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Partnership in Sustainable Development

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“MATCHING HYDRAULICS AND ECOLOGY IN WATER SYSTEMS”

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The written contributions to the workshop have been synthesized by the authors on the basis of the discussions during the workshop.

Editing took place by: M. E. van Boetzelaer, L. A. van Geldermalsen, J. K. Vrijling and J. E. Prins.

Editor's Note

At the 1989 Congress in Ottawa IAHR members expressed the view that IAHR should devote more time and energy to demonstrate its awareness of and contribution to environmental problems. Although it was appreciated that this is already fairly widely happening a higher IAHR profile in environmental issues was advocated. In response to this call Council approved the formation of an Advisory Board for the Advancement of Sustainable Development and Environmental Protection (ASDEP) composed of H. Bandler (Australia), M. Benedini (Italy), T. M. Dick (Canada), Ö. Starosolszky (Hungary) (IAHR Vice President) and J. E. Prins (The Netherlands) (IAHR Secretary General) as convenor. This group was given the task to explore methods and realise actions to meet the objective of both increasing the awareness of environmental issues within IAHR membership and, perhaps more importantly, to acquaint the scientific community in general and ecologists in particular with the potential role of IAHR and its membership in dealing with the interaction of technology and the environment and to promote mutual understanding between hydraulic engineers and ecologists.

The ASDEP Board proposed two workshops under the common heading: Hydraulics and the Environment – Partnership in Sustainable Development. The first dealing with “Matching Hydraulics and Ecology in Water Systems” was hosted by the Rijkswaterstaat of the Netherlands and held in Utrecht in March 1991 under co-chairmanship of J. K. Vrijling, representing the host and P. Hjorth, chairman of the IAHR Section on Water Resources Management, participating with the ASDEP Board in the preparation of the workshop. It is intended to hold the second workshop in 1992 – to be hosted by Canada – under the heading “Hydraulics and ecology for environmental impact assessment”.

IAHR Council released funds for the publication and dissemination of the proceedings of the 1991 Utrecht workshop in this special and additional issue of the Journal of Hydraulic Research. I would like to express my thanks to the authors and particularly to M. E. van Boetzelaer, L. A. van Geldermalsen, J. K. Vrijling, and J. E. Prins for editing this special issue.

P. Novak

Editor, Journal of Hydraulic Research

Note du rédacteur en chef

Au Congrès de 1989 à Ottawa des membres de l'AIRH ont émis le souhait que l'Association dépense plus de temps et d'énergie à démontrer qu'elle est consciente des problèmes d'environnement et qu'elle contribue à leur solution. En réponse à cet appel, le Conseil a approuvé la formation d'une "Commission consultative pour l'avancement d'un développement à soutenir et de la protection de l'environnement" (ASDEP) composée de H. Bandler (Australie), M. Benedini (Italie), T. M. Dick (Canada), Ö. Starosolszky (Hongrie) (Vice Président de l'AIRH) et J. E. Prins (Pays-Bas) (Secrétaire Général de l'AIRH) en qualité de modérateur. La mission de ce groupe était d'explorer des méthodes et de réaliser des actions visant à la fois à faire mieux prendre conscience des questions d'environnement parmi les membres de l'AIRH et, ce qui est peut-être plus important, à faire connaître à la communauté scientifique en général et au milieu des écologistes en particulier le rôle potentiel de l'AIRH et de ses membres par l'interaction de la technologie avec l'environnement et enfin à promouvoir une meilleure compréhension entre ingénieurs hydrauliciens et écologistes.

La Commission ASDEP a proposé deux réunions de travail sous le thème commun: l'Hydraulique et l'Environnement - Partenariat dans le Développement Durable. La première, consacrée au sujet "Harmonisation de l'Hydraulique et de l'Ecologie dans les systèmes liés à l'eau", a été accueillie à Utrecht aux Pays-Bas en mars 1991 par le Rijkswaterstaat sous les coprésidents J. K. Vrijling, représentant du Rijkswaterstaat, et P. Hjorth, Président de la Section de la Gestion des Ressources en Eau de l'AIRH, collaborant avec la Commission de l'ASDEP à la préparation de la réunion de travail. Il est prévu de tenir la seconde réunion de travail au Canada en 1992 consacrée au sujet "Hydraulique et Ecologie pour évaluer l'impact sur l'Environnement".

Le Conseil de l'AIRH a alloué des fonds pour la publication et la diffusion des compte-rendus de la réunion de travail d'Utrecht en 1991 dans ce numéro spécial supplémentaire du Journal de Recherches Hydrauliques.

Je tiens à remercier tous les auteurs et plus particulièrement M. E. van Boetzelaer, L. A. van Geldermalsen, J. K. Vrijling et J. E. Prins qui ont assuré la rédaction de cette édition supplémentaire.

P. Novak

Rédacteur en Chef du Journal de Recherches Hydrauliques

1 Introduction

Water and its environment, water and development are strongly interconnected. One of the pillars of social and economic development is rational freshwater management. This development may, however, conflict with the preservation of the natural environment.

The protection of human life and the prosperity of mankind need measures against natural catastrophes like floods and droughts. However, these measures can disturb the sensitive ecological equilibrium. So the technical capabilities of the hydraulic engineers to protect men against lack or surplus of water, and/or utilizing available water resources, may change the natural environment of both human and natural life.

An example can be given by the development of the upper Rhine. In order to master flood damages and associated diseases, a "Rhine correction" was performed in the middle of the last century, by training the river into a straight river bed, thereby increasing the bed slope by about 30%. This in turn gave rise to an erosion process that even today has not yet come to an equilibrium state. Also the natural river with channels and bars was changed into a normalized cross section, thus reducing the diversity of habitats.

The Rhine water level dropped steadily due to the erosion. Furthermore, the construction of a French shipping canal, built in the 1920's, distracted a large portion of the river discharge. As a consequence, groundwater levels dropped also severely with drastic consequences for the vegetation in the Rhine valley. The reduction of habitat damaged the resilience of the river ecology and the self purification ability of the river. In the 1970's, the groundwater problems led to the construction of so-called "Kulturwehre" (special weirs) on the river, which serve the purpose of raising the river water level even at very low discharges, and consequently to elevate and stabilize the regional groundwater table.

Thus, humanity is in a rather controversial situation. The growing population needs more constructions designed for safe living space, food and water, but will not, at the same time, tolerate the harmful effects of these constructions on the environment.

In some recent cases, in various parts of the world, hydraulic engineers, charged with a pioneering role in water resource projects, were, regretfully, confronted by environmentalists and ecologists, that denied the value of the creative activities of the hydraulic engineers (flood control, river training, drainage etc.). On the other hand, certain engineers reject any, even justified, criticism from the life sciences.

Professionals: engineers, economists and ecologists, should realize the necessity of mutual understanding and collaboration, since mankind badly needs a sustainable development. The preservation of the environment should be realized together with the economical development in a balanced compromise.

Hydraulics, hydrology and ecology are the sciences which must form the sound basis for environmental management and a sustainable development.

As far as water pollution control is concerned, a good agreement already exists. The effects of hydraulic structures in general, and the impacts of large dams in particular are the subjects of heavy debates.

A common language between hydraulic engineers, hydraulicians and ecologists is needed in order to enhance "professional" discussions, communication, joint research and concerted actions.

The role of engineers and economists is well known in the decision making process ever since the development of modern technology enables the creation of large man-made structures. The role of ecologists should become equally important. Therefore, this role must be refined and specified. If this role is neglected, it may cause delicate situations and act as a "brake" for economic developments.

Engineers, ecologists and economists must recognize their partnership and share their responsibility to society and the environment.

