medium. Both can be done by hydrology (Box 1). Such application of ecohydrological processes has been attempted locally, e.g. creation of sedimentary ponds and wetlands along rivers and at their deltas. The Balaton Kis, a shallow reservoir covered by reeds at the delta of the river Zala, reduces up to 80% of the nutrient load into Balaton Lake (Jolánkai *unpublished*). Such hydroconstructions incorporate natural elements of the landscape to function as traps for the excessive nutrient loads transported, especially by flooding. If they are combined in the given river system with ecotonal buffering zones, which retain nutrients, reduce erosion and transport of eroded material downstream, such measures may improve water and aquatic environment quality at very low cost.

Box 1. Reduction of nonpoint source pollution from agricultural catchment. An example of control nutrients flow at the landscape by creation land/water ecotones: riparian vegetation, sedimentary pool and wetland (after Schuller pers. comm.).



Consequently, there exists an urgent need to integrate the existing information from different geographic regions about functioning, efficiency and socioeconomic aspects of the similar activities.

1.2. The effect of hydraulic processes on biotic communities and water quality

After temperature, water is the main factor determining the successional development of aquatic ecosystems. Floods contribute to sedimentation and nutrient transport, stimulating high biological productivity in flood plains. However, vegetation cover of the flood plain traps organic matter and nutrients, thus reducing concentrations and loads transferred downstream. The periodicity of floods also influences matter circulation in the flood plain and neighbouring ecosystems, because the activity of micro-organisms depends on the periodicity of wet and dry phases.

Temperature is an important factor because it influences the metabolic rate of poikilothermic organisms, doubling the rate approximately every 4°C rise in some temperature ranges. Thus, decomposition of organic matter, nutrient recirculation, and transfer along the river continuum is greatly dependent on climate and hydrology

Another important gap to be covered by ecohydrology is the spatial diversification of the hydrological characteristics of aquatic ecosystems. Especially important are reservoirs, where the spatial variation of retention time can have a great influence on nutrient recirculation through biota and therefore on water quality.

1.3. Moderation of nutrient loads and catastrophic flood peaks by biotic communities

The complexity of the flood plain increases water retentiveness in the system, nutrient trapping, and conversion into biological productivity. Some nutrients exported from the aquatic and semi-aquatic environment are eventually harvested as timber or as fish. Also, nutrients are transferred out of the freshwater ecosystem. Emerging insects may remove up to 50% of the phosphorus load provided as the atmospheric input to the aquatic system situated in undisturbed catchment (Hillbricht-Ilkowska 1993). Flood plains and river channels possess a buffering capacity, which means that they not only trap nutrients, but also release them in certain periods. When the concentration of phosphorus in the water is about 200 μg/l, stream sediments can function as a sink for nutrients. However, when phosphorus concentrations are approaching 30 μg/l, the sediments release nutrients into the environment. Such phenomena need further intensive studies under various climatic and biotic conditions.

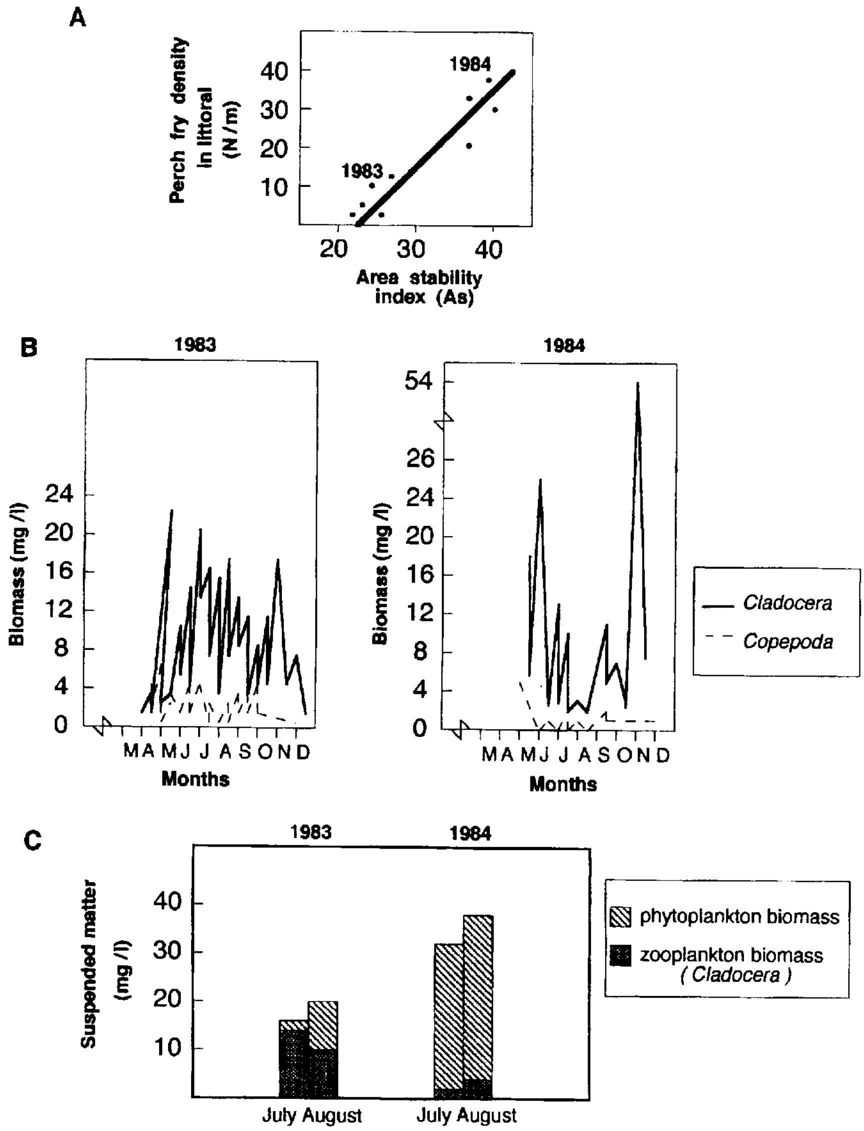
1.4. Buffering potential and vulnerability of aquatic ecosystems expressed as resistance and resilience

Every ecosystem possesses an inherent ability to buffer environmental variability. This property has been developed by evolutionary adaptation to the changing environment - which was triggered by climatic processes, catastrophic events such as floods and fire, and population dynamics of plants and animals. In this way, the structure of the community has adapted morphologically and physiologically to the natural variability of the environment.

In the aquatic environment management and conservation of biotic structure can be an important factor increasing tolerance to human impact, thus potentially reducing the costs of water quality management. For instance, in lakes with a well developed macrophyte zone dense algal blooms appear at two to three times higher concentrations of phosphorus than in lakes or reservoirs where littoral macrophytes cannot develop due to water level fluctuations.

A more advanced step in the control of biotic processes by hydrology can be the reduction of fish reproductive success, in order to enhance the filtering zooplankton community, and so improve water quality in reservoirs (Box 2).

Box 2. The regulation of water level in reservoirs as a tool for control of zooplanktivorous fish and zooplankton density toward reduction of toxic algal blooms (Zalewski and Dobrowolski 1993).



The regulation of the water level during spawning period is an efficient way for reducing an excessive density of young fish, and so for maintaining a high density of filtering zooplankton (Zalewski *et al.* 1990, Zalewski and Dobrowolski 1994). By reducing the juvenile fish density at the beginning of the summer to a level less than 5 fish per sq.m, the zooplankton stabilised at 12-16 mg/l . This was sufficient to reduce the biomass of algae by 80% and avoid toxic algal blooms.

1.5. Ecohydrology as a vector of transition from descriptive ecology, restrictive conservation and over-engineered management to a creative operational phase with predictive planning and sustainable use of the aquatic ecosystem

Ecology as a science appeared at the end of the XIX Century and was devoted initially to the description of the structure of ecosystems, leading to the first observations and descriptions of trophic relationships, succession, predator/prey relationships and other phenomena which drive the dynamics of the ecosystem. However, the predictive ability to manage an aquatic system was lacking. As a result, two extremes appeared: over-engineered management of the aquatic environments and restrictive environmental conservation, with the general assumption that the aquatic environment should be maintained in its pristine condition. Such an unrealistic approach did not lead to effective environmental laws. This is why the integration of ecology and hydrology should accelerate the process of transition ecology and environmental sciences from a descriptive, restrictive phase to an analytical, functional, operational phase (Fig. 2), which should generate integrated and creative environmental conservation.

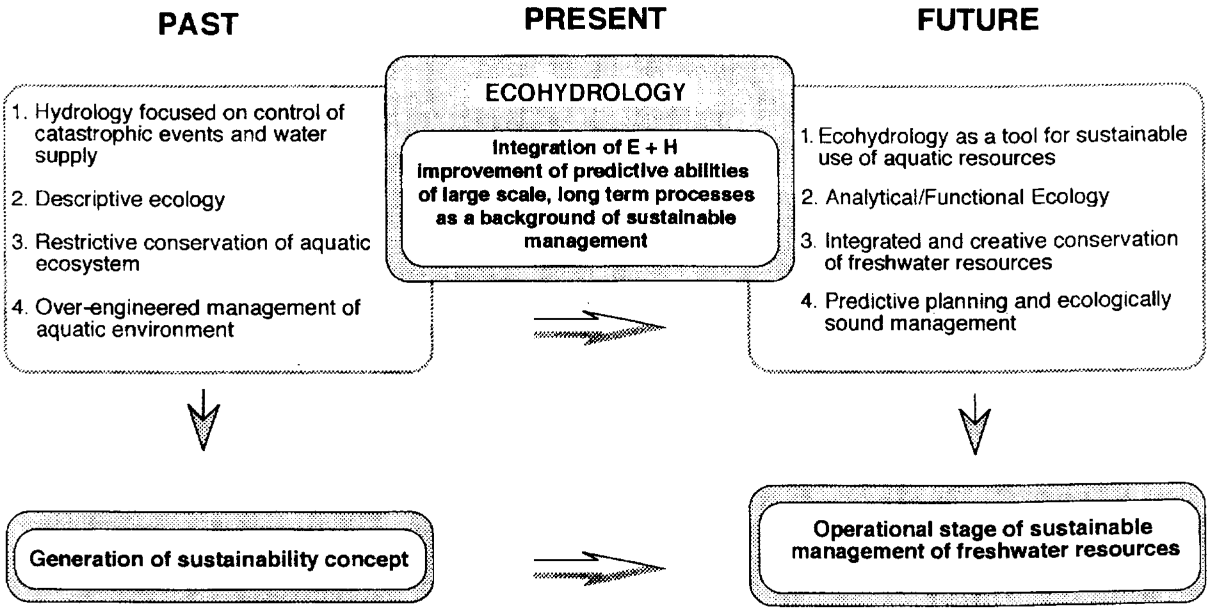


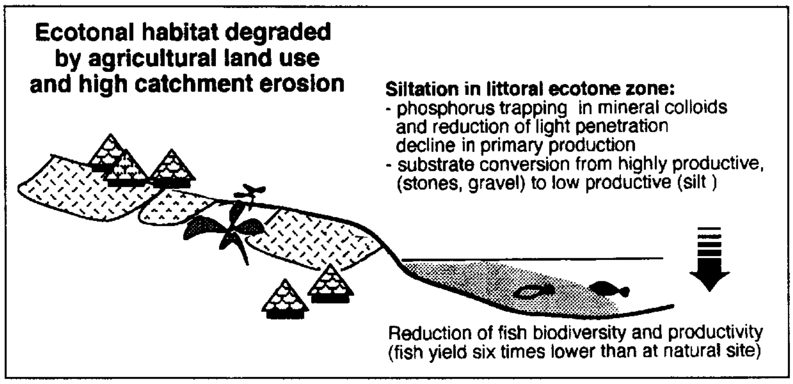
Fig. 2. Ecohydrology as a factor accelerating the transition from descriptive ecology, restrictive conservation and over-engineered management of aquatic ecosystems to analytical/functional ecology, and creative management and conservation of fresh waters (Zalewski 1996).

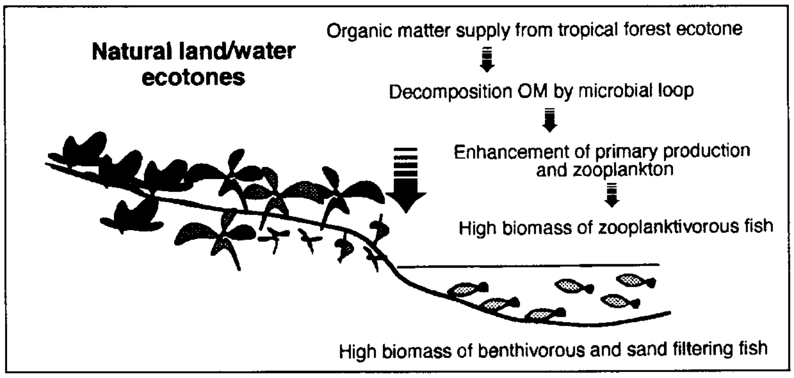
In recent years great progress in ecology has been made. To a considerable extent it was stimulated by MAB and IBP - one of whose key achievements was in ecological energetics (Grodzinski *et al.* 1975). The new paradigm forced ecologists to examine quantitative processes, leading to an improvement in predictive ability over the next 20 years. Such improvements make possible regulation of biological processes for the improvement of water quality on a small scale (Gulati 1990).

In parallel, large international programmes in hydrology - IHP UNESCO, WMO, WCRP, IIASA - stimulated important progress in understanding and developing predictive powers associated with large scale climatic and hydrological processes. Consequently, both ecology and hydrology have achieved a phase of maturity that allows us to integrate them successfully, toward improved assessment, development, and management of aquatic resources.