The practical problems to be solved, need a joint study in hydraulics and ecology since the phenomena are unseparable (e.g. the effects of vegetation on flow, the effects of flow on ecosystems). The major aims of IAHR's efforts in connection with matching hydraulics and ecology for freshwater systems are as follows:

- to promote a better understanding between hydraulicians and ecologists;
- the selection of the major problems to be solved jointly and the demonstration of successful collaboration by case-studies;
- to promote the application of systems theory for the joint treatment of basic aquatic-types (e.g. rivers, lakes, estuaries and groundwater);
- to stimulate the estimation of the uncertainty of the predicted values for both the hydraulic and ecological aspects and to ensure that these uncertainties are equally acceptable and equally treated;
- to describe flow phenomena and the interrelated ecological systems jointly, by using the basic laws of hydraulics and ecology and to select agreed numerical parameters for characterising the main conditions;
- to apply numerical hydraulic and ecological models for the prediction of changes in the aquatic environment due to a natural change in the water regime or due to the construction and/or the operation of hydraulic structures.

The International Association for Hydraulic Research recognizes the need of a forum where the representatives of the two sciences can meet and discuss problems and their solutions, potential frictions and their eliminations, targets for development and requirements for preservation. The Rijkswaterstaat of the Netherlands has long-lasting experience in joining ecology and hydraulics and the experts, who execute large water projects, will pay full considerations to ecological aspects. The concepts of water development plans in the Netherlands are fully reflecting the mutual understanding of water experts and environmentalists.

IAHR is grateful for the kind hospitality extended by Rijkswaterstaat, which facilitated to effect the IAHR aim: a forum for creating mutual understanding and good spirit and compiling the findings in a publication to be presented and disseminated at the occasion of the XXIV IAHR Biennial Congress in Madrid, 9-13 September 1991.

The need for continuation of our efforts to harmonize design of hydraulic structures and to assist in preparation of environmental impact studies for water schemes and hydraulic structures was responded by the kind invitation of the Canadian National Institute for Hydrology to host a second workshop in Saskatoon in 1992.

The results of the workshop may also help the International Conference on Water and Environment (ICWE, Dublin, January 1992) to conclude and suggest further actions for the United Nations Conference on Environment and Development (UNCED, Rio de Janeiro, June 1992). The recommendations may help to solve the problems related to freshwater resources of the world and the harmonized utilization of the freshwater resources for the benefit of the whole population of the World.

The future of mankind needs the perfect and friendly cooperation of hydraulicians and ecologists. IAHR takes care of establishing these links through its activities.

Ö. Starosolszky
Vice-president IAHR

2 Relating hydraulics and ecological processes

2.1 Introduction

Any major modification of the hydraulic system results with some retardation in a response of the ecosystem trying to adapt to the new conditions. It is difficult to imagine situations where hydraulics and ecosystems are not related. Thus, harmonizing hydraulics with ecology means to identify alternative hydraulic measures which yield simultaneously economic benefits and improvement, preservation or at least a best fit of the environmental situation. Often, these objectives are subjected to an inherent conflict and therefore harmonizing is dependent on the preference structure of the modern society, which is inclined to sustainable development.

The objective of this chapter is to develop a framework (methodology) which might assist in relating hydraulics and ecology with respect to specific goals under site and problem dependent constraints.

2.2 Systems approach

Although the concept of environmentally sound water resources planning [David (1986); Viesmann and Schilling (1986)] and the framework for appropriate institutional settings [Haines and Allee (1982); Sewell and Biswas (1986)] have been developed and proper planning tools to consider economics and ecological objectives in an integrated system are also available [Goicoechea et al. (1982), UNESCO (1987)], the matching of social and ecological needs has not been achieved yet. Analyzing various case studies (Chapter 6), the question can be raised whether improper matching might be due to:

- a lack of knowledge about the physical-biological or ecological processes;
- improper criteria and standards to evaluate environmental impacts;
- improper institutional structures in the decision making processes.

The complex problems of the sustainable development of water bodies can only be addressed by a systems approach.

Only by seeing the water-body and its environment as a system, containing numerous elements that are related to each other and the environment, the problem can be reduced to the size of the human mind.

The total river system starting in the mountain and ending in the sea, may be divided in sub-systems as mountain river-reaches, lakes, reservoirs, low land rivers, estuaries, groundwater, etc., that match, for instance, the grasp of the human analyst or the limits of institutional structures. To facilitate a multi-disciplinary approach a (sub)system can subsequently be divided into aspect-systems containing mainly the elements and the relations of the total system, that are studied by one specific scientific discipline.

The ecological aspect-system describing the biological entities and their relations with each other and the physical environment is the subject of ecology. Within this ecological aspect-system, often indicated as eco-system, a biotic and an abiotic sub-system can be discerned (Fig. 2.1). The biotic system contains the flora (phyto biotic system) and the fauna (zoo biotic system) and their mutual relations.

The abiotic system contains aspect-systems as the hydraulic system, the sediment system, the chemical system, etc.

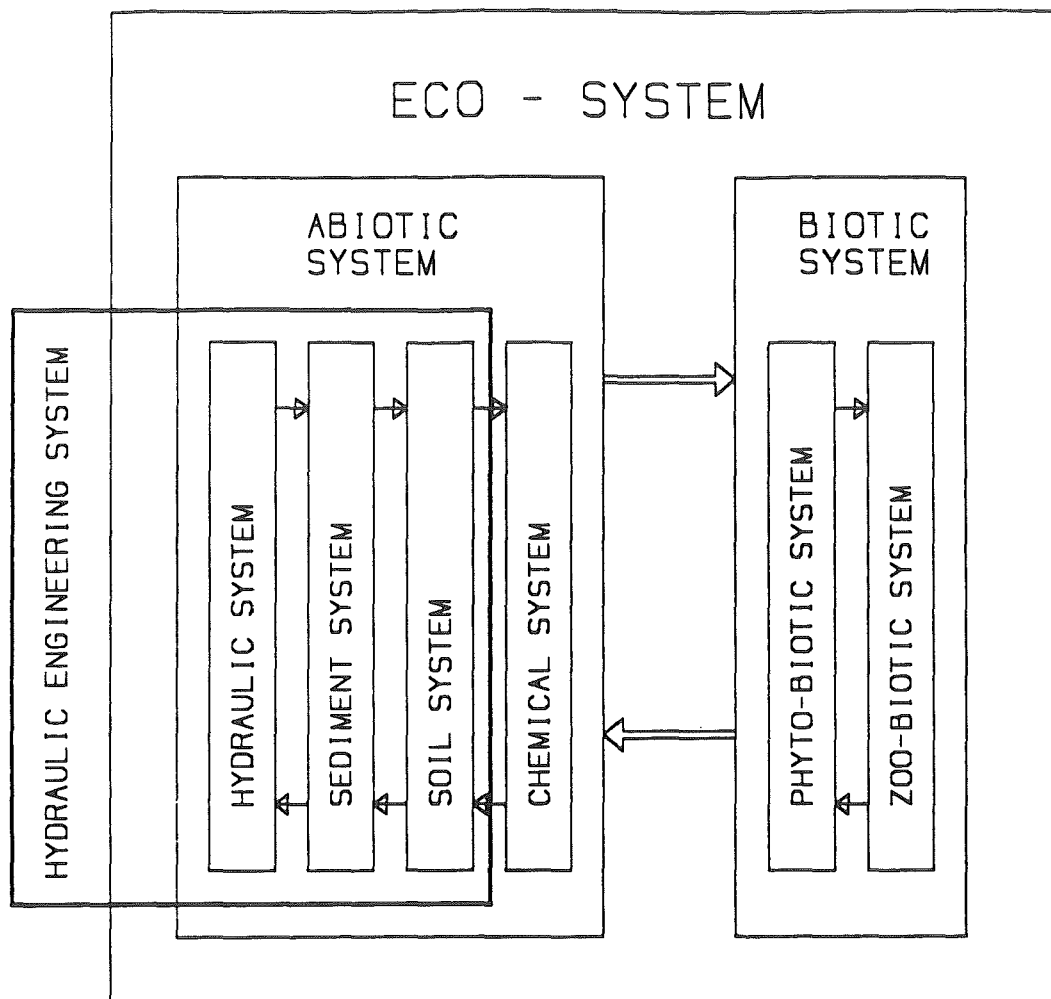


Fig. 2.1 Systems approach of ecology.