An important aspect of the new EH programme should be the provision of a new solution to socio-economic problems. The decline in fish harvest in Lake Tanganyika from 0.5 to 0.3 million tonnes is an important example. The drastic decline in catches cannot be explained by increased fishing efforts. The UNESCO/DANIDA project in the framework of the Ecotone Programme provided important insights into the situation (Box 3).

Box 3. The effect of the development of the shoreline ecotone zones of Tanganyika Lake on the biogeochemical processes and fish protein production (Zalewski 1995c).

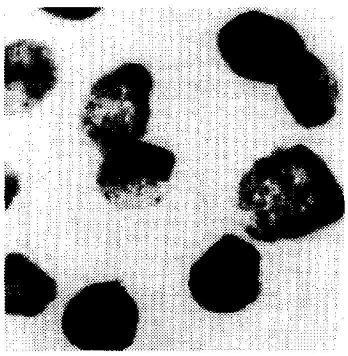




The doubling of the human population during the last twenty years resulted in the conversion of many shoreline areas into cultivated land. This in turn led to siltation which converted the productive stony/gravel bottom into a silt covered substratum. There was also a reduction in the supply of organic matter of terrestrial origin which regulates the trophic pyramid, i.e. primary productivity, zooplankton, zooplanktivorous fish *Limnothrissa miodon*, numerous benthivorous fish, and juveniles of large pelagic predators. The diversified and highly specialised aquatic community, one of the most ancient ecosystems of the world, was not able to adapt into the dramatic changes in the impacted environment. The proposed solution should be based on the creation of a buffer zone along the shore, and sedimentary ponds at the tributaries. During dry periods, mud from these ponds, which will be rich in nutrients, can be used for agriculture.

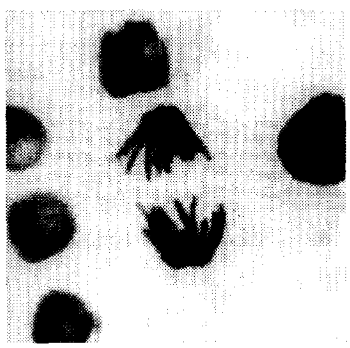
In the developed regions of the world, one of the most important problems which has been resolved by ecohydrology is eutrophication. The most vulnerable systems are reservoirs which operate as traps for nutrients along the river continuum. Recently evidence has accumulated that the most adverse symptoms of degradation are the appearance of toxic and carcinogenic algal blooms which are more potent than strychnine (Box 4).

Box 4. Example of the effect of bluegreen algae hepatotoxins - microcistin - from a eutrophic temperate lowland reservoir on the genetic apparatus of a test cell culture (Osiecka 1995).



A - intrerphase nuclei in control;

B - interphase nuclei treated with cyanobacterium extract;



C - anaphase stage in control

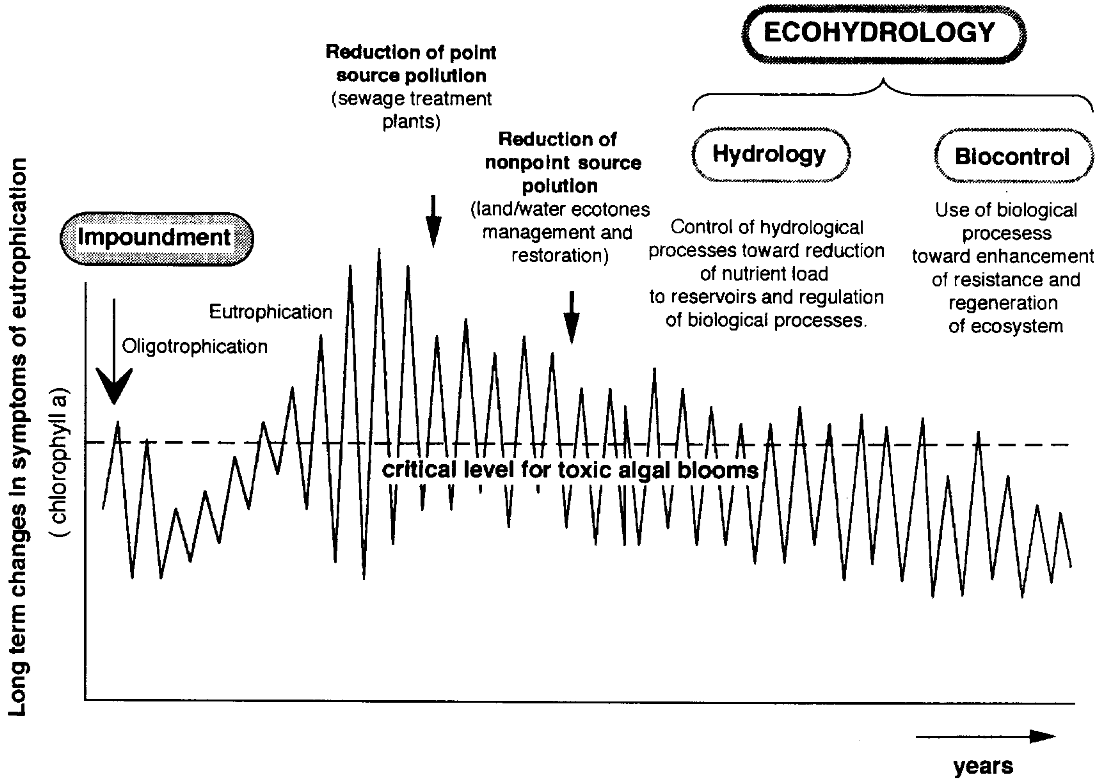
D - anaphase treated with cyanobacterium extract

The malformations of the chromosomes are similar to those found when using highly toxic pesticides. These important effects define the restoration limit and should be expressed as the measurable value of the nutrient and thermal conditions in different aquatic ecosystems in different geographic regions.

Efficient restoration of such eutrophic reservoirs needs to be based on hydrological and ecological understanding, as demonstrated by the 25 km^2 Sulejów Reservoir which supplies drinking water for 1 million people (Box 5).

Why is it necessary to integrate so many phases of restoration? In the past the general assumption was that to improve water quality it was sufficient to invest money only in sewage purification plants. However, Statzner and Sperling (1993) demonstrated that in many situa-

Box 5. Hypothetical scenario of the application of ecohydrology to the restoration of eutrophic Sulejów Reservoir (Zalewski 1996).



The first and most fundamental step should be the reduction of phosphorus at the point sources of pollution in the river system above the reservoir. The second is reduction of nonpoint source pollution by land water ecotone management and restoration, in the whole river and reservoir catchment. The third phase is directly connected with ecohydrology which should be the control of hydrological processes toward the optimal timing of nutrient supply and/or release to and from reservoirs, e.g. the intensity of algal blooms in summer in some reservoirs depends on the pattern of the water release from the reservoir at the end of winter. The fourth phase should be the use of hydrological processes to regulate the biotic interactions, e.g. control of the water level at the spawning period of fish for regulation of the trophic cascade toward reduction of algal blooms (see Box 2). The final phase which can be achieved by controlling the hydrological conditions should be the use of biological processes for increased resistance and resilience of freshwater ecosystems against excessive nutrient loads, e.g. creation of a vegetated littoral zone as a nutrient trap, which is possible if the water level is stabilised.

tions, e.g. for small settlements, it is less expensive and more efficient to integrate moderate technology treatment plants with biological subsystems (e.g. nutrient trapping wetland) than to upgrade treatment plants by expensive technology (Fig. 3).

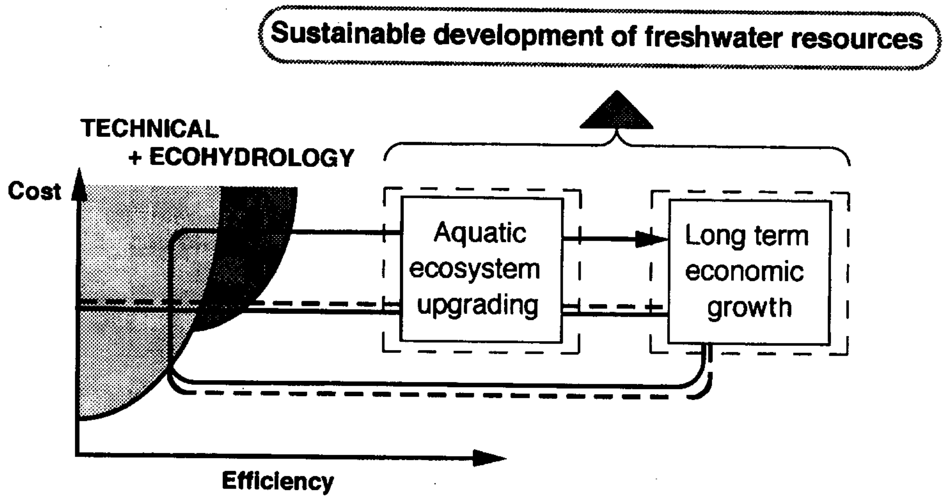


Fig. 3. The positive spiral: toward sustainable use of aquatic resources in a river valley. The key point should be the integration of technical methods with ecohydrology toward efficiency improvement and cost reduction. As an effect of the cost efficient upgrading of the aquatic ecosystem the attractiveness of the region will increase, generating economic growth which in turn provides further funds for conservation and management of the freshwater ecosystem (after Zalewski 1995b).

The above model is also an example of how integration of the two scenarios can eliminate threats (sewage treatment plants) and amplify chances. The use of ecohydrological processes as a tool for upgrading the quality of freshwater resources is an efficient way to reduce costs and increase the efficiency of protection and restoration activities, thus improving the sustainability of the systems.

The low quality of water not only affects costs of water purification which is often unsatisfactory after purification, but also reduces popularity of the area for recreation. This reduces the income of local people and subsequent taxes which can be reinvested for upgrading the quality of the environment (aquatic resources). A further positive socioeconomic outcome from the efficient restoration of ecosystems for improvement of water quality at moderate cost (EH) is the stimulation of recreational use of resources balanced with the carrying capacity of the environment, which is concordant with the idea of sustainable development.

Generally the objectives of the Ecohydrology 2.3; 2.4 Programme have been to collate and review existing information on the interrelations between hydrological and ecological processes; to review their predictive potential and to define the most important directions for future research; to identify a hierarchy of environmental problems associated with hydroecological processes; and to quantify the links between abiotic and biotic factors and their role in transport, and transformation of water sediments, nutrients and pollutants, toward defining the pathways from the local to the catchment scale. This should be done to an accuracy sufficient to predict the effects of the control and regulatory measures, to allow development of an integrated programme of river system management in connection with International Hydrological Programme (IHP V).

However, one of the goals of the ecohydrology programme is that it should create a background of transition towards operational procedures aimed at sustainable development and generate new ways of thinking among scientists, and policy- and decision-makers. This means that to achieve sustainability of freshwater resources, the freshwater ecosystem and its catchment should be considered a "superorganism", which by the biogeochemical evolution possesses the ability to maintain dynamic self-regulatory equilibrium. This equilibrium state has been disturbed to various degrees by structural damage to the biotic component by human impact, and modifications to the hydrology of the system. By more profound understanding of the interrelations between biotic, hydrological and geochemical components, the black box approach in freshwater management will be reduced and chances to achieve sustainable use of freshwater resources should increase.

2. Hypotheses

Hypothesis 1

To achieve profound understanding of the present hydrological regime and distribution of biota in fluvial corridors, historical changes should be analysed, and interpreted for application.

Rationale:
The present hydrological regime has been dependent to a great extent on the distribution of elementary patches of landscape and ecotonal zones. The knowledge of historical changes in the fluvial corridor and the adjacent catchment will contribute to progress in management, rehabilitation and restoration of the river valley resources, and to optimisation of the flood retention.

Today various regulatory measures appear in most flood plains. Whenever there is a need to change this status, as in restorative activities or during the implementation of new flood protection schemes, the knowledge of earlier stages of the status of the river valley is the fundamental information needed to reach a more natural situation of river valley morphology and to restore its biotic structure.

Hypothesis 2

The ecohydrological approach can be a tool towards the sustainable use of aquatic resources by enhancement of the resistance, resilience and buffering capacity of fluvial corridors.

Rationale:
Ecosystems are characterized by resistance and resilience to anthropogenic and abiotic stress, and are maintained within certain ranges by homeostatic mechanisms. If exploitative use or catastrophic events exceed resistance or resilience of an ecosystem, the required resources cannot be provided any longer.
The process of ecological succession is reflected in structural change, and both can also be expressed by changes in resistance, resilience and buffering capacity against anthropogenic stress. Thus, for sustainable use of aquatic resources in the face of elevated anthropogenic pressure, it is necessary to modify by management and restoration the ecosystem structure by increasing its resistance, resilience and buffering abilities.

By planting macrophytes in lakes a tolerable level of turbidity can be maintained at three times higher nutrient loads than in lakes with no macrophytes.
By invasion of freshwater molluscs (*Dreissena sp.*) to the lake, filtration of algae increased and part of the phosphorus pool has been blocked, increasing the transparency several times (e.g. Lake Erie).

By restoration and management of riparian ecotones of intermediate complexity, the nutrient retention capacity and biological production in the river channel increases several times reducing transportation of nutrients downstream.

By the development of a sequence of habitats like riparian vegetation, ponds and denitrificating wetlands, between the river and intensively used agricultural areas, a 10 times reduction of nitrogen input can be achieved

Hypothesis 3

Vulnerability of rivers, reservoirs and estuaries is dependent on the seasonal pattern of hydrological and biotic processes and can be changed by human impact.