Classically, the study field of hydraulic engineers concerned with water projects is limited to a part of the abiotic system. As however any change in the abiotic system causes changes in the biotic system, the views of hydraulic engineers and ecologists should be widened. Therefore the eco-system gets special attention in this publication.

2.3 Interaction between hydraulics and ecological processes

2.3.1 Some general aspects of ecological systems

The internal processes of ecological systems contribute and culminate in a dynamic equilibrium of the system.

The main structure in an eco-system is provided by the foodchain. Although the foodchain or foodweb can be extremely complicated in various aquatic ecosystems, the main principle can be simply explained (Fig. 2.2).

The foodchain in a system starts with the input of nutrients (chemicals like phosphorus, nitrogen, silicates, carbon dioxide) and solar radiation (energy).

Algae (micro phytes) and plants (macro phytes) produce organic matter and oxygen by means of

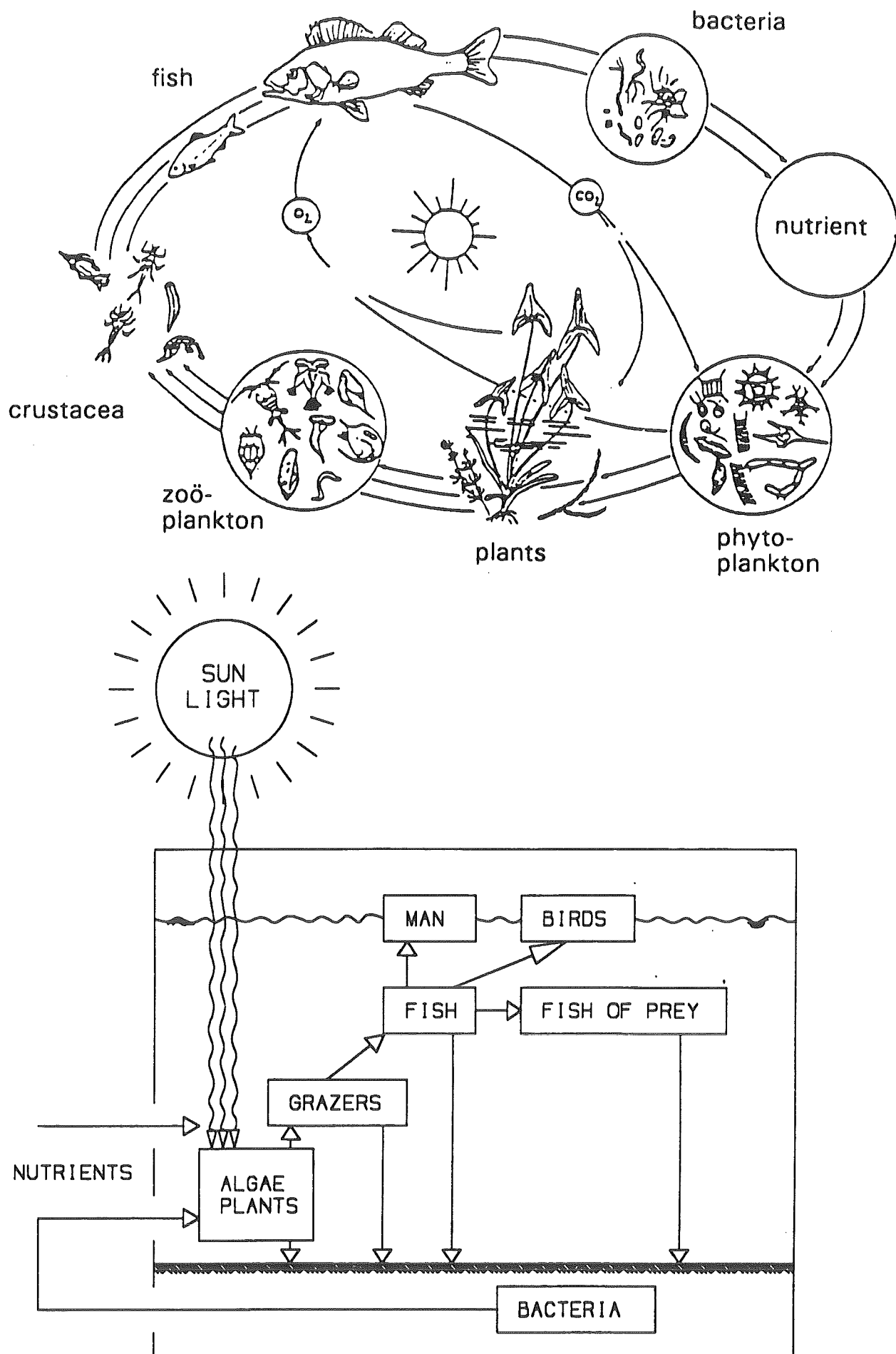


Fig. 2.2 The food chain as the structuring element of a simple eco-system; a picture and a system analysis.

photosynthesis, while consuming nutrients and using sun light. This is called the first trophic level.

The organic matter (biomass), produced by these primary producers, is grazed upon by zooplankton, small crustaceans and small fish to cover their food demand. (This group is mostly indicated as the primary consumers or the second trophic level).

The zooplankton and the other small animals are in turn consumed by larger fish species. The larger fish is preyed upon by even larger fish, birds, mammals and man (the third and higher trophic levels).

The excrements and/or dead bodies of the species in the food chain (detritus) drop to the bottom of the water system, where they are eaten by bacteria and digested into minerals that serve again as nutrients.

Thus, the nutrient cycle is closed.

Any shock in the input variables caused by the stochastic component in hydrological or meteorological variables is buffered by the ecological system, slowing down the fluxes of energy and mass by filtering, transformation, accumulation and adaptation processes. Non sustainable human impact may be described by the exploitation of resources faster than their natural reproduction or the release of waste products in greater amounts than can be integrated into the natural cycle of nutrients. Any input of non-natural (anthropo-genetic) substances puts stress on the ecological system.

How an ecological system reacts to a limited change in the input can be described among others by the *resistance concept*, [Lindemann (1942); Odum (1957)]. It focuses on internal control and redundancies buffering against disturbances. The concept of internal control, which was derived from cybernetic theory, is based on feedback mechanisms such as interaction and replacement among organisms to damp the rate of change in the affected processes. If the stress exceeds the biological capacity of one component (species) at least one functionally duplicate component is recruited to serve the systems resistance. In general, functional simplicity of an ecosystem tends to reduce the resistance [Waring (1989)].

Systems with large storage capacities show a high stability. Such systems are rather complex structures with high internal recycling rates and elaborate food webs.

Ecosystems exposed to major shocks such as big flood events, extreme winters or land slides are mostly able to recover. Some of them, such as flood plain forests or estuaries, even require disturbances to maintain their resilience. In flood plain areas, sediments and debris rich in nutrients are supplied while organic material is washed out during floods. In estuaries, a daily exchange between the sea and the brackish water takes place. *Resiliency* [De Angelis (1980)] expresses the system's capability to recover from shocks. The recovery period is rather short in cases where the energy and nutrient capture is high, while ecosystems with a high buffer capacity and high internal recycling exhibit a high resistance, but require a long recovery period.

A schematic diagram describing the recovery of a river in the flow direction from a point source of waste water is given in Fig. 2.3. Dependent on the quality and quantity of the load, the chemical and subsequently the biological parameters are changed over a long downstream section. The existence of food chains is the basis for the restoration of the original situation downstream. This process can be stimulated by the drift of species from upstream reaches and by the shape the river bed in the polluted stretch. Channelized rivers with a uniform cross section and a uniform gradient exhibit a reduced self purification capacity compared to natural rivers. One of the reasons is the increased, uniformly distributed flow velocity and a second is the uniform habitat with a reduced diversity in plants and animals.