Rationale:
The vulnerability of the freshwater ecosystem depends on its structure and on the intensity of biotic processes. This in turn depends on temperature, nutrient status and matter transport/ circulation which are determined to a great extent by hydraulics.
The understanding of spatial/temporal relations between hydraulic patterns and biotic cycles of communities should create a basis for evaluation of ecosystem resistance/robustness to the various forms of human impact.

Hypothesis 4

Nutrient loads reaching aquatic systems depend highly on the man-induced disturbances of the natural hydrological and ecological characteristics of the catchment

Rationale:
Although nutrient loads are major driving factors that induce the eutrophication of receiving aquatic ecosystems, the means of estimating their yield rate from a catchment are inadequate. This is caused by insufficient knowledge of how the structural properties of landscape units and their man-induced modifications will influence the runoff processes of water and the associated processes of nutrient leaching, transport and transformation.

The major objectives of experimentally defining the flow-paths of water, sediment, nutrients and pollutants imply the finding and quantifying of cause-and-effect relationships between natural inputs of water, sediments and nutrients to the catchment, e.g precipitation, and atmospheric deposition, vs. man-made inputs to the catchment, e.g fertilizers, manure, sewage water etc. As a context for these analyses the man-induced disturbances to the landscape patches should be considered.
Besides, these objectives imply that the water demand and the maximum permeable loads (ecosystem tolerance levels) of nutrients and pollutants should be specified quantitatively.
Further implications include tracing the pathways of water, sediment, nutrients and pollutants through the catchment with special consideration of the influence by vegetation cover, ecotonal-mosaics and their alterations (agricultural plots, urban-rural settlements, infrastructure lines), with special regard to the modifications of water courses.

A general guideline is to derive unit area loading (L_{UA}) rates (kg/ha.year) of nutrients and pollutants for subcatchments of different hydrological regimes and landscape/landuse patterns. This can be accomplished on various spatial scales: for a larger catchment consisting of several sub-catchments (macro-scale studies) and for its subcatchments (meso-scale studies), and finally for plot-size catchments (micro-scale studies), that is actually for the primary sources of nutrients and pollutants. In evaluating the results of these studies of different scale, one eventual task is to compare the L_{UA} rates of the various scales and learn (also quantify in functional form) how these rates vary as functions of the size of the area considered. This provides basic information on the transport properties (delivery or retention) of the system concerned.

In the next step (in a more sophisticated study) one might wish to investigate the variation of L_{UA} rates (of identical spatial scale and hydrological properties) as functions of the natural and man-induced patterns of the catchment (such as fractional distribution of land use forms, e.g. range land, forest, wet-land, pasture, arable land, settlements). L_{UA} rate versus runoff functions can be developed for certain characteristic patterns and for each spatial scale. GIS based land-use and land-cover information can be of great help in such studies. These types of functions (models) can already provide certain information for planners and decision makers, as they are able to quantify the effect of human impact (fraction of arable land and settlements) on the magnitude of nutrient and pollutant yield rate of the catchment or similarly of the favourable effect of the presence of wetlands.

In a more advanced step of ecohydrological catchment studies, implying also the availability of the data of a dense hydrological and water quality monitoring network along with that of digital terrain maps (DTM), landuse-landcover maps, and soil maps, one might wish to develop a complex model of the catchment, of its runoff, pollutant transport and transformation processes. This is called the integrated catchment modelling approach. The term integration means, in this case, that hydrological, water quality and ecological assessment methods are integrated for the purpose of evaluating the integrated or combined effects of natural and man-made patterns and inputs of the catchment. The tools developed in this manner are elements of the actual Decision Support Systems (DSS), that can be used for quantitatively and qualitatively (numerically) describing (simulating) cause-and-effect relationships, that is the response of the catchment, as a system, to natural and man made inputs and to man-induced modifications of the catchment patterns.

Some further practical guidelines include the following:

- In calculating unit area loading rates of catchments of various scales it is necessery to subtract point source loads from the in-stream load of the outflow point of the catchment, before dividing the annual total load by the catchment area, the calculation step that results in the L_{UA} rate. However, error is introduced in this way, since point source loads are also subject to retention, while they travel from the source to the outflow section.

- For deriving L_{UA} vs. runoff functions, geochemically and hydrologically comparable catchments (soil type, geology, hill-slope) should be selected. and analysed by multivariate analysis.

- In calculating the in-stream load from the records of flow and water quality constituents (nutrients and/or other pollutants) one should usually avoid the most simple method of calculation in which flow (Q) and concentration (C) data pairs are multiplied with each other and the average of the product is considered the annual load. This is because flow data are usually more frequent than water quality data, and one must not disregard the extra information of the flow record. The correct method of calculation is to multiply a concentration value with the total water volume of the runoff that corresponds to the period of time that has elapsed between taking two water quality samples and to sum up these partial loads over the total year. That is, the annual total in-stream load of a substance is calculated as

1 $$L_{Annual} = \sum_{i=1}^{n} C_i \sum_{j=1}^{m} Q_j \Delta T_j \approx \sum_{i=1}^{n} C_i Q_{(mean,\Delta T_i)}$$

where

L_{annual} - is the annual total calculated in-stream load of the substance (mass per time dimension)

C_i - is the i-th water quality concentration value of the record (mass per volume dimension), i= 1...n, where n is the number of quality samples in a year and

Q_j - is the j-th water discharge value of the record (volume per time dimension) in the period ΔTi, j= 1....m, and m is the number of flow-gauge readings in the period ΔT_i

ΔT_j - is the time elapsed between two flow readings in the period ΔT_i,

ΔTi - is the period of time between the centres of time between two subsequent quality samplings that is $\Delta T_i = (T_{i+1} - T_i)/2 - (T_i - T_{i-1})/2$,

where

T_i - is the time of the i-th quality sample,

$Q_{(mean, \Delta Ti)}$ is the mean flow in the period ΔT_i

Then the unit area yield rate L_{UA} of the substance (in mass per time per area dimension) from the catchment is calculated as

2 $$U_{AL} = \frac{1}{A}\left[L_{annual} - \sum_{k=1}^{L} LP_k \right]$$

where

LP_k - is the annual total load of the k-th point source of the catchment, k=1...L, where L is the number of point sources of the catchment

Hypothesis 5

Intensity and duration of floods are modified by the biological characteristics of fluvial corridors, which in turn are modified by the hydrological regime

Rationale:
At present there is insufficient quantitative information available on the structural and ecological properties of flood plain ecotones, and on how the ecological properties of fluvial corridors influence the flood discharge capacity of the main channel and the flood plain.
Even less understood is the interactive process of how the height and duration of a flood is influenced by biological characteristics of the fluvial corridor, and in turn how other flood properties, the sediment and nutrient transport and deposition modify these ecosystems.

As floods are one of the most dangerous and devastating natural events that endanger human societies, and as flood plain ecosystems are one of the most valuable genetic and natural resources of the catchments, it is an extremely urgent task to describe quantitatively the insufficiently described interactions between floods and flood plain ecosystems.

Consequently the objectives of related studies should be the most reliable determination possible of the following types of relationship:

- Dependence of the flood plain roughness coefficient on the quantitative and qualitative properties of flood plain ecotones and elementary patches
- Dependence of hydraulic free surface area and hydraulic radius of the greater channel (the flood plain) on the quantitative and qualitative properties of flood plain ecotones and elementary patches
- Dependence of the slope of the water surface of the greater channel on the quantitative and qualitative properties of flood plain ecotones and elementary patches;
- Dependence of the structural and functional properties, including the stability, resistance and resilience, of flood plain ecotones and elementary patches on
    - the morphological properties of the channel (slope, width, shape and indices expressing the ratio of the flood plain-channel to the main channel)
    - the hydraulic properties of the channel (flow velocity over the flood plain and its relation to that of the main channel); height and duration of floods (e.g. the depth and duration of inundation of the flood plain ecosystem).
    - the nutrient and sediment discharge (deposition) over/onto the flood plain.

Of these multiple (and probably long term) objectives, the most urgent and immediate tasks might be specified as
- the finding of ecosystem structure vs flow velocity (roughness/smoothness) functions, and
- ecosystem stability characteristics vs. flow velocity/depth functions.

Probably the most relevant information, from the hydraulic point of view, would be the measurement of water surface slope data over longitudinal sections of various characteristic flood plain ecosystems. This would require high level geodetical surveying (levelling) methods to be applied.

Simultaneous estimation of the free cross-section area (among the stands of the vegetation) would also be needed. Water depths should also be measured over the flood plain. Knowing the total water discharge of the river reach concerned (for which river reaches should be selected in the neighbourhood of well calibrated high-flow gauging stations) and being able to estimate main-channel properties relatively well, one can derive the roughness (smoothness) factor of the Strickler-Manning formula (and thus the mean flow velocity) that corresponds to the flood plain ecosystem concerned. The formula which can be utilized for calculating the smoothness factor $K_{\text{flood plain}}$ of the flood plain ecosystem from the above described surface slope measurement data, as derived from the discharge equation and the Strickler-Manning formula is as follows:

3
$$K_{floodplain} = \left(\frac{Q}{\sqrt{\frac{Z_1 - Z_2}{\Delta X}}} - K_{mc} A_{mc} R_{mc}^{\frac{2}{3}} \right) \frac{1}{A_{Fl} R_{Fl}^{\frac{2}{3}}}$$

where:

- Q - is the total discharge of the combined channel, as measured simultaneously with the slope measurement;
- Z_1, Z_2- are the upstream and downstream elevations of the water surface;
- ΔX - is the distance between the two surface elevation measurement points
- K_{Mc} - is the smoothness factor of the main channel (the relatively reliable value of which can be obtained from respective hydraulic guidebooks);
- A_{Mc} - is the cross-section area that corresponds to the main channel;
- R_{Mc} - is the hydraulic radius of the main channel (cross-section area divided by the wetted perimeter);
- A_{Fl} - is the estimated cross-section area of the flood plain part of the combined channel (the full area corresponding to the given water level, between the bankline of the main channel and the flood levee)
- R_{Fl} - is the hydraulic radius of the flood plain part of the main channel (this can be well approximated with the average water depth over the flood plane)

Measurement and/or collection of data on flow velocities v_{Fl} over flood plains of different characteristic ecosystems would provide perhaps the most valuable information for validating the estimates of $K_{\text{flood plain}}$. The corresponding equation is

4
$$v_{Fl} = K_{floodplain} R_{Fl}^{\frac{2}{3}} \sqrt{I} = K_{floodplain} R_{Fl}^{\frac{2}{3}} \sqrt{\frac{Z_1 - Z_2}{\Delta X}}$$

Since direct discharge measurement data of combined (flood plain + main) channels are rarely available, due to the difficulty of the task and to the extremely (and duly) strict safety regulations and thus to the extremely high costs involved, even individual point-like flow-velocity measurement data over flood plain ecosystems would be highly valuable, especially so if such data can be collected for flood plains of different ecosystems. Float or tracer measurements can be recommended. In many cases flow velocities in the flood plain forests are very low even at high flows and direct current meter measurements can also be carried out, by experienced staff, without being exposed to extra risk.

Collection of sediment concentration and deposition (sediment depth) data of flood plains during and after floods could also provide valuable information, especially when such data can be related to the changes of fluvial ecosystems

Statistical analysis of long (perhaps historic) records of flood stages and durations in conjunction with data (records) on the natural or man-induced changes of the ecosystems of the respective fluvial corridor could also yield valuable information (or even regression models) on how riverine ecotones influence flood stages and durations.

Remote sensing (GIS type) information, aerial and space photographs, could also provide very valuable information, especially when they are compared to those of flooding periods. Having also earth-based hydraulic reference data of the same floods, one might be able to end up with certain experimental relationships for the estimation of the fate (flattening) of flood hydrographs as functions of the type of flood plain ecosystem.

Hypothesis 6

The nutrient status of rivers is influenced by ground water inflow and the biotic structure of the river valley.

Rationale:

There exists permanent exchange of water between the river channel and ground waters. Ground water inflow from the catchment can modify temperature and nutrient status in the river especially during the period of low flow. With respect to a given river stretch, this status depends on river valley character and can be reduced considerably by wetlands and forests. However, detailed information on hydrological effects on ecological systems is not at all sufficient.
(for further explanation see "Conceptual background")

Hypothesis 7

The transport and transformation of pollutants are highly influenced by the hydraulic-hydrological regime and by the ecological characteristics of fluvial corridors

Rationale:

Although the advective and dispersive transport processes are strongly influenced by the ecological properties of the channel and the flood plain, the knowledge of how these properties influence the final destination (the deposition) of pollutants is still inadequate. Similarly, numerical information on how the state, the physical, chemical and biological properties, of the aquatic ecosystem influence the transformation of pollutants is also insufficient. Further it needs verification whether there exist threshold values of flow velocity and depth at and above which ecotones degrade. Similarly it must be studied if there are threshold characteristics exerted by ecotones at and above which flow depth and flow velocity of the main channel will dramatically increase.

Although in hydrological handbooks there are nomograms and tables which relate certain characteristics of the channel vegetation to flow velocity and discharge carrying capacity of the channel, these are usually very rough estimates that need upgrading and updating. It is also implied that in these attempts for upgrading estimates, the ecosystems of the fluvial corridors should be represented by characteristic indices and parameters, used also by ecologists, so as to arrive at a common platform for the two disciplines.

The magnitude and cross-sectional distribution of flow velocity determine the discharge carrying capacity of channels and the advective plus dispersive transport of pollutants. Methods for the estimation of flow velocity distribution and of dispersion (mixing) coefficients should try to include those channel and flood plain characteristics that are influenced by ecological properties.