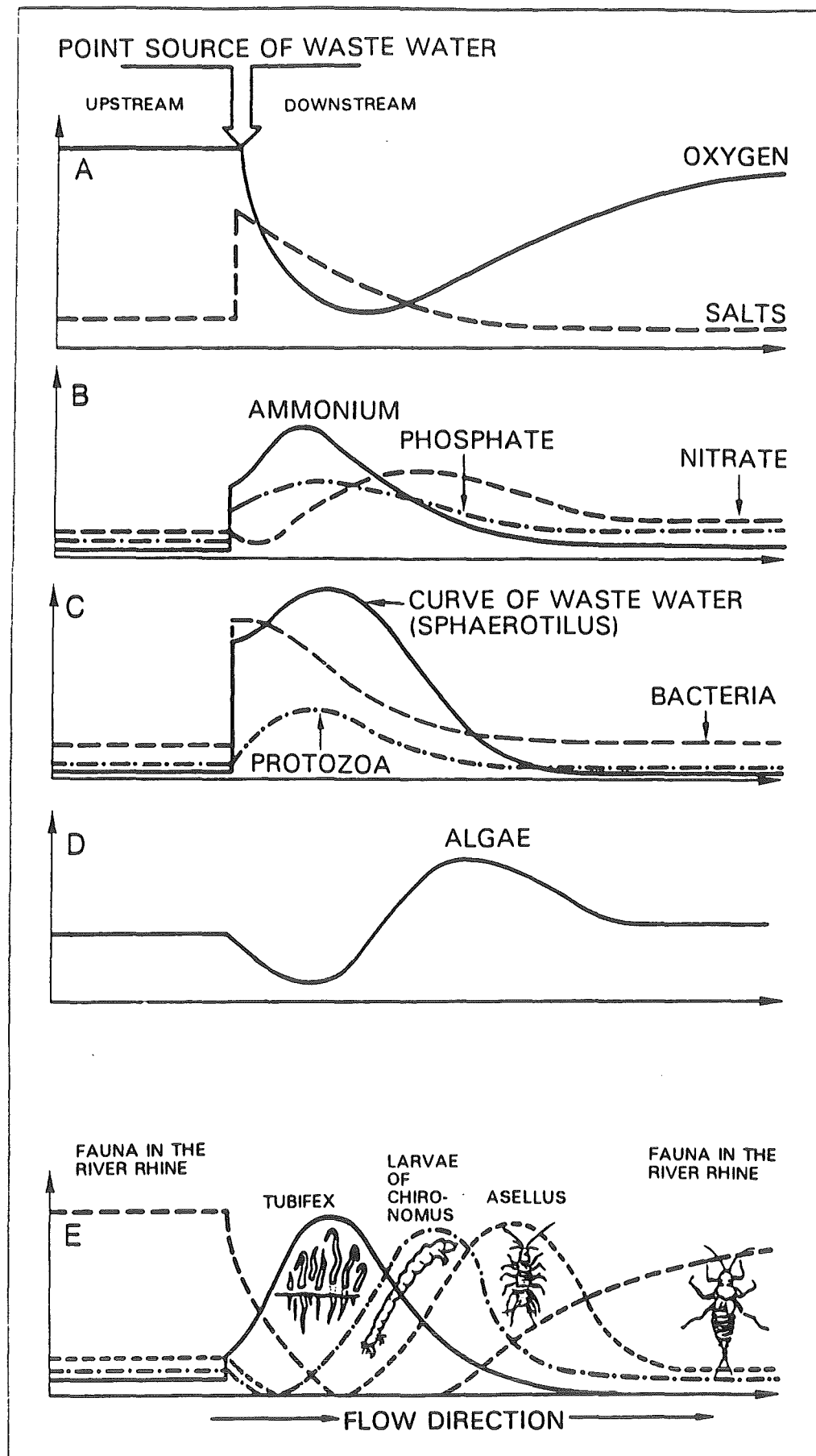


Fig. 2.3 The recovery of a river after an input of waste water.

2.3.2 *Interactions between hydraulics and ecological processes in water subsystems*

The identification of pathways connecting ecological changes with hydraulic changes constitutes the scientific basis for harmonizing hydraulics and ecology. Aquatic ecosystems [Straskraba and Gnauk (1983)] are often envisaged as systems where processes are linked by the flow of water, energy, mass and biomass transport. This concept assists in developing a holistic picture of aquatic ecosystems and provides a tool for identification of governing hydraulic variables. In other words, the change in the abiotic system drives the reaction of the respective biotic system. Some examples will be given referring to different subsystems of the total aquatic ecosystem, such as rivers, lakes, estuaries and groundwater to demonstrate the links between hydraulic conditions and the ecological aspects of the subsystem. A more detailed analysis is given in Chapter 4 of this publication.

Rivers

Rivers transport water and sediment from the catchment area to the sea.

The course and the shape of the bed of the river result from a, not perfectly understood, interaction of water and sediment in the river in the existing terrain.

The prediction of the hydraulic phenomena (flood waves, low flow) is well developed. The modelling of the erosion and sedimentation processes that drive the form of the course and the bed of the river (morphology) is less advanced.

One of the earliest successful approaches to combine chemical and hydraulic parameters of rivers is given by Streeter and Phelps (1925), which was subsequently improved by Goodman and Tucker (1971), Willis et al. (1975).

Due to human activities, the longitudinal and the transversal exchange of water, anorganic mass, energy, biomass and biotic communities in the river are disrupted [Decamps et al. (1988)].

The emission of waste water in a river was mentioned in the previous paragraph.

Levees to combat flooding separate inundation areas from the riverine ecosystem. Thus, the storage capacity, not only of water, but also of anorganic mass and biomass, is reduced. Moreover, the downstream habitats are exposed to major shocks due to a modified hydrograph and a change in biomass input. This might result in a shift of biological communities to downstream reaches. The damming of a river will cause a sharp discontinuity in the longitudinal profile. The river ecosystem will be seriously modified up- and downstream of the dam. Due to the impoundment, the flow velocity and thus the transport capacity will be reduced, sedimentation will occur, the water temperature will increase and, dependent on the depth of impoundment, stratification might occur. One of the ecosystems approaches to fluvial ecosystems, the continuum approach (Fig. 2.4), is based on the spatially changing gradient of physical conditions. According to this concept, stream order, slope, discharge, width, depth, flow velocity, sediments, temperature, and entropy gain, determine the biological organization in rivers.

In head-water rivers, the forests provide the allochthonous input, e.g. in the form of dead leaves which constitutes the major food source in the upstream section. While in the downstream region, the riverine forests filter and store biomass input between the river and the riverine terrestrial system.

In principle, stream communities adapt to the average local conditions and their seasonal fluctuation and are more physically than biologically controlled open systems. Thus, system engineers and hydraulicians have to provide a sufficient prediction of the physical environment including not only mean values of flow velocity, discharge and sediment transport, but also information

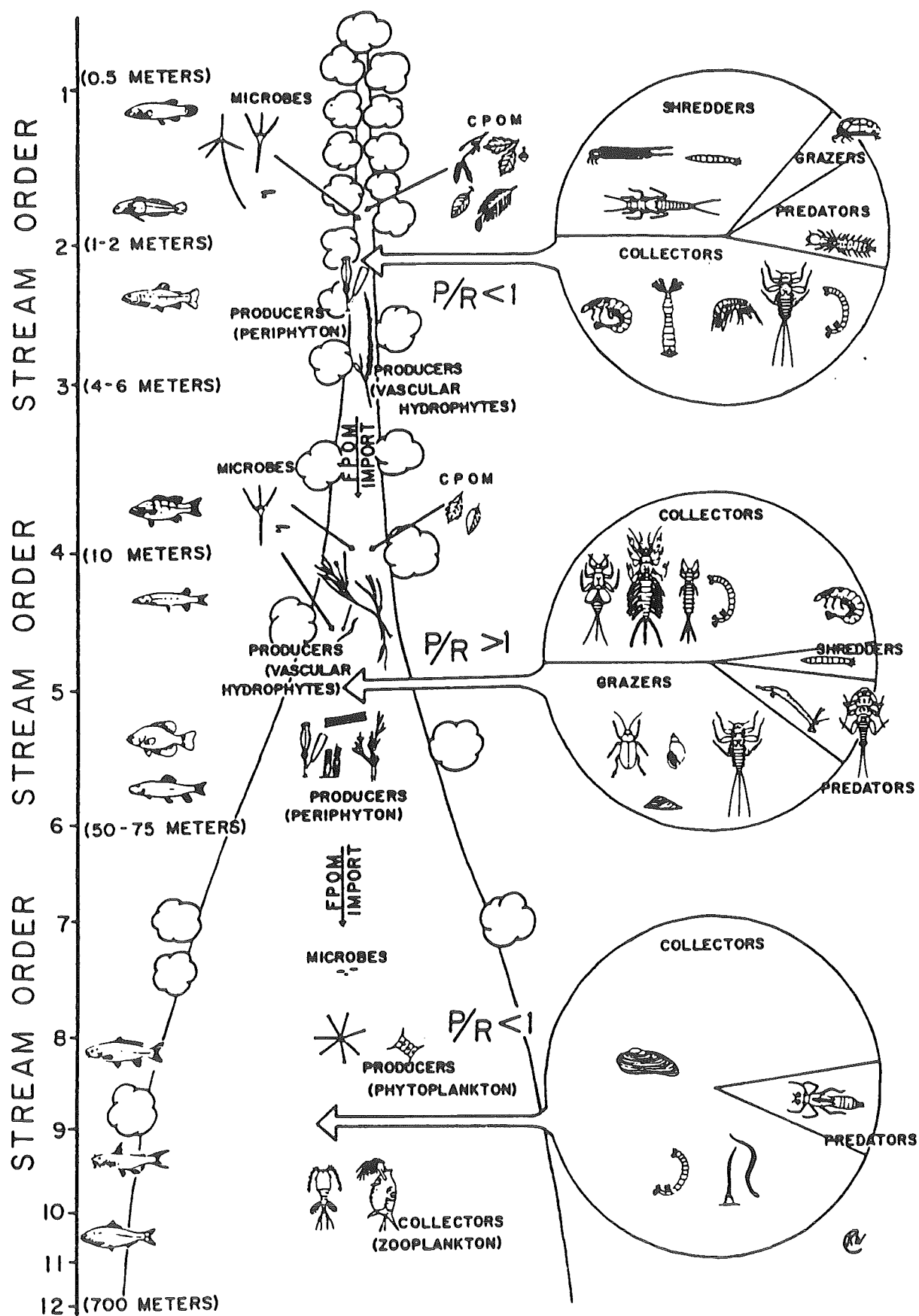


Fig. 2.4 Stream communities in the fluvial eco-system.

about the spatial and temporal fluctuations of these parameters [Statzner and Higler (1986), Newbury (1984)].

Emphasis should be given in hydraulic projects especially to fluxes and processes in the interface zones located between water and bed and water and bank.

Hydraulic measures should try to maintain interface zones within the river and between the terrestrial and aquatic ecosystem. If flood protecting measures are implemented, such as embankment dams, they should be located at some distance from the river banks to maintain riverine forests and wetlands.

Lakes

Lakes and reservoirs are freshwater bodies with an average retention time of water up to several years. The most important controlling factor in a lake ecosystem is the thermal stratification. Consequently, a large portion of the studies on lake dynamics has been devoted to the development of models for the seasonal development of the thermal stratification, e.g. Aldama et al. (1989), Henderson-Sellers and Davies (1989), Octavio et al. (1977). A warm top layer, which is heated by the sun and homogenized by the wind and other currents, floats on top of the lowest layer, which is not heated by the sun and which is too deep to be circulated directly by the wind. The transition between the two is the metalimnion or thermocline. Imberger (1985) and others have begun to produce information on newly found processes contributing to vertical and horizontal mixing in the epilimnion and metalimnion which lead to departures from this classical one-dimensional stratification model.

The abiotic effects of a hydraulic project upon a lake or a reservoir may be generalized into three categories:

- A change in the elevation of the water table or a disruption of the seasonal pattern of variation of the water table. Thereby, the water is brought into interaction with parts of the shore that it has not previously interacted with. Erosion processes will start that may have a significant impact upon the shoreline. The vegetation is damaged or destroyed, fine sediments are washed out, and nutrients are leached out.
- The internal circulation and mixing is changed by means of the introduction of some kind of structure in the lake or by means of water intakes and water discharges. Such measures may affect the horizontal and vertical mixing as well as the exchange conditions at various phase boundaries.
- An additional influx of nutrients, oxygen-consuming matter, or toxic matter and other chemical constituents, in the form of waste water. These substances are likely to spread very unevenly in the lake. Therefore, for the prediction of the effects of the project, it is absolutely necessary to have a fair idea about the circulation and mixing conditions in the lake.

Different parts of a lake have different characteristics, and, as a consequence, processes related to light, nutrients, thermal stratification, and geographic position are differentiated within the lake [Clapham (1973)]. Hence they are inhabited by distinct biological communities.

The productivity of a lake depends apart from nutrient (nitrogen and phosphorus) sources, on the amount of oxygen, and the water retention time in the lake. This has given rise to the commonly used nutrient load models (Fig. 2.5) to predict water quality. These loading relationships are all based on the mass balance between nutrient sources and losses [Vollenweider et al. (1980)]. Essentially, the size of the primary producer population grows as the loading rate increases. The link between ecology and hydraulics can be shown in a number of hydraulic phenomena which have impacts upon planktonic organisms. These impacts may be positive or negative