Knowledge of the dispersion coefficients, and especially of the longitudinal one, is of extreme importance in analysis and predicting the effects of accidental pollution incidents. The peaks of downstream travelling pollutant waves strongly depend on the longitudinal dispersion parameter, which in turn depends mostly on the turbulent properties of the flow, which latter can be highly influenced by the aquatic vegetation.

The fate of nutrients is also strongly connected with the presence and properties of the aquatic vegetation (both with phytoplankton and macrophytes), *via* uptake, that is the growth of the vegetation, and in turn the aquatic vegetation highly depends on the nutrient supply.

The fate of other pollutants is also strongly influenced by the state and properties of the aquatic plants. Biological uptake and bioaccumulation can play a significant role in addition to the already mentioned effect on the transport properties of the flow.

Studies aimed at the better understanding and description of the transport and transformation properties of flowing waters, as influenced by the aquatic ecosystem and as the ecosystem is influenced by these processes, can be carried out at many different levels and with many different partial objectives.

One relatively simple method is the making of mass balances over longer river reaches with different characteristic ecotones and to relate the outcome of the budget to certain characteristics and parameters/properties of these ecosystems. In doing so, GIS based information of fluvial corridors can be very useful for deriving the above mentioned characteristic parameters or indices of the given river reach.

The mass balance method is simple but it needs, as contrasted to routine water quality monitoring, cross-sectional sampling, that is the taking of several water samples, preferably vertically across the flow velocity measurements that shall be carried out for determining the discharge simultaneously with the water quality sampling. Measurement and calculation techniques of water quality and the corresponding flow can be the same as those for determining suspended sediment discharge (as described in hydrological-hydraulic handbooks; and not as practised sometimes by chemical laboratories, using only one TSS sample date for the calculation of the sediment discharge). The essence of these methods is that the vertically averaged concentration value is multiplied by the vertically averaged flow velocity and by the partial cross section area that corresponds to that velocity. The final result is the total flow of the channel Q and the flow-weighted mean cross-sectional average concentration C_{mean} of the substance concerned.

Next, the mass balance of the river reach concerned is calculated as:

$$\mathbf{Q_{in} \cdot C_{in} = Q_{out} \cdot C_{out} + r \cdot Q_{in} \cdot C_{in}}$$

where
$\mathbf{Q_{in}}$, $\mathbf{Q_{out}}$ and $\mathbf{C_{in}}$, $\mathbf{C_{out}}$ are the inflowing and outflowing discharges of water and concentrations of the substance to/from the reach, respectively and **r** is the retention coefficient (fraction of the inflowing load retained in the system). Since over relatively shorter reaches of a river (of say a few 10 km length) the $\mathbf{Q_{in}=Q_{out}}$ approximation can be allowed, the expression for **r** becomes

$$\mathbf{r=1 - C_{out}/C_{in}}$$

This value (the fraction of input load retained within the river reach concerned) is a characteristic measure of the physical (morphological), chemical and biological properties of that reach (for the given hydrological state), in respect to their influence on the pollutant transport and transformation properties of that river reach.

Carrying out the respective water quality and water discharge measurements for a series of characteristic ecotone types, channel-morphological patterns, and hydrological conditions one can end up with experimental multivariate relationships between the pollutant (nutrient, sediment, etc) retention factor and the characteristics of fluvial ecosystems, channel formations and hydrological conditions.
Over longer river reaches, and with more efforts towards sophistication, one can use various water quality models for describing the fate of pollutants, depending on the measurement data available. For example calibrating against longitudinal profile measurement data of certain water quality parameters (nutrients, sediments, BOD, COD, etc) one can use a simple exponential decay model of the form

$$\frac{dC}{dt} = -K_r C \qquad 5$$

This equation (the principle of first order reaction kinetics) states that the decay/decomposition of a pollutant is proportional to the concentration of the pollutant and the factor of proportionality is K_r, the decay rate coefficient (T^{-1}).

Solving the equation for the initial conditions $C=C_0$ at $x=x_0$ that is $t=t_0$ the following simple exponential decay equation is obtained:

6 $$C = C_0 e^{-K_r t}$$

where t is the time of travel $t= x/v$, the distance covered by the water (and pollutant) particle divided by the mean flow velocity of that reach.

Next one can repeat the same type of investigations for the decay rate coefficient K_r (relaying also on GIS based information on ecotones) that were briefly described in relation to the retention factor **r** above.

For the effects on dispersion one either has to rely on tracer studies (that are cumbersome and very expensive) or select river reaches where the polluting parameter concerned exhibits either a marked diurnal variation (due to the nearby presence of a source of pollution, a larger town for example, and in this case the measurement data can be used for the assessment of the longitudinal dispersion coefficient) or a marked cross-sectional plume in the river (this can be used for the estimation of the transversal mixing coefficient). The corresponding basic equations are included in water quality modelling handbooks and lecture notes, but in this level of sophistication the ecohydrologist researcher must get a water quality modelling specialist involved in the studies.

The other part of the mutually interactive effects of this field of ecohydrology, namely the effects of pollutant transport and transformation on the structure and functions of the ecosystem, can be handled within the framework of even more complex experimental setups. The general advice could be to set up parallel investigations on ecotones of similar types (or what could be of similar types if there were no anthropogenic influences); one with relatively low anthropogenic impact as a control, and another one where the pollutant concerned arrives in high concentrations or with high deposition rates. Comparative studies on the degradation (or alteration) of these ecosystems might reveal interesting qualitative and quantitative facts and relationships.

An interesting type of study might be the investigation of river reaches, oxbow lakes etc., that are being loaded relatively recently with nutrients in such a way that one could follow the relatively fast changes of the trophic state, with special regard to overgrowth with macrophytes. Then later the other resultant effects on flows, velocities, sediment transport and deposition, along with the subsequent changes of the vegetation and so on, can also be studied.

Hypothesis 8

The application of GIS-based ecohydrological approaches to subsystems of catchments consisting of ecotones and elementary patches, makes hydrological and ecological information gained in these microscale systems aggregable into higher levels of abstraction. The integration of this information into hydrological concepts will lead towards a more profound interpretation of the hydrological regime of catchments.

<u>Rationale:</u>
The objective of classical hydrology in the successful prediction of processes in the total catchment, relies mainly on a top down strategy of using land-use features and aims at verification of models at certain input points. However, biological information is usually not available at this level of integration and area coverage.

To achieve integrated information indispensable for the decision making process biology as well as hydrology will have to focus on key variables which can be aggregated via GIS. In this way the top down approach of hydrology and the bottom up strategy of ecology can be merged at the input points of catchment models.

To achieve efficiency with respect to research programs and practical applicability special attention should be given to such key variables, as can be directly influenced by management.

Hypothesis 9

Comprehensive understanding of ecohydrological processes and improving predictive ability forms a basis for a cost efficient management of water resources and landscapes.

<u>Rationale:</u>
The primary factors which regulate a biotic community are of abiotic /stochastic character in aquatic systems. Thus the regulation and control of biological processes by using hydraulic measures in water management can be low cost, high efficiency methods of improvement of water quality and aquatic resources.
Therefore, enhancement of buffering capacity and sustainability of the ecosystem should be achieved by e.g. modification of ecotone structure or replacement of existing unfavourable ecosystems.
(for further explanation see chapter "Conceptual background")

Hypothesis 10

Optimization of the structure of ecotonal zones like riparian buffer zones, wetlands or flood plains is a main tool for the reduction of nutrient transfer from the catchment to the river and other downstream recipients.

Rationale:
There is a considerable shortcoming with respect to the numerical description of the hydraulic and ecological properties of manageable structural flood plain elements like ecotones and vegetation patches, which are influencing the surficial filtering capacity of the fluvial corridor.
(for further explanation see chapter "Conceptual background")

Hypothesis 11

Indices for predictive planning and sustainable management of aquatic resources should be based on point/local data and studies on large scale hydrological processes.

Rationale:
For efficient management and sustainable use of aquatic resources, the decision making process, based on predictive planning needs standardised indices of aquatic environment quality. The indices should be formulated concerning the structure and functioning of biological communities, at local scales and integrated with large scale hydraulic processes.
Besides, indices should be elaborated on the basis of comparative studies, to be conducted on a given type of ecosystem in different geographic regions.
(for further explanation see chapter "Conceptual backgraund")

3. Interactions between river systems, flood plains and wetlands (IHP-V; Project 2.3)

3.1. Introduction

The optimisation of the use of freshwater resources was seen as a major objective for years ahead by the International Conference on Water and Environment, held in Dublin in 1992. Four Dublin Principles were stated: Principle 1, marking freshwater as a finite and vulnerable resource; Principle 2, calling for a participatory approach in water development and management; Principle 3, on women's part in dealing with water resources; and Principle 4, which focuses on the economic value of water. All four principles point out the importance of developing ecohydrology as a tool of directing research, planning, and management of water.

These ideas are reflected in the framework and general outline of IHP-V (UNESCO IHP, 1996), which calls for a stronger interrelation between scientific research, application and education with respect to water resources and makes the support of planning and management by a scientifically proven methodology a key feature of future approaches to this issue.

With respect to the thematic background of Project 2.3 one of the principal areas of concern is the role of scales in ecohydrological processes. It is important to understand the complex interactions of hydrological and biogeochemical cycles with respect to man's impact on the environment. Considering this impact especially on the local and regional scales, it is evident that possibly all geographical regions of this world should be considered. To predict the behaviour of river systems, flood plains and wetlands successfully, and the interactions between them and landscape units, the transposition of information among different spatial and temporal scales is essential for ecohydrological studies. It should be kept in mind that the scales of ecohydrological experiments may range from experimental setups in the laboratory to full catchment experiments. However, emphasis should be put on those scales where a low level of information is available at present. In hydrology this is most likely the scale of subunits of catchments and micro-catchments. This is also the scale of ecologically and hydrologically relevant biotic landscape elements like ecotones, ecotone complexes and elementary ecosystem patches. By successfully describing the respective properties, vulnerability assessments (see Project 2.4) and predictive models for the management of river systems, flood plains and wetlands will enable managers and politicians to link their actions with the respective results. The ultimate goal must be an integrated water resources management, which incorporates the knowledge of the complex interactions between land and water ecosystems and all human activities.

A common basis for different geographical, spatial and temporal assessments will be the use of geographic information systems (GIS) which can also cross the thematic gap, which divides and connects Project 2.3, and Projects 2.1 and 2.4, respectively.

3.2. The objectives of Project 2.3

IHP-V deals with eight proposed Themes, of which Theme 2 is directed to ecohydrological processes in the surficial environment. Within this scope, Project 2.3 focuses on the interactions between river systems, flood plains and wetlands. These hydrologically and ecologically relevant landscape units are part of the whole catchment of the river. There are influences of the rest of the catchment on these landscape units, there are hydrological and ecological processes within these landscape units, and there are actions of these landscape units on the rest of the catchment.

Project 2.3 is seen as a chance to integrate basic knowledge in hydrology on small catchment subunits, and ecological knowledge on landscape elements like ecotones, ecotone complexes and elementary ecosystem patches in an interdisciplinary approach to explain the action of structural biotic elements on hydrological, and hydraulic processes in a catchment in more detail.

Since hydrology and ecology are intensively influencing each other at the level of biotic structures, it is necessary for both fields of science to leave the traditional tracks and to start an approach, where the findings in each field contribute to the quantitative basis of knowledge in the other field. The numerical investigation of spatial and functional properties of biotic structures and hydrological elements like wetlands, flood plains and river systems will enhance the predictive potential of hydrological models.

On a general level, the hydrological processes influencing the flow of water in a catchment and the respective properties of wetlands, flood plains and river systems, are known. The same applies to the isolated knowledge of species composition and ecological processes of these landscape units. However, in hydrology as well as ecology, these systems very often remain black-boxes. Therefore, surveys within Project 2.3 should reveal the numerical basis for ecohydrological models. This can be achieved by extended experimental approaches. In the hydrological part this means that the properties of input points with respect to flow, discharge and loading must be covered by the experimental surveys in much more detail than in the past. The picture of the hydrological situation received so far is one of an aggregated level.

The next level of detail must deal with the hydraulics of smaller hydrologically and ecologically relevant landscape elements. Influx and efflux processes in the fluvial corridor, which connect the river systems and flood plains, as well as the hydraulic features of wetlands are fundamentally influenced by the structural properties of ecotones, ecotone complexes and elementary patches, which should be studied in much more detail. In ecohydrology, biologists and hydrologists have to deal with the size, number and structure of the biological elements which compose ecotones. These elements can be herbaceous plants, reeds, swampland vegetation, bushes, trees, etc. and/or complex arrangements of these structures. Hydraulic assessments make it possible to describe the effects on flow retention, changes of water level, filtering processes with respect to the sedimentation of suspended materials, nutrients and pollutants, along with infiltration, seepage and leaching processes. From these data the effects of extreme events can be deduced with predictive models. This will lead to a better interpretation of the effect of floods and other surface runoff situations on the organisms composing these hydrologically relevant structures and the biocoenoses of organisms using these biotic structures as a habitat.

From the ecohydrological interpretations of such processes, the aggregation of this information, e.g. by the evaluation of the effects of ecotone complexes and ecosystem patches, should lead to a more detailed picture of the large, catchment-related hydrological black-boxes. On the other hand, this knowledge will lead to ecological predictions with a higher level of probability when evaluating the effect of regular and extreme hydrological events on the biota of landscape units.