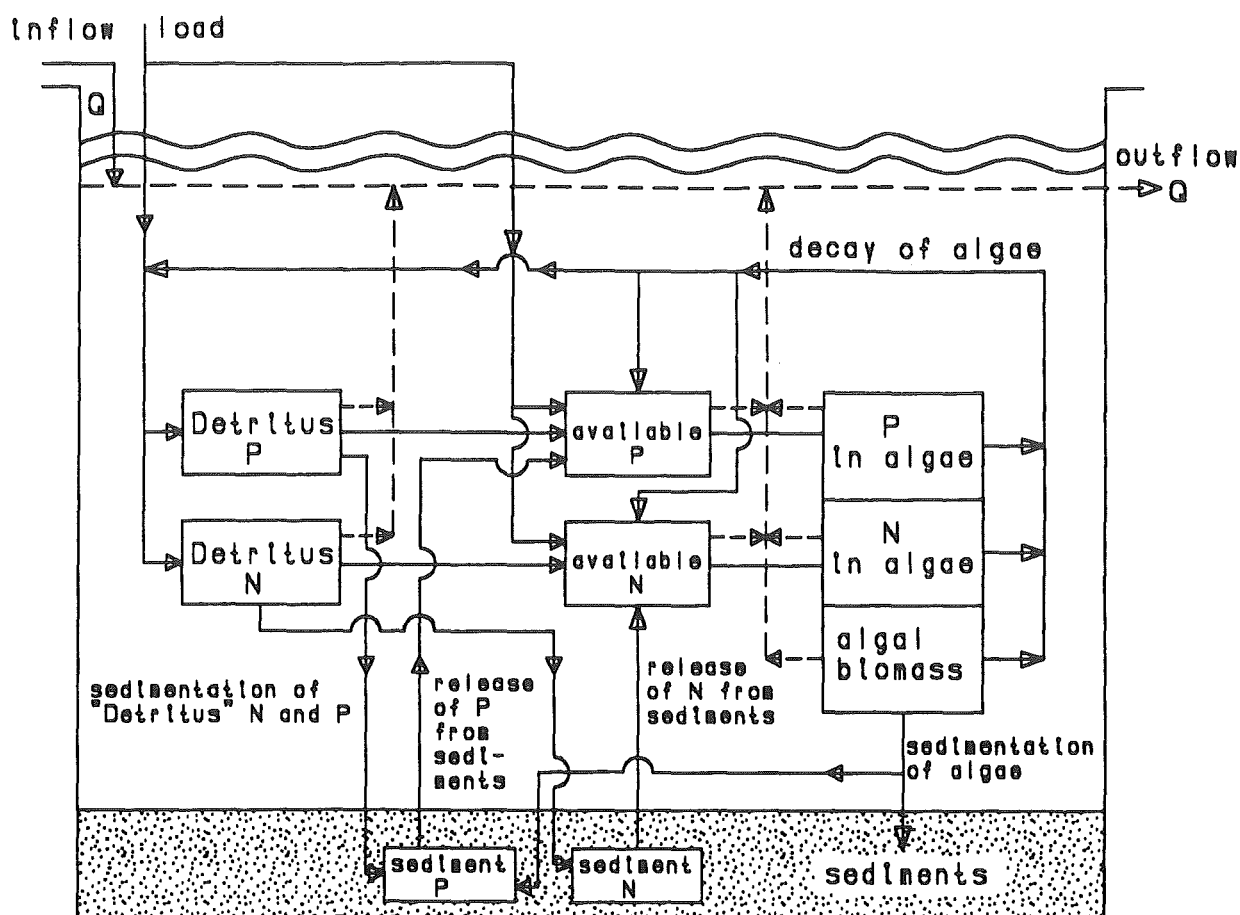


Fig. 2.5 A box diagram of the Lavsoe model (Nyholm, 1978).

depending upon a particular organism's ability to adapt to, or take advantage of the ambient situation. Examples of such phenomena are seiches, or internal waves, Langmuir cells, and diurnal mixed layers. Seiches may move organisms living at the thermocline, and who may be low-light adapted, to a higher light environment which could exceed their physiological ability to survive. Langmuir cells and diurnal mixed layers create changes in the ratio between euphotic (lighted) and mixed layer.

Changes in the hydraulic structure in lakes can lead to significant changes in the species composition and productivity of these populations which will affect higher levels of the food web. Physical changes may also directly affect higher organisms. For example, zooplankton is affected by changes in light penetration and by daily and seasonal stratification patterns. Especially in the reservoirs, the stratification pattern will be affected by sudden release or input of water. Dynamic models of the lake ecology have been developed to describe the seasonal variations in biomass production under varying nutrient loading or nutrient availability. The eutrophication models normally used are based on hydrodynamic models, ranging from a simple stirred tank models to complex box-models which account for convection and dispersion in the horizontal and/or vertical direction.

Estuaries

Estuaries provide the connecting link between the freshwater and marine environment. The estuarine morphology is the result of a strong interaction of water and sediments. The physical,

chemical and biological characteristics of estuaries are primarily controlled by the nature of the hydraulic interactions occurring between the fresh water and salt water which vary according to estuarine topography. Freshwater organisms fade out quickly and mineralize partly. River sediments are deposited. Plants and faunistic species in this region live in a nutrient rich water body, but are subjected to a continuous stress due to changing physical-chemical conditions. Consequently, by altering the hydraulic regime through measures undertaken within the estuary itself, within the river system, flowing into the estuary or within the adjacent, interacting coastal waters, man can deliberately or inadvertently alter the basic functioning of the estuarine system that is the result of interacting hydraulical, morphological, chemical and biological processes. For instance, the presence of a barrage structure will significantly modify existing water circulation patterns in the estuary. Thus, the freshwater discharge will be retained for much of the year and movement of the saline wedge up the estuary, on the flooding tide, will be restricted affecting the pattern of gravitational circulation in the lower estuary. As a result of these changes, the pattern of sediment transport, sediment deposition and suspension, dispersal of domestic and industrial effluents, and the distribution and abundance of aquatic biota will be affected to greater or lesser degree (Fig. 2.6).

Typically estuaries have a complex, highly dynamic structure which fluctuates over short, medium and long term time scales. Consequently, they exhibit great spatial and temporal variations in abiotic and biotic processes. The scales of hydraulic processes and ecological processes, however, can differ significantly from one another. Thus, hydraulic process models

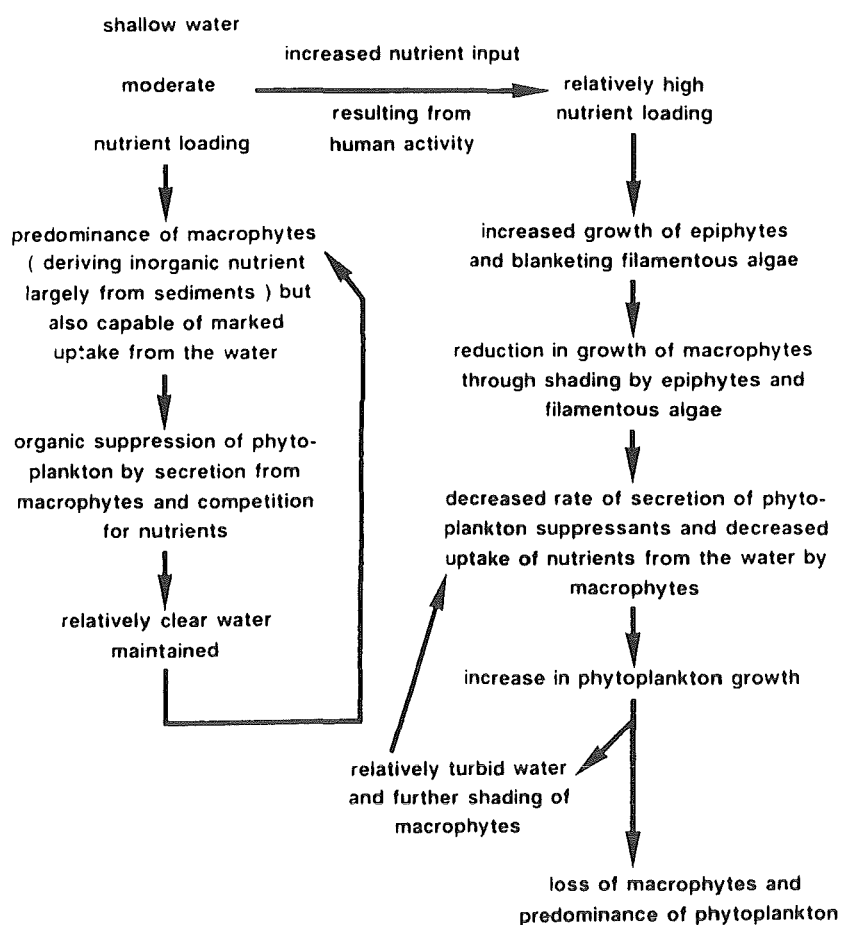


Fig. 2.6 Hypothesis to account for decline in macrophyte populations when estuaries are fertilised.