Finally, a prime objective of the framework and outlines of IHP-V is an emphasis on environmentally sound integrated water resources planning and management. This indicates that both aspects, the hydrological and the ecological aspect in particular, must find a common basis to start out from. Since planning and management are the main goals, it is necessary to concentrate in both fields on manageable ecological features. Without questioning the intrinsic values of many ecological investigations, the outline of IHP-V focuses on those properties of ecologically relevant landscape elements which in some way or the other can be influenced by man. Only by following this approach will hydrology and ecology find a basis where the data can be interrelated. Ecohydrology requests both partners to study their respective properties of the same items. Situations like ecologists studying the transpiration of a single tree, and hydrologists expecting data on the evaporation of a whole flood plain, have to be avoided in the future.

It can be deduced from interdisciplinary studies that true interdisciplinarity was achieved only if the freedom of each individual scientific field was sacrificed to some extent for the benefit of the mutual results. Therefore a prime requirement of the ecohydrological approach is a preliminary project phase, during which both contributing fields of science, hydrology and ecology, have to exactly define what and, with respect to the spatial definition, where the hydrological and ecological properties of structural landscape elements shall be investigated. Sacrifices with respect to the usual approaches must be faced in both fields: ecohydrology demands a new concept and part of this is modified, or even new methodologies.

3.3. The structural organisation of aquatic / terrestrial ecosystems

River systems, flood plains and wetlands can be interpreted as aquatic/terrestrial ecosystems or parts of such ecosystems. They consist of structural elements, which are of hydrological and ecological importance. A common feature of these systems is their transitional status between the permanently aquatic and the permanently terrestrial environment. This has led to the concept of interpreting river systems, flood plains and wetlands as ecotonal, or transitional, landscape units. However, this large-scale view leads quickly to a black-box approach completely insufficient to describe the influence of structural landscape elements with respect to their hydrological and ecological properties.

The habitat is a fundamental, primarily niche of a species. However, the dynamic units of biota in a landscape are the biocoenoses. Their respective structural environment can be described as ecotones (which can be patch boundaries), ecotone complexes and elementary patches. These landscape elements, or compositions of them, make up landscape units, which can be identical with sub-units of catchments or microcatchments. Within ecotones, which are transitions between elementary ecosystem patches of very variable size, highly diversified and ecologically valuable biocoenoses of plants and animals can be found in many cases. Ecotones can be regarded as ecological units with respect to their species composition and their ecological processes.

With respect to their structural properties, ecotones consist mainly of vegetation. In an ecohydrological approach, the structural properties of the vegetation elements, which are trees, bushes, herbaceous vegetation, reeds, swamp vegetation and aquatic vegetation, must be studied in detail. Black box approaches will be unavoidable even in such a detailed study, e.g. retention and filtering properties of vegetational strips will rarely be analyzed now to the individual plant, but the detail of the hydrological background will have to be consistent with the spatial extension of the ecological structural elements. The level of detail which can be achieved will depend largely on the resources which are available for a certain study.

With respect to hydrological and ecological relevance, ecosystem patches, ecotone complexes and single ecotones with a few examples shall be mentioned.
In river systems, a differentiation should be made between the river bed and the river banks up to the bank-full line. Especially on the banks, important structures like sand and woody debris and many regulation structures like levees are located. They form a sometimes dense mosaic of different habitats and micro-habitats which result in an ecologically rich ecotone type.
Descriptions of the hydrological and hydraulic features of these structural elements, and the types of biocoenoses inhabiting these elements, are necessary. Based on experiences by different studies, it has to be pointed out, that the interrelation of hydrologic and ecologic data is only possible if the sampling points are spatially related.
Flood plains can be described as a mosaic of ecotones or ecotone complexes. They consist of structural elements like forests, bush belts and flood plain meadows, and the system of flood plain waters. One can find aquatic/aquatic ecotones in the side channels, oxbows and relict meanders, where the aquatic vegetation varies according to the hydraulic and hydrological situations given by the morophology of the channels and the respective hydrological effects. Aquatic/terrestrial ecotones are found at the banks of the flood plain waters where marshlands, reeds and bush belts differentiate the environment with respect to its structure. Terrestrial/terrestrial ecotones occur at different heights with respect to the water level regime and consist of different combinations of vegetation structures, like reeds, herbaceous vegetation and flood plain meadows, bush belts of different spatial extension and forest patches of different composition. Detailed hydraulic investigation of certain structural types may help to illuminate the black-boxes of these ecotone types to some extent with reasonable investment in human and financial resources.
Wetlands, which occur as parts of river systems in certain locations of catchments, can be seen as ecosystems or ecosystem patches, which can effectively influence the hydrological regime of down-river stretches. However, they show variations in retention and filtering capacity with respect to their status of water saturation. When saturated, only the structures on the surface of these ecosytem patches act as filtering elements.

Experiences from the MAB-ecotone project have shown that the level of a truly ecohydrological approach is reached only if the hydrological experiments go into very much detail, with respect to the scale of the ecological structural elements of ecosystems. It is evident that not every single landscape unit can be described totally with respect to its hydrological or ecological properties. However, when concentrated on the most important ecotone-types and ecotone-complexes relevant to specific geographic regions and catchments, a much higher level of information can be reached with respect to the present state and a better basis for planning and management.

Objective 1: To contribute to the understanding of the role of the hydrological cycle in different ecosystems.

In river systems, flood plains and wetlands, the seasonal variation of the vegetation and the fauna is largely dependent on the hydrological cycle - which is affected by man's influence on the environment, especially by certain land-use types. Although this is well known on a general level and predictive hydrology has developed highly accurate models for large landscape units, reasonably detailed data-bases on hydrological steering factors of ecosystem patches, ecotone complexes and individual ecotone types are practically not available today.

To achieve a more thorough understanding of the action of hydrological factors in space and time with respect to the ecologically relevant landscape units, highly detailed experimental approaches in the hydrological field must be undertaken. By scaling down the input values for hydrological models to the size and scales of ecotones and their structural properties, the respective mathematical models will become more accurate for small sub-units of catchments. Through this process of focusing on ecological and hydrological details of catchment units, scales can be reached where the influence of single land-use effects by individual farmers on separate landscape elements can be properly described. By this process the effect of human actions on the environment becomes predictable, with respect to characteristic types of landscape elements.

The benefit for the hydrological aspect of the environment lies in the more accurate description of flow, discharge, retention of suspended matter, nutrients and pollutants. The benefit for the ecological interpretation of landscape units lies in the prediction of the effects of the action of flow, the estimation of the height and duration of flooding under the influence of various types of ecotones and ecotone complexes, and in a better predictability of the temporal development of the biocoenotic complexes of river systems, flood plains and wetlands.

Objective 2: To identify links between abiotic and biotic indicators in order to maintain the filtering capacities of flood plains and wetlands, with respect to sediment nutrients and pollutants and the buffering capacity against extreme hydrological events.

Flood plains and wetlands are made up of structural elements influencing their filtering and retention capacities. During flood periods ecotones and ecotone complexes regulate the surficial flow and the sedimentation of suspended matter, which carries nutrients, and in special cases pollutants. To gain more detailed knowledge in this field, ecohydrological approaches should focus on the filtering properties of ecotone types, ecotone complexes and elementary ecosystem patches, which are a result of land-use by man.

According to Objective 2 either individual ecotone types or - in more detail - the structural types of vegetation elements building these ecotone types, could serve as biotic indicators for various categories of filtering potential. By the description of the hydraulic and hydrological properties of these indicators, the input data for ecohydrological models on filtering capacity of flood plains and wetlands can be worked out.

The second part of Objective 2 refers to the same biotic indicators, the ecotones and ecotone complexes, with respect to their buffering capacity against extreme hydrological events. The same structural properties of the flood plain and wetland vegetation, which predict the filtering and retention potential, are the basis for the buffering capacity against floods. Therefore, the same methodological approach is valid for a) the evaluation of filtering potential, b) buffering capacity and c) ecological evaluation, since the diversity of species and biocoenoses is predicted by the structural properties of these landscape elements.

3.4. Conclusions

In the framework of IHP-V, emphasis is given to the present situation and to the development of the water resources of the world, with special respect to the numerous negative influences which lead to a gradual degradation of these life-supporting resources. Intensified agriculture, urbanisation, infrastructural development, deforestation and improper landuse practices, erosion and negative changes in surface water quality along with sedimentation are a few examples. Other negative aspects of environmental development are connected with the artificial drainage of wetlands, the channelisation of river networks and/or the reduction of flood plain areas. On the other hand, a growing awareness exists for the role of flood plains and wetlands: they are seen as low cost water purification systems, and as buffers against floods. But they are also recognised as recreation areas and highly valuable ecological complexes, which serve as a retreat for rare biota and as zones of high biological diversity.

Many aspects of landuse are related to the type, number and composition of biotic structural landscape elements like ecotones, ecotone complexes and elementary ecosystem patches. Fluvial corridors as well as subunits of catchments show a high correlation between their structural form and content and their hydrological properties. Defining different types of structural furnishing and assessing the resulting hydrological features at input points in a highly detailed experimental scheme, should lead to double benefit. Hydrological prediction and the basis for water resources management will profit from a better description of the surficial flow regime. The ecological evaluation and landuse management of landscape units will benefit from the inventory and the evaluation of ecologically relevant structural landscape elements. By comparison of well equipped and badly equipped subunits of catchments, it should be possible to derive more promising rules for landuse patterns with respect to their effects on hydrology and ecology in these areas.

As pointed out earlier, the truly innovative aspect of the ecohydrological concept is the tackling of the large black-boxes, which are integrated in the hydrological - and ecological - models for the numerical descriptions of catchments, which is in strictest sense, the main objective of ecohydrology.

4. Comprehensive assessment of the surficial ecohydrological processes (IHP-V; Project 2.4)

4.1. Introduction

According to the Dublin Principle No.2 of IHP-V, water management should be based on a participatory approach, which involves users, planners and policy-makers at all levels. This principle is taken into account in the framework of IHP-V, which requests special support for environmentally sound integrated water resources planning and management by a scientifically proven methodology. It is evident that a comprehensive assessment of ecohydrological processes should be able to transpose information among different spatial and temporal scales. It should also lead to a better understanding and more effective control of the consequences of landuse effects. Such an assessment should also form a scientific basis for preservation and restoration measures on rivers and wetlands, as pointed out by Theme 2 of IHP-V.

Bearing this in mind, Project 2.4. should be differentiated from Project 2.1 (Vegetation, land-water use and erosion processes) and Project 2.3 (Interactions between river systems, flood plains and wetlands). According to the framework of IHP-V and the recommendations of the Steering Committee for the Implementation and Development of IHP-V, Project 2.1, which met in Exeter (UK) in 1996, the main issues are

- to assess the effect of land-water use on erosion processes, and water partitioning into surface runoff, infiltration and natural groundwater recharge; and
- to trace and identify possible impacts of the flow-path of nutrients and pollutants effected by erosion processes.

Project 2.1 is area-related with respect to types landscape of vegetation cover, while Project 2.4. focuses on the complex composition of primarily linear elements structuring definable parts of a catchment, like ecotones, ecotone complexes and ecosystem patches.

On the other hand, Project 2.3 is oriented on structural elements within fluvial corridors, which consist of the river systems and their associated flood plains, and it includes the internal structures of wetlands with respect to the surficial flow. In contrast to that, Project 2.4 is oriented toward catchments and sub-units of catchments, but for the structural description of the vegetation adjacent to the fluvial corridors and wetlands, elements like ecotones and ecotone complexes should be used.

A potential overlap with other projects is, however, intended by the fundamental framework of IHP-V. This overlap also meets the demand for transposition of information among different spatial and temporal scales, which is mirrored by the recommendation to use GIS as a tool which will cut across all IHP-V projects. With respect to Theme 8, the Transfer of Knowledge, Information and Technology (KIT), the use of GIS will become essential for Program 2.4 as well.

4.2. Objectives of the Project

i, To develop a methodological framework, through experimental research to describe and quantify flow paths of water, sediments, nutrients and pollutants through the surficial ecohydrological system of different temporal and spatial scales, under different climatic and geographic conditions;

ii, To develop an integrated approach for managing the surficial ecohydrological environment including the consideration of non-structural measures;

iii, To improve the methodology for water ecosystem vulnerability assessment.

Objective 1: Methodological framework for experimental research to describe and quantify flow pathways through the surficial ecohydrological system

General considerations

The description and quantification of flow/transport/transformation of the pathways of water and its constituents must, in principle, concern all sources of water and substances carried in the water. A comprehensive assessment of these surficial ecohydrological processes makes it necessary to express the differences between certain observation or monitoring points, which should be called input points. In an integrated catchment basin concept these points are situated in the outflow section of catchments or sub-units of a catchment, and they are equivalent to the input point of a further part of the river system or a subrecipient in the catchment. This principle is well reflected by figure 4 (adopted from UNESCO MAB/IHP workshop on landuse impacts on aquatic systems, Jolánkai & Roberts, Eds., 1985).

With respect to the traditional hydrological methodology, a step forward would be achieved, only if the usual experimental layout is changed. For a successful assessment of ecohydrological processes, a much higher level of detail is needed for the experiments. This leads to a much denser spatial distribution of input points as compared with the studies conducted in the past. Input points must be placed at each of those sub-units of catchments, which are composed of different types of hydrologically relevant surface cover. With respect to the intentions of combining hydrology and ecology in the ecohydrological approach, surface cover is to be seen as the spatial distribution, orientation and functioning of different types of ecotones, ecotone complexes and ecosystem patches.

In the ecohydrological approach, the ecological part will have to focus on a) ecologically relevant structural elements of the landscape along the banks of the river systems, rivers and all smaller systems of running water, and b) on the composition of these elements within areas of the catchment relevant to the hydrological models.

The inevitable existence of economic, legal and administrative constraints makes it necessary to define the prime issues in catchments and, thereafter, the main objectives of the study. The prime issue would always be the water demand of all human and natural users in the surficial

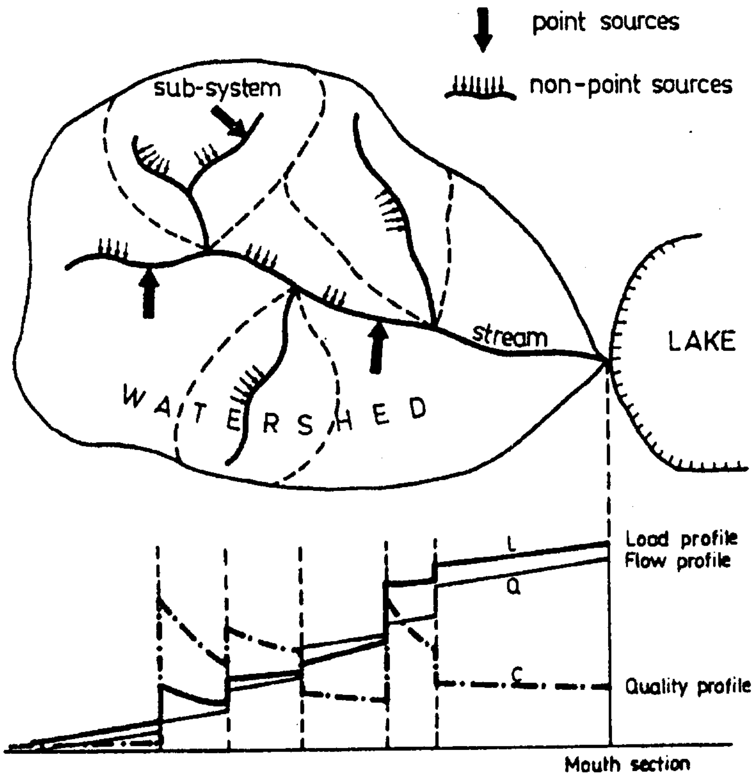


Fig. 4 . A schematic example describing the transformation of point source and non-point source loadings into L, C, Q output variables at the mouth sections of a river system.

ecohydrological environment. But in this case the term water demand is interpreted in a much broader meaning than usual. Aside from all demands of man, the demand for water by ecologically relevant landscape elements must also be considered. Moreover, this term includes protection against extreme surficial runoff resulting in floods.

Identification of issues

In any studies of the surficial ecohydrological environment, the first task is to perform a baseline survey of the catchment in order to identify problems (issues). In doing so, one should

- evaluate the data of existing hydrological monitoring networks (if any), and
- evaluate information available on the compensation of structural landscape elements (e.g. ecotones), which may include satellite information and aerial photography.

This work should include the following basic group of activities

A. Assessment of quantity of water resources. This is the assessment of the availability of water at various points with respect to the water demands of the surficial ecosystem. This approach should, among other objectives, include:

- Water demands of the ecosystems of fluvial corridors, which are composed of ecotones, ecotone complexes and ecosystem patches. It should be exactly specified what inundation depth, and what temporal duration is needed, to support the different plant and animal communities. It is to be expected in most cases, that these data of ecological relevance do not exist.

- Water demands of wetlands and flood plain waters like oxbows, which contain aquatic/ aquatic ecotones and aquatic/terrestrial ecotones. Exchange rates of water necessary for sustaining the existence of these landscape elements and the demands for seasonal distribution should be specified if possible.
- Data on water demands of the terrestrial parts of fluvial corridors can also be aggregated. However, not much information will be available at first sight.

B. Assessment of the quality of water resources. A new approach with respect to ecohydrology should be the comparison of water quality and the qualitative demand of aquatic ecosystems.

C. To complete this basic group of activities, the available biological information should be reviewed on the biotic structural elements of fluvial corridors and the sub-units of catchments in between. It should be noted at this point, that all other approaches concerning the area of the catchment and its sub-units are covered by the objectives and activities combined and aggregated in Project 2.1.

The experimental research programme

The experimental research program must identify cause and effect relationships. It is necessary to define the surficial flowpaths with respect to the biotic structural landscape elements, which influence the hydrology and ecology of fluvial corridors and sub-units of catchments.

Experimental research methodologies to determine surficial pathways

With respect to the ecohydrological approach, interrelated macro- and micro-scale studies are suggested. The objective of the macro-scale is to obtain an insight into the broader relationships at the catchment scale. The objective of the micro-scale is to identify the processes along the major pathways that actually determine the fate of water and its constituents in the surficial ecohydrological system. In this case the actual scale will depend on the absolute magnitude of the catchment concerned, and may vary when dealing with sub-units of catchments.

Macro scale experiments

The macro scale experiments are focused at the determination of water and mass balances of the catchment and the construction of longitudinal hydrological (flow, water depth, and velocity) and water quality (load and concentration) profiles along selected main pathways of the water system. In this part of the study perhaps the main emphasis of experimental work is to be laid on the determination of the times of travel along these major pathways. This parameter is the one that actually determines the changes along the pathways, whether it is the travel of a flood hydrograph or the changes due to biochemical and physical reactions. Suggestions for relevant experiments are:

- Longitudinal sampling programmes of both point sources of pollution and in-stream water quality, following as much as possible the time of flow;

- Diurnal sampling programmes (e. g. hourly samples for 24 hours) at selected river cross sections downstream of major discharges (e.g. larger cities or industrial plants). This intensive sampling program should be carried out for pollutants which are distinctly higher downstream of a discharge than the background concentration. Corresponding diurnal peak concentrations of the cross sections will allow the determination of the time of travel for the given hydraulic condition. Repeated studies of this type can reveal the variation of the time of travel as a function of the flow (and season) over the entire system. A less reliable method is the estimation of flow velocities as a function of the channel slope and channel roughness.

It must be stated that only very detailed cross section measurements are of relevance for plants and animals living in the river channels. Hydraulic studies with respect to the flow conditions inside plant beds and their near vicinity have been started only recently.

- The analysis of flood hydrographs of subsequent monitoring stations will yield information needed for conditions of high flow.

This set of experiments, which ends with the determination of water and mass budgets for the catchment, gives an insight to non-point source pollution also. The mass budget component which cannot be explained by the point sources comprises all unidentified point sources and the non-point portion. As the resultant pollution load of the downstream section is not the algebraic sum of the input loads of the catchment, certain models explained later should be considered for the description of the ecohydrological processes (longitudinal profiles).

These macro-scale experiments are the level at which to set up a data bank on natural and anthropogenic inputs to the catchment (e.g. atmospheric deposition of pollutants, field application rates of fertiliser, manure, sewage sludge, etc.).

Micro scale experiments

The objective of these experiments is to gain insight into, and gather data on, the processes that determine the fate of water and its constituents between their primary sources and their final destination. Since these experiments will depend on the issues identified (see above) only some general suggestions as to the type of the experiments can be made.

In this set of experiments the main task is the explanation of the functioning of structural abiotic (morphological) and biotic (ecotonal) landscape elements. Micro scale experiments shall gather data on processes influenced by ecotones, ecotone complexes and ecosystem patches. Some general suggestions as to the type of the experiments can be made:

- Comprehensive experiments should focus on selected sub-units of catchments with respect to the content of structural landscape elements. Recordings should include precipitation, irrigation, runoff and its sampling for sediment and selected pollutants. A dense setting of input points should reveal the flowpath as influenced by the structural landscape elements.

- Biological surveys of vulnerable ecological resources, like marshlands, wetlands, oxbow lakes, flood plain forests etc., possibly including the identification and quantification of the main pathways of nutrients and pollutants within these systems.

Objective 2: Methodology for the integrated approach for managing the surficial ecohydrological environment.

General consideration

The eco-hydrological approach proposed here is a systems approach. It is aimed at an integrated management of catchment basins as the whole. It is integrated with respect to scale, which means that the hydrological units studied by the implementation of input points and by the description of area properties through their structural composition are of such a small size that the remaining black boxes are considerably smaller than in the past, and by a bottom up approach the numerically defined parts of whole catchment models reach a high level of predictability and accuracy. It is also integrated with respect to the scientific fields taking part in this approach, by defining a) that only manageable structures of landscapes are studied and b) hydrology and ecology definitely work on the same features of these structures.

Integration also means that the demands of all water uses of the catchment should be met in an optimal and sustainable way. In this equal rights approach, the demands and needs of the biota (ecotones, ecotone complexes and ecosystem patches) and that of the human society are considered in the same quantitative and qualitative terms. These ecohydrological terms comprise the demand for the quantity and quality of water, but also the demand for the decrease of the excessive abundance of water.

This means that the traditional water engineering approach in which water management activities are planned to meet the needs of mankind *"but in harmony with the demands of the environment and the ecosystem"*, should be rejected. The traditional environmental or ecological approach, in which practically all activities of man shall be excluded and the ecosystem re-established in *"its original or natural state"*, should be rejected as well.

The new, ecohydrological approach needs to specify in scientific terms the demands of the surficial environment. In water engineering and in environmental terms this means specifying precisely the quantity and quality of water requested, and the site and duration, where and for which period this supply of water is needed.

The two disciplines involved in the ecohydrological approach are still far from harmonisation, even if notionally they have long ago accepted the needs for integration. The basic reason is the lack of interdisciplinary knowledge and understanding. The present IHP-V Project represents a most significant step forward towards the development of this integrated ecohydrological approach.

On the integrated catchment models of the surficial ecohydrological environment

The crucial element in the systems approach to the management of the surficial ecohydrological environment is the development and adoption of analytical tools, which are the catchment models.

Before any models or analytical tools can be applied, appropriate data bases must be developed. Two interrelated and interconnected types of data bases should be established.

a. Data bases of monitoring networks. These networks collect time-varying data (records). The prime resource for such unified data bases will be data available at various locations (agencies), such as those of the hydrographic service, water quality management, emission inventories, hydrometeorological service, etc. However, most (or all) of the data necessary for the numerical description of the effect of structural landscape elements on the hydrological flowpaths will have to be collected in the field. The relevant number of input point measurements will form the backbone of the highly detailed hydrological experiments envisioned by the ecohydrological approach. In addition to that, the data bases must contain all information on the structural and ecological properties of the landscape elements under investigation, e.g. the ecotones.

b, Geographical information systems (GIS). These systems must combine the information of the data-bases, the attributes with their spatial location. They must also contain the information necessary to define the spatial description of each area or stretch of a fluvial system (however small this will be), where the same values are valid as in the input points, or where mathematically described and scientifically defined gradients between areas / stretches of different influence are located, or thresholds exist, respectively. Modified or new dispersion models with respect to hydrological features and ecological information could be applied here. In general the geographical information system will include digital maps of the topography (digital terrain model), on landuse, infrastructures influencing the hydrology of catchments, soil-properties, etc. Other information on the catchments and their sub-units may include aerial deposition and application rates, such as precipitation, fertiliser application, etc.

The methodological key element of the system of ecohydrological models should be a GIS-based model of fluvial systems and catchment units which describe the hydrological and ecological properties of landscape elements and, in an aggregated way, of landscape units up to the catchment level. From this combination of structure-related hydrological and ecological information those catchment-oriented processes influencing the surficial pathways of water, nutrients and pollutants can be derived. It is stated here, that the term processes is used in a different way than in the biological sciences. Physiological or reproductive or population dynamics processes are of no direct relevance here. In the context of ecohydrology and the effects of ecotones, ecotone complexes and ecosystem patches on hydrological properties of the surficial environment, ecological processes are those actions of biotic structures which influence surficial flow with respect to direction and time in a quantitative and qualitative way.

Although there is a wide choice of commercially available catchment models offered by this professional field, it is still not certain that one will find the one that would be best suited to the description / simulation of surficial eco-hydrological processes of a given catchment. One of the reasons is that GIS based hydrological and pollutant transport / transformation models tend to be excessively complicated ones with an enormous data demand. It is the intention of these guidelines not to name any one of them, as no commercial advertisement (and even less the counter advertisement) can be the purpose of these guidelines. Another problematic part of this approach is that commercially available GIS are usually not too well suited to the handling of hydrological and related transport and transformation processes. However, the spatial definition of hydrological and ecological properties of landscape units in a catchment, will have to be based on a GIS to be able to combine these properties of sub-units of catchments with the structural furnishings.

One will definitely need the Digital Terrain Model (DTM), as this is the most practical way of finding the pathways of flow, sediment, nutrients and pollutants. Aside from the primary description of landscape features in the GIS, the hydrological modelling work could start with an algorithm (a model) that defines the pathways of runoff from the terrain on the basis of the DTM. In catchments with rather homogeneous runoff parameters, these algorithms will be easier found than in catchments with numerous biotic (and man-made) structures influencing the surficial flow. Especially in the latter case, the description of the structural properties of hydrologically effective landscape elements, which are collected in the GIS, will have an important effect on the algorithms describing runoff. This will be one of the important points of interrelating the GIS and the numerical hydrological models.

The results of one highly descriptive, DTM-based numerical model, which does not yet explicitly contain information on the structural composition of a catchment, and therefore still contains black boxes with respect to the ecological properties, is shown in a map of runoff flow directions (Fig. 5) where the entire surface water system can be defined, without having entered the lines of the stream network to the data base. However, as stated before, such a model in combination with GIS information, and in combination with information collected at certain input points will certainly fulfil the needs of the ecohydrological approach.