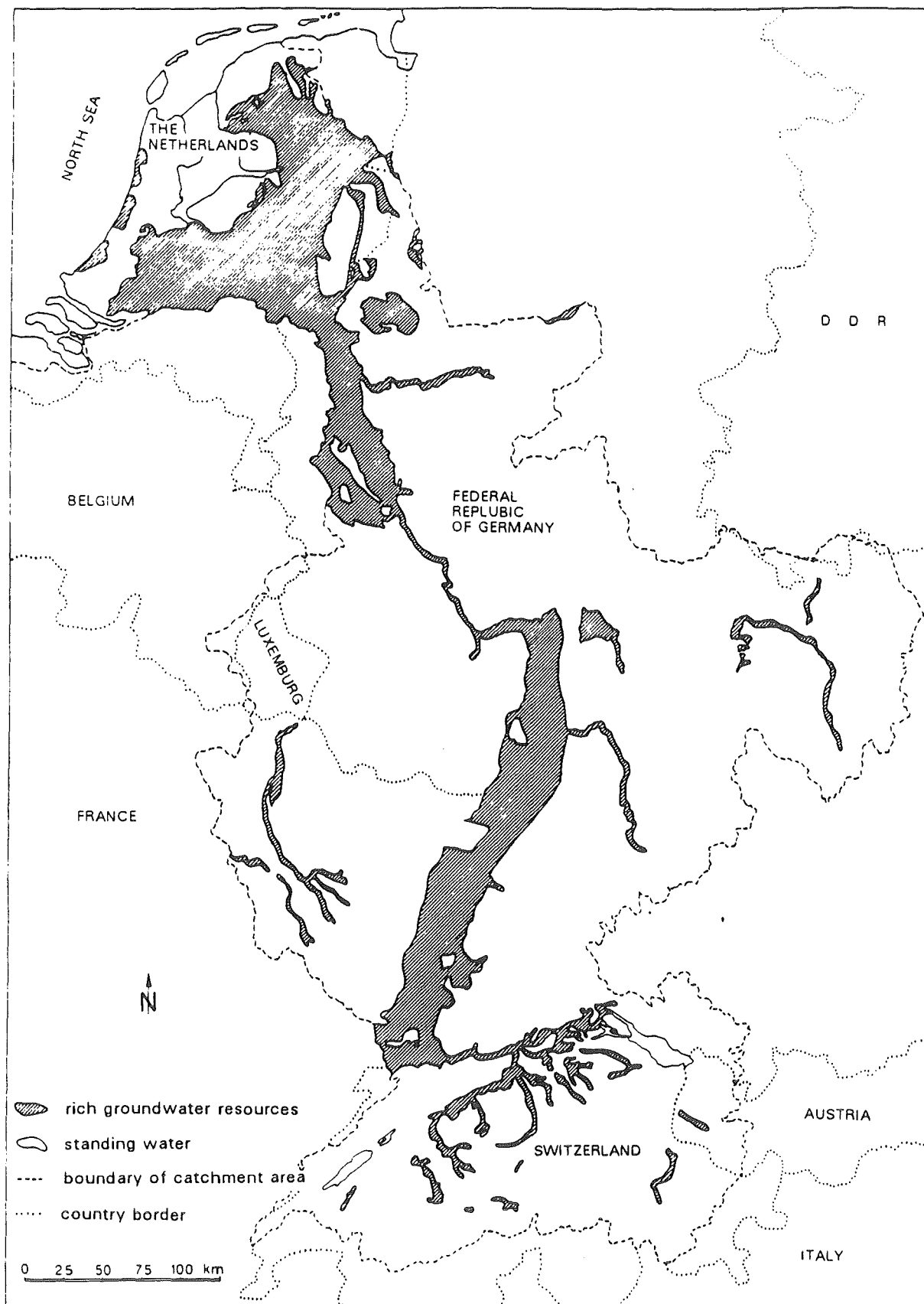


Fig. 2.7 Groundwater bodies of the Rhine basin.

typically operate on small space and time scales, e.g. the simulation of sediment deposition and re-suspension processes in an estuary requires consideration of events occurring over time steps of a few minutes (to within a given tidal cycle) and, because spatial variation is significant, high resolution is required and, consequently, the space scale is also restricted. In contrast, both space and time scales for ecosystem processes tend to be much longer as most important ecological processes are generally considered in terms of seasonal variations.

Indeed, apart from improving our overall knowledge and understanding of hydraulic and ecological processes through appropriate research studies, the most pressing requirement for facilitating the linkage of hydraulics and ecology in estuarine (and other aquatic) systems is the need to reconcile and couple these disparate spatial and temporal time scale. For estuarine systems this can be achieved by averaging the output of hydraulic models, in both space and time, to give medium to long term values which can then be used to drive appropriate ecosystem models.

Groundwater

Large ground-water basins are located in the alluvial sediments of river networks (Fig. 2.7) and constitute a major water resource to serve municipal and industrial demands. The ground-water bodies are strongly connected with the surface water system which should be considered in analyzing ecological processes in the subterranean medium.

There does not exist just one subterranean medium, but differentiated subterranean media. One has mainly to distinguish porous, fractured, and karstified media on one hand, saturated and unsaturated media on the other hand. These distinctions stand primarily on purely physical criteria and they are familiar to the hydraulician who applies typically the basic Navier and Stokes equations to the flow in these media.

The recognition of subterranean media as ecosystems is rather new and far from being entirely reached. It has been difficult to conceive an ecosystem without light, and, therefore, without photosynthesis, founded on autotrophic bacteria production and/or on fossil autochthonous or imported organic matter. In fact living beings have been observed everywhere in subterranean media from worms in soils to highly adapted insects, crustaceans, mollusca and fishes in caves and galleries. Bacteria are found even in the most remote sediments and ground-water bodies. Bacteria are the significant form of life in ground-water as far as the increase in geothermal heat with depth allows bacterial life. We still are in an early descriptive stage of these bacterial ecosystems. But it is already known that micro-organisms cause many important chemical effects. The ground-water system also affects the water-dependent surface ecosystem. The interaction between plant patterns and the subsurface water body has been investigated by Barendregt and Nieuwenhuis (1991). The regional hydrology in a dune area constitutes boundary conditions for local hydrological subsystems which are ecologically dominant. These ecological relationships indicate the importance of ground-water flow for the aquatic ecosystem and provide also a basis for sustainable ground-water management.

3 Involvement of ecology in the decision process

3.1 Introduction

Human needs and economic considerations are generally the driving forces behind the planning and decision process, that results in the undertaking of projects to limit the damage caused by water or to use water effectively. Schemes for flood protection, agricultural water supply, navigation, hydropower etc. are clear examples.

However in the last decades it was realised that these types of projects could produce a range of undesirable environmental effects, if insufficient attention was paid to a multitude of aspects beside the classical hydraulic engineering approach.

Sediment problems, pollution or water quality problems, the decline of fishery, the loss of unique landscapes are some of the adverse effects, that may be brought about by thoughtlessly executed hydraulic projects.

To improve this situation, it should be realised that in fact the decision process starts at the first moment that the societal need is felt to change a water body. Traditionally this planning and decision process will lead finally to a hydraulic engineering measure or the construction of a hydraulic structure.

One of the causes for this limited approach may be caused by the delegation of the task to formulate solutions for the societal need to professional hydraulicians and civil engineers. The