In addition to finding flow pathways, the DTM approach can also be applied for describing the nutrient transport and transformation processes, a key issue in most of the catchments. Digitised soil maps can yield the information on the nutrient content of the soil and also the fertiliser usage should have a digitised map form. Last, but not least, the digital map of the land use will actually specify the mosaics that would be most needed in the quantitative evaluation of the surficial ecohydrological processes. For example wetlands and riparian flood plain ecotone complexes and ecosystem patches will appear in the digital map, and will be utilised in the relevant model system as sinks of both water and nutrients (unless otherwise specified by the experimental data), representing water storage and increased evapotranspiration, or the uptake of nutrients by aquatic plants. Thus in the model, as well as in reality, these patches shall act as regulators of the entire flow and mass transport scheme.

Calibrated catchment models, like the one described above, could be used for designing flow regulation systems. With respect to vulnerable wetland ecosystems, an appropriate supply of water throughout the seasons could be envisaged. Small upland reservoirs could regulate flow by withholding some of the abundant springtime, or summer, rain period runoff water. Such principles of flow regulation could be justified by the fact that ancient landscape conditions,

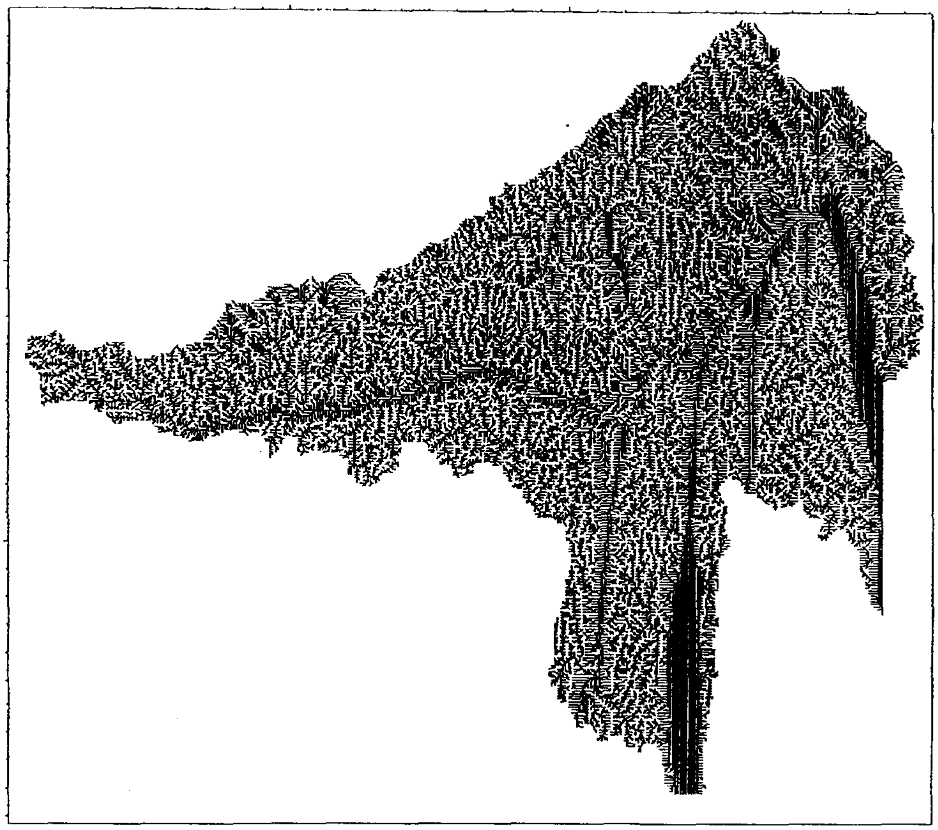


Fig. 5. Detailed map of the "pathways" of flow and pollutant transport in a catchment basin (derived from the digital terrain map, DTM)

landuse types, and therefore landcover, were acting in a similar way. However, the conditions of today's anthropogenic landscapes have to be kept in mind to define practical designs. It is also an example which proves that water management, like the construction of small dams, can be beneficial for the status of nature. If climatic changes should become definite in the future, such solutions will also become increasingly important.

It is intended to give general guidelines only, since the actual cases may differ considerably with respect to the data bases available and the environmental conditions in the various climatic regions of the world. However, some important analytical tools and models are referred to, which are of potential support to the ecohydrological approach.

- Statistical evaluation of monitored data to reveal trends, if any, and to establish critical and/ or design conditions (e.g. flood flows, critical low flows, excess of water quality criteria, etc.);
- Using bi- and multivariate regression models, assessments can be made of the changes in river discharges through climatic variation as a function of temperature, precipitation run-off etc.. However, it should be noted, that so far no definite and uniform trends of global warming or climatic change have been found and that the contribution of statistical variation to potential - or just interpreted - trends may be considerable. Yet, model approaches on pollutant export of various landuse forms (as functions of fertiliser usage, soil property parameters, rainfall and/or runoff parameters, etc.) may be included in overall models as a basis for the evaluation of certain future scenarios.

- In the context of hydrological, precipitation and runoff models, a careful selection of the time step of simulation is necessary. Either event-based dynamic simulation is to be made, or steady state water budget models are applied. In this latter case, the time base should be longer than the time of concentration. Monthly time steps would allow in many cases more simple steady state simulation and still allow for the consideration of seasonal changes. These time steps should be especially valuable for the identification of seasonal changes of the hydrological properties of biotic structures. However, it should not be overlooked, that for the sake of economic efficiency, only seasonal periods with effective influence between hydrology and structural ecological elements should be investigated. However, the spatial retention of snow by biotic structures should not be overlooked.

- Certain attempts should be made to combine ecological models of still waters and running waters with their hydrological background in a more profound way than in the past. It is not intended to go into the biological details of lake models, but the numerous approaches to the description of running waters like the river continuum concept, different assessments of disturbance, connectivity or flood pulses show clearly that there is no uniform explanation based on the mutual integration of hydrology and ecology, which could explain the dominant influence of hydrological parameters on the biotic contents of ecosystems in detail at various scales. Some very large scale model approaches and some very small scale approaches are available, but both work with considerably large black boxes and there is no way of transgressing the differences in scale. A concise basis should be found for the hydrological effects of structural biotic landscape elements and their related hydrology, which can be used in a bottom up approach to describe catchment properties. Novel ways will have to be approached, since existing ecosystem models are not accurate enough to be generalised with respect to scales and climatic and geographic regions.

- The final system of models is that of the recipient streams; their water quantity and quality. Again a large variety of models are available from the literature, both for flow and the chemical and biological processes within the water body.

For working within the scope of IHP-V, Project 2.4, one of the main intentions must be the efficient concentration of resources towards the most important issues of catchments under investigation. Necessarily, this is combined with missing out on less important goals. Another directive is to study only those ecohydrologically relevant features of landscapes, where ecology and hydrology can pursue their studies on the same, and manageable, object. The study of non-manageable items of a landscape has been done in excess in the past - at least in the biological field - but IHP-V denies its full support to studies with only scientific interest. Therefore, the selection of the experimental approach and the models to be applied should be restricted by the following principles:

- Models should be suitable for the description of the main surficial ecohydrological processes concerned.

- The only justification for the modelling approach with respect to IHP-V is the transfer of scientific knowledge into practical management and political decision making. Simple models with few input parameters stand a much higher chance of being used. Therefore, V support to end up with multi-compartment ecohydrological models needing hundreds of model parameters and coefficients is certainly the situation that one wishes to avoid.

- It is essential to focus on the key processes (having the experimental work also designed for them). In the surficial ecohydrological system, these keys are the ecotone, ecotone complexes and ecosystem patches. The regulatory role of these transition zones, which comprise wetlands, riparian forests, oxbow lakes, flood plain marshlands etc. is the one that should be included in the analysis, both in terms of flow regulation and the uptake of nutrients and other substances.
- Relatively simple source-and-sink schemes can be considered for accounting for such processes in the overall catchment models. With respect to the information on filtering, buffering and water demands of ecological structures these models will also include the description of effects of excessive discharge events which form part of the assessment of ecological systems. Through these approaches the objectives of ecohydrology will be met.

Objective 3: An ecohydrological methodology for the assessment of water-ecosystem vulnerability

General consideration

The first statement of the Dublin Principles reads: Freshwater is a finite and vulnerable resource, essential to sustain life, development and the environment. (UNESCO, IHP-V, 1996). It is stated, that the development of water resources should preserve, or rather enhance the buffering capacity of the environment against unexpected shocks or long-term trends.

Technological and political actions in water resource management are linked to their respective outputs by different spatial and temporal scales. To assess the vulnerability with respect to these actions, appropriate criteria for describing the changes in the environment must be identified. This implies that the transitions from one landscape status to the other, and the sequence of ecological and hydrological processes, are understood. To assess management impacts, relevant indicators have to be identified, which properly trace the consequences of change. They will be different with respect to scales, and climatic and geographic regions.

The concept of ecohydrology is focused on the interactions between ecological and hydrological components of landscapes. It can provide a basis for the more detailed analysis of changes from one environmental and hydrological status to the other. This will help to consider adequately uncertainties in the planning and management of water and water-related resources, which are one of the fundamentals of environmentally sound sustainable development. Following these concepts, the transfer of knowledge, information and technology can be achieved, which is the essence and primary objective of IHP-V.

Vulnerability of the environment: a definition

With respect to the environment and its hydrological and ecological resources, vulnerability seems to be easily understood as far as its general meaning is concerned. However, a more precise definition is desirable, if scientific methods for its assessment shall be developed. Vulnerability of the environment can be interpreted as the occurrence of unfavourable changes with

respect to the availability and quality of water resources and the ecological contents of landscapes. It must be realised, that the term "unfavourable" applies only from a human viewpoint. Natural changes, however extreme they may be, are not covered by this term.
"Unfavourable" implies that a given system is transgressing a threshold from one status to an other. With respect to the general outline of IHP-V, this can be triggered by extreme hydrological events which change the ecological status of a landscape unit, which may be a catchment or a subunit of a catchment in the hydrological sense. On the other hand, human impact by landuse or water management can result in extreme changes of the ecological composition of landscapes, which in consequence result in a new status of the hydrological factors and processes.

Vulnerability applies to different levels of complexity, which describe hydrologically relevant elements of landscapes and the composition of biocoenoses. Aside from the individual organism and its physical integrity (Level 1), communities or biocoenoses (Level 2), habitats, ecotones, ecosystem patches, and other structural landscape elements (Level 3), as well as larger landscape units and integrated landscape complexes (Level 4), can suffer from severe changes of their status. Vulnerability takes effect as soon as the limits of resilience are transgressed and the threshold of resistance is crossed. Vulnerability also implies changes which seem to be irreversible with respect to short-term periods limiting man´s scope. Periods with relevance to processes of biological succession, which may measure between many decades and centuries, as well as periods of geological relevance, do not fit into the scope of IHP-V and the present potential of environmental management by man.

An ecohydrological methodology for assessing vulnerability of the environment

Vulnerability in the ecohydrological context becomes apparent as a result of extreme hydrologically relevant events caused by man or nature. These events are usually stochastic with respect to their temporal and spatial occurrence and monitoring them is possible only on a long-term basis. For predictive models, other approaches are necessary, which give access to ecohydrological methods, which have the potential of influencing the management of water resources and political decisions.

Geographic and climatic differences, in combination with certain types of landuse-derived human impact on the environment, have produced a wide variety of landscape units, which can be classified with respect to the extent of unfavourable changes in the past, and to their alienation from the natural environment.

The limits of resilience can be detected, if such landscape units can be described in a highly detailed way, concerning two aspects of their hydrological features:

The hydrological aspect must focus on the experimental assessment of subunits of catchments, defining a dense net of input points, roughly comparable to the method of finite elements in technology.

The ecological aspect has to deal with relevant landscape elements, which are ecotones, ecotone complexes, and in some cases ecosystem patches. This information on the structural elements must be supplemented with their respective hydrological properties, e.g. hydraulic resistance or filtering capacity, to work out the ecohydrological features of landscape units, or catchment sub-systems, respectively.

Geographic information systems (GIS) are the most appropriate and advanced tools available at present to carry out this work. The GIS should be used to interpret, and to predict the transgression from a favourable state to an unfavourable one by modelling, thus indicating the extent of vulnerability. Proof of the predictions can be found by comparing the predicted status with real catchment sub-units of different hydrological and ecological composition.

The understanding of ecohydrological processes by integration with socioeconomic conditions in the given catchment should provide the foundations for sustainable development. The basic tool for selecting the most appropriate methods for the given project can be provided by IHP Technical Papers and MAB Digest series (Fig. 6).

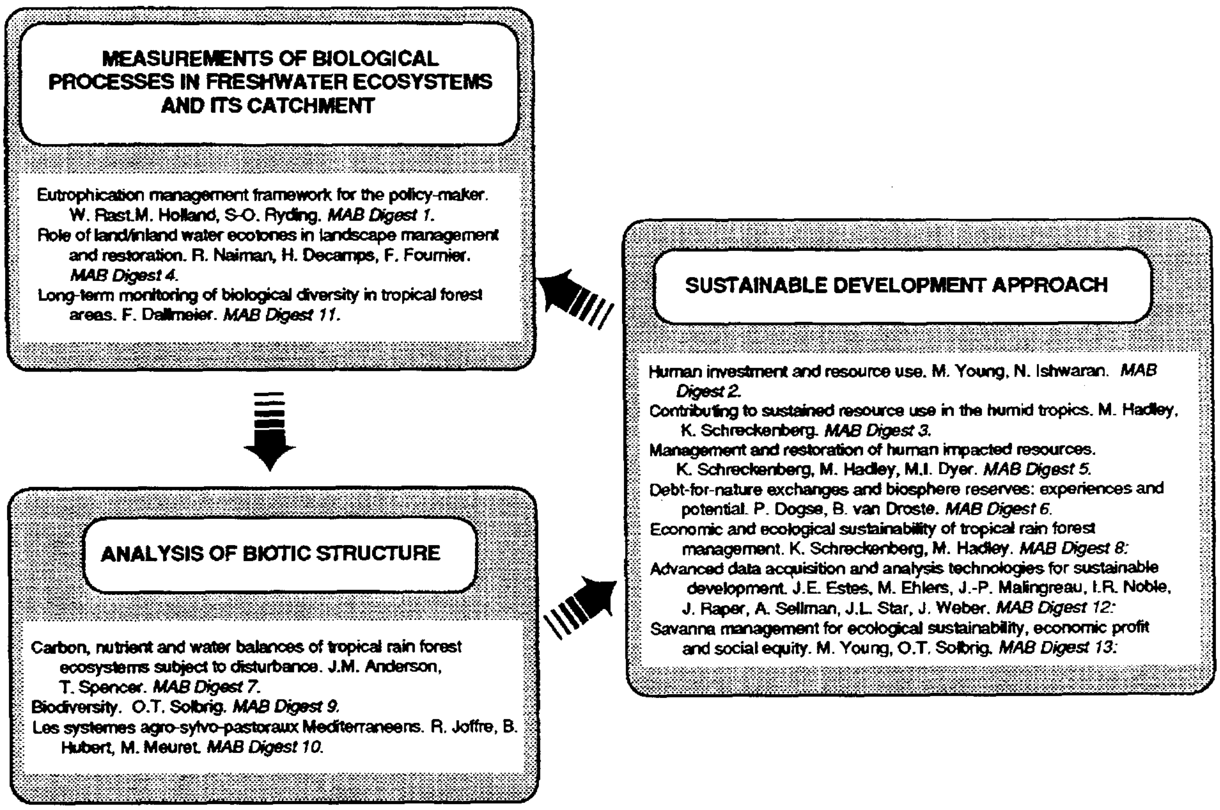


Fig. 6. General methods approach.

It should be stated that the approach for assessing vulnerability described here is different from the objectives of Program 2.1, which focuses more on processes relevant to the area and the vegetation of the catchment with respect to erosion, whereas in Program 2.4 the focus is directed to the fluvial corridors of all spatial scales, to the ecotones in their functioning as patch-boundaries with special emphasis on ecotone complexes in the area, and to riparian ecotone compositions.

The methodology of the assessment of vulnerability will certainly be a major item of the International Symposium on Ecohydrology, to be held in Dienten (Salzburg, Austria) in May 1997.

Steps of the systems approach to integrated management of the surficial ecohydrological environment

As stated above, the approach is essentially the concept of integrated catchment management, with the meaning that surface water ecosystems are managed by integrating natural and social processes. Steps of the systems approach to integrated management are shown in Figure 7.

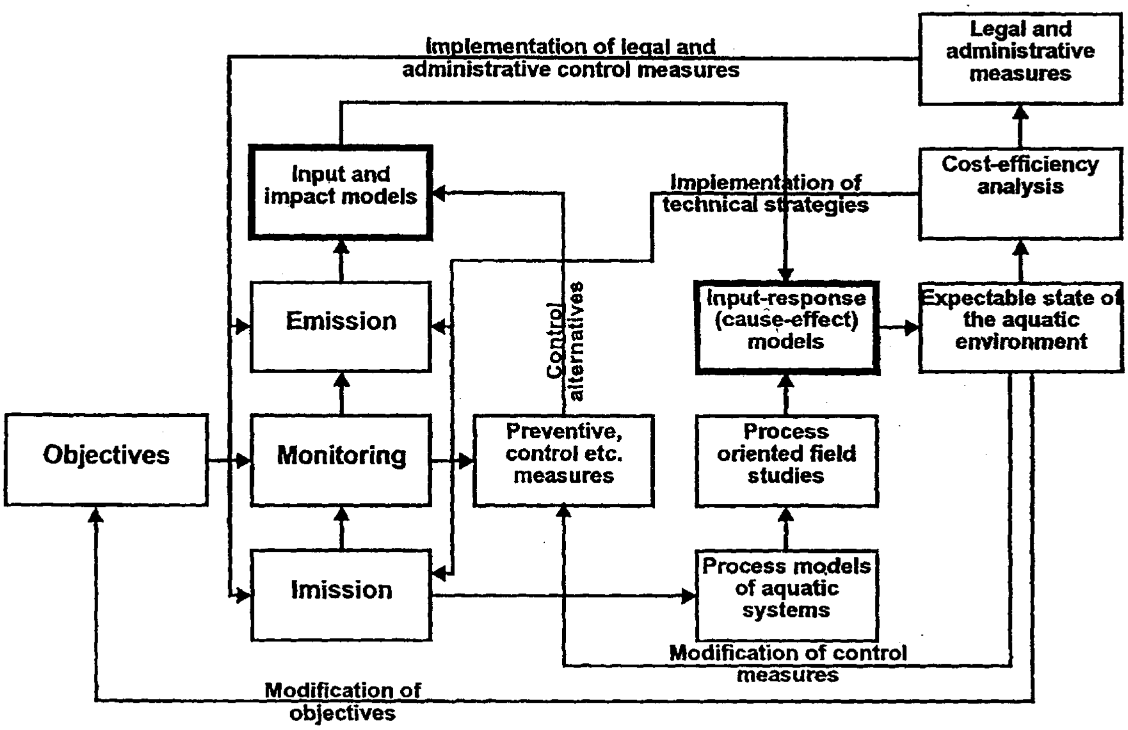


Fig. 7. Systems approach to managing the aquatic environment.

They include:

1. Setting of objectives, scientifically specifying the needs (the criteria or standards) of both society and nature (as discussed in somewhat more detail above).
2. Establishment, operation and maintenance of surface water monitoring systems (hydrometeorological, hydrographic and water quality, the latter including both output and input)
3. Assessment of the state of the surficial ecohydrological environment and the identification and quantification of key issues (problems) that need management (see also above).
4. Elaboration of a strategic action plan, to be followed by the development of the alternative options of management strategies. This is actually the outcome of the Catchment Management Planning (CMP) procedure. To the systems approach, however, the alternatives should be expressed in scientific terms, that is in such a way as to allow their use as input data (or forcing functions) in the analytical tools (models) to be discussed below.
5. Development of analytical tools (models) that describe/simulate the response of the catchment (the water system, including the aquatic ecosystem) to various changes of the input.

This key element of the systems approach is actually a set of much varying analytical tools (computer software) which are constructed/adopted for describing the fate of water and its constituents through the entire surficial ecohydrological system, including the possible pathways, if the data will allow, of transport and transformation.

6. Carrying out of process-oriented field experiments (see Section 1) and data collection since the first analysis of available data (see Macro scale studies above) will eventually indicate that knowledge and information is not sufficient for finding the pathways and identifying/quantifying the processes with the desired accuracy and details.
7. Due and careful analysis of all the constraints that will limit the introduction of the desired strategies (control or management measures) including technical (physical), legal, administrative and most of all financial/economic constraints.
8. Selection of the best feasible technologies of control and management along with the best feasible means of non-technical control; formulation of the final feasible set of alternative strategies of management.
9. Running the models with input data (forcing functions) that correspond to the above mentioned alternatives.
10. Checking whether desired objectives can be met or not, followed by the modification of strategies and ultimately the objectives if so required by the conditions of the basin (and the constraints involved).
11. Restart of the analysis from step 1.
12. Forward the results of the comprehensive ecohydrological assessment process to planners, designers and decision makers, or alternatively develop a computer tool on the basis of the work done that will support the decision making process.

Evidently there are several internal loops in this approach such as the modification/development of the analytical tools to suit the data that can be made available, or the processes that were revealed during the experimental investigations.

5. The project on Ecohydrology within the framework of the IHP-V: Project Implementation Plan

The project on *"Ecohydrology - A New Paradigm for Sustainable Management of Water Resources"* is an integral part of the Fifth Phase (1996-2001) of the International Hydrological Programme as approved by its Intergovernmental Council, during which the emphasis will be put on *"environmentally sound integrated water resources planning and management supported by a scientifically proven methodology"*. The programme, aiming at the improvement of the links between research, application and education, constitutes therefore a framework for applied research and educational projects, which can be classified in three main clusters of activities as follows:- Resources process and management studies;- Regional studies;- Transfer of knowledge, information and technology.

Within this set of clusters, eight themes have been identified as a support structure for the various projects to be implemented within the framework of the Programme in cooperation with the IHP National Committees and GO/NGO partners (as IAH, IAHS/ICSW/ICT, IAHR, IRTCES, ICSU/SCOWAR, IGBP/BAHC and WMO). ***"Ecohydrological processes in the surficial environment"*** is one of these themes, and initially included four projects:

1. Vegetation, land use and erosion processes (2.1);
2. Sedimentation processes in reservoirs and deltas (2.2);
3. Interactions between river systems, flood plains and wetlands (2.3);
4. Comprehensive assessment of surficial ecohydrological processes (2.4).

In its twenty-third session, the IHP Bureau decided to combine the last two into one project entitled *"Ecohydrology - A New Paradigm for Sustainable Management of Water Resources"*. The main aim of this project is to assist the sustainable use of environmental resources, especially land and water. To achieve this objective, a major area in need of exploration has been defined. This would lead first to a better understanding of the vulnerability of land-water systems to human activities. And in order to preserve and restore rivers and wetlands, a need to apply the ecohydrological approach was also identified, that means the study of the interrelations between mechanisms and processes of water circulation with its biotic and abiotic content, and the functioning of ecosystems in its environment.

Considering the recommendation made in the final Plan of IHP-V to establish an International Working Group including specialists from the MAB National Committees who are willing to cooperate (these projects 2.3/2.4 on ecohydrology can be seen as the logical continuation of the Ecotones Project launched in 1989 within the framework of the MAB Programme), nominated two IHP coordinators (G. Jolankai - Hungary, and C. Montes - Spain) who, in cooperation with two representatives from the MAB programme (M. Zalewski - Poland, and G. Janauer - Austria), are responsible for the elaboration of the present scientific guidelines of the project, and will assist the IHP Secretariat in the preparation, coordination and execution of its programme of activities.

This structure, involving also 6 Regional Coordinators who will work in straight collaboration with their respective Regional Hydrologists, affords an effective basis for undertaking the project.

After a first phase of definition and planning (1996), concluded with the publication of the present booklet, the activities to be undertaken within the framework of the project will be organized in four main phases distributed between 1997 and 2001 as indicated in the following table. These activities will also be divided in two levels: the global level (involving mainly the International Working Groups and the Regional Coordinators of the project) and the regional level (involving mainly an open cooperating network of IHP NC's and GO/NGO's representatives/experts).

Phase	Years	Activities	Level
I	**1997**	<u>*Launching of the project:*</u> distribution of working hypothesis and guidelines, publication of an Ecohydrology Handbook, International Symposium on concepts and methods of eco-hydrology, Experts' consultations	Global
II	**1998-1999**	<u>*Execution of the project:*</u>	
		☑ Regional Workshops and Meetings, Comparative Studies, Experts' missions	Regional
		☑ Preliminary synthesis of results and reports to IHP Council	Global
II	**2000**	<u>*Final Symposium and Conclusions of the project:*</u>	
		☑ Reports on research activities and meetings	Regional
		☑ Final Symposium (preparation by Working Groups on theoretical, methodological and applied aspects of ecohydrology)	Global
IV	**2001**	<u>*Outputs of the project:*</u> Publications, Dedicated Software, Technical Reports, Teaching Material, Final Report	Global

Proposed Implementation Plan

Year	Month	Event/Result	Actors involved: IHP Secretariat Steering Committee	Focal points Experts	Regional Officers and Coordinators
1996	X	**Steering Committee meeting in Warsaw (10-16 October)**			
	XI-XII	**Publication of the Working Hypotheses and Guidelines for the Project**			
1997	I	**Distribution of the Guidelines**			
	I-IV	**Collection of National Committees'**			
	V	**International Symposium on Ecohydrology as a Basis for Development of Water Resources (Salzburg, Austria)** *Scientific Symposium (Concepts, methods, case studies)* *Preparation of Ecohydrology Handbook (Authors)*			
	VI-XII	**Ecohydrology Handbook** *Elaboration of contents*			
1998	I-III	**Ecohydrology Handbook** *Final Editing and Publication* *Distribution among participants of the project*			
	I-III	**Review of the National Committees' responses to the recommended Working Hypotheses**			
	III-XII	**Regional Workshops and Meetings focusing on the first results obtained after aplication of the Working Hypotheses**			
	III-XII	**Expert's missions**			
	III-XII	**Scientific meetings on topics related to Ecohydrology (*deriving from the 1997 International Symposium and from NC's proposals*)**			
1999	I-XII	**Regional Workshops and Meetings focusing on the integration of the results of comparative studies in Ecohydrology**			
	I-XII	**Experts' missions**			
	I-XII	**Scientific meetings on topics related to ecohydrology (*derived from NC's proposals*)**			
	IX-XII	**Preliminary synthesis of results and reports - Report to IHP Council**			
2000	I-IX	**Preparation of the final Symposium of the Project (3 working groups)** *Theoretical aspects (Global changes - Sustainability)* *Methodological aspects* *Applied aspects*			
	IX-XII	**FINAL SYMPOSIUM OF THE PROJECT**			
2001	I-XII	**Publications/Software:** *Book of the Symposium* *Technical reports* *Teaching material (textbook, CD-ROM's, SW...)* *Dedicated Ecohydrological GIS*			
	VI-XII	**Final Report of Projects 2.3/2.4**			

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