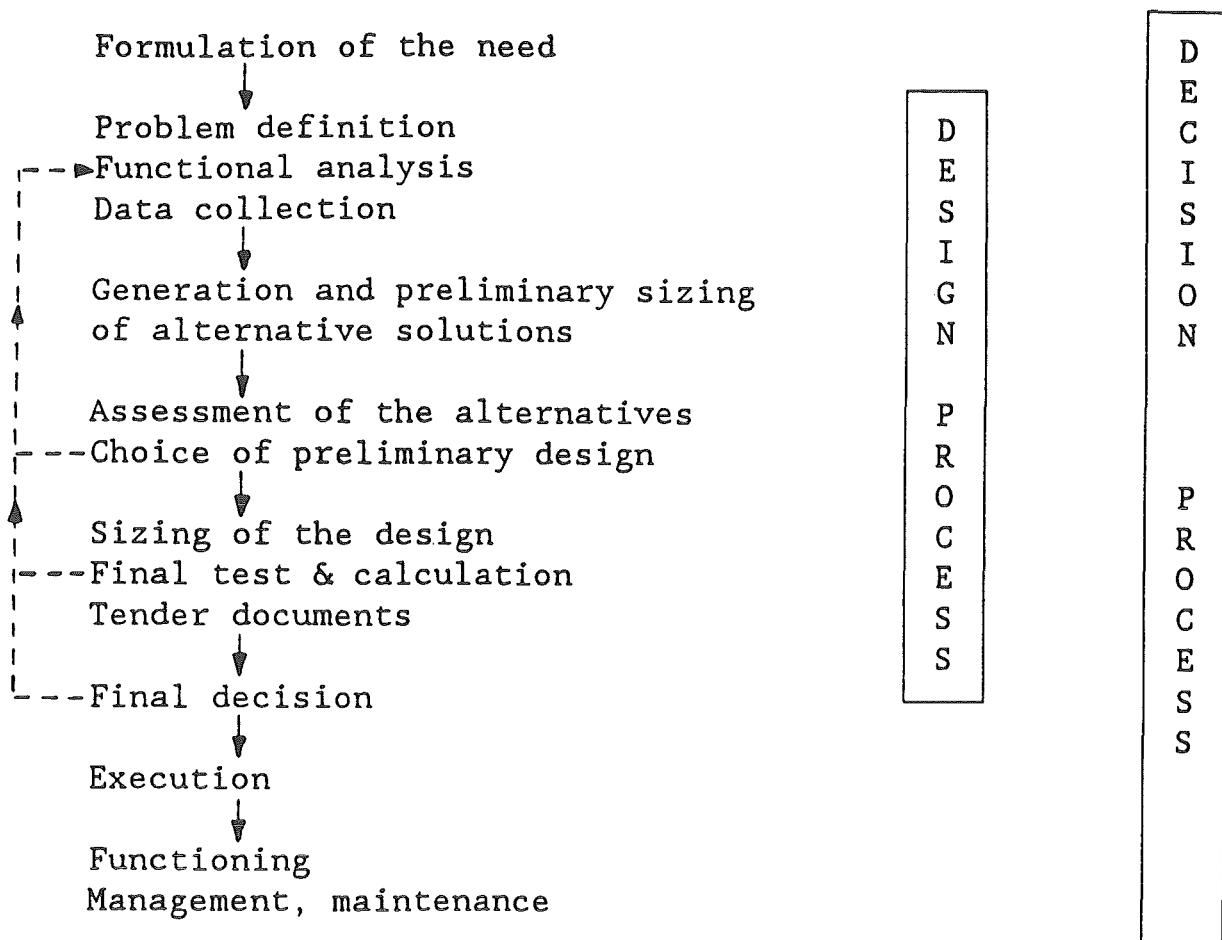


Fig. 3.1 The design and decision process.

performance of this task by these professionals, in interaction with society, is indicated here as the design process. Until very recently these professionals tended to reduce the problem to the hydraulic and techno-economic aspects before design solutions could be proposed.

Experience has shown, that the quality of the design process, that develops in reaction to the perceived need, is decisive for the quality of the decision process and consequently of the final decision.

From Fig. 3.1 it is clear that the design process, as a sub-process of the societal decision process, starts with the problem definition. If the designers treat the design as a techno-economic solution for the societal need, the decision process is in many cases bound to be halted in the final decision stage by politicians or democratic action, because the ecological aspects of the problem got insufficient attention.

The halting of the final part of the Dutch Delta flood protection scheme, the damming of the Eastern Scheldt estuary, by environmental pressure groups is an example.

The Eastern Scheldt storm surge barrier, that combined flood protection and the preservation of the estuarine ecology, was the final outcome of the societal decision process [Knoester, e.a. (1983)].

Another example refers to an Austrian hydropower project. After a number of hydropower development projects had been implemented successfully, a similar project failed due to lack of agreement on the importance of social welfare criteria, lack of guidelines for the environmental impact study and insufficient public involvement in the decision process [Bleed e.a. (1990)].

3.2 The design process

A successful development of the societal decision process requires a widening of the design process.

During problem definition and functional analysis not only the primary function that will satisfy the need but also the secondary functions and the side effects must be identified.

In a modern context it could be stated that the ultimate goal of every engineering project to change natural water bodies concerns the protection of the environment, comprising the living system of air, water, soil, flora and fauna with man as the top-component.

And in some cases the emphasis on sustainable development and the scarcity enhanced value of ecological systems will lead to civil engineering projects where the protection or the restoration of the environment is the primary goal. In Holland projects to restore riverine forests, that were lost due to water transport and flood protection schemes in the 19th century, are on the drawing board (Chapter 4).

A limited view on the societal need in the problem definition and consequent formative stages will eventually limit the evoked set of alternative solutions. Thus, the set of proposed design solutions will most likely not contain alternatives that comply with a sustainable development of natural resources.

A multi-disciplinary approach is necessary to define the relevant aspect systems, like the hydraulic system, the chemical system, the biological system, the ecological system, the technical system, the economic system and their mutual relations with sufficient clarity (Fig. 2.1).

This multi-disciplinary systems approach should guarantee the correct and sufficiently accurate prediction of the secondary or side effects of the alternative solutions besides the estimation of the techno-economic effect. One should think of water quality, groundwater storage, ecological effects, diversity of species, recreational opportunities, etc.

To predict and judge the changes in these factors in a reliable way, the present and preferably also the historical state of the water body has to be monitored and recorded from the initial phase of the project. These data can be used to validate insights gained during the design.

The basis of the choice between the alternative solutions must be formed by the societal weight of all costs and benefits, including long term sustainability.

The multi-criteria analysis (MCA) methods are schematisations of this societal weighing process. Along the vertical axis of the MCA matrix the primary and secondary effects are listed and horizontally the proposed alternative solutions are mentioned.

As the matrix shows, the environmental impact study, that is now obligatory in many countries, should form an integral and not a separate part of the design and decision process. This is necessary to guarantee sufficient attention for all aspects of the valuation during the design, the realisation and the subsequent operation of the project.

Table: Matrix for the weighing of the societal costs and benefits

	W	A ₁	A ₂	A _n
economic cost/benefit	x	.	.	.
safety	x	.	.	.
environment				
geomorphology	x	.	.	.
water quality	x	.	.	.
groundwater	x	.	.	.
flora	x	.	.	.
fauna	x	.	.	.
recreation				
hiking	x	.	.	.
swimming	x	.	.	.
boating	x	.	.	.
etc.				

It is clear that the original task of the hydraulic engineer, the calculation of the techno-economic effect of the solutions (hydro-power output, navigable water depth, storage), has expanded, as predictions of water behaviour relevant to ecological, recreational and other questions must be made.

Also the consequences of failure of, for instance, a dam for people and investment down stream may have to be assessed, because the safety of technical systems (dams, nuclear reactors, chemical plants, etc.) is a major public concern in the present era. The probabilistic analysis of extreme events like dam bursts, flood waves, etc. will be a relatively new terrain.

The risk of failure to reach the planned ecological equilibria should be analysed with the same probabilistic techniques.

3.3 The decision process

When the effects of the various alternatives have been estimated, they have to be transformed to one value scale and aggregated after an appropriate weight has been attached. The Multi Criteria Decision Methods (MCDM) provide many formal and mathematical rigorous ways to perform this task [Duckstein e.a. (1989)].

The use of these methods is aggravated by the uncertainty that is attached to the variables themselves to the impact functions and the sometimes relatively imprecise criteria that have to be met.

The application of probabilistic or fuzzy methods can be of great help to the informed and educated designer to select proper alternatives under uncertainty. However the blind use of these methods may lead the decision makers astray, unless the results are clearly explained and presented.

The best approach may be to identify the relevant democratic decision making bodies and the various interest groups like e.g. fishing shipping, tourist industries and environmental pressure groups. And subsequently to involve representatives of these various interest groups from the initial stages of the design process in the decision process.

This early involvement appears essential as already in the problem formulation stage and during the generation of alternatives, the convergent process of societal decision making takes its form. In this early stage favorite solutions of special interest groups should be taken into account and the list of criteria could be agreed upon.

It is felt that the formal and mathematical rigorous MCDM is needed to analyse and to organize the many valued decision process in a proper way. The convergence of the decision process to an optimal solution is however a political responsibility, that cannot be carried by engineers or decision analysts.

If the decision processes proceed and projects are not halted, the history in Holland shows that nature is a powerful and flexible ally in the process of preserving and even creating ecological values, not withstanding our present lack of knowledge of the biotic system.

For instance on a "bad" and low lying part of the Flevo-polder in lake IJsselmeer the magnificent wetland Oostvaardersplassen developed spontaneously. Today it is managed in a scientific way to maximize the ecological diversity.

From this and other experiences it seems that the matching of ecology and hydraulics has a great future.

When the interaction of water and the environment is quantitatively understood the knowledge will be used to preserve and enrich the existing environment and to create new ecological systems. The latter in some cases to replace systems that were lost to techno-economic progress and in other cases just to increase human welfare.

4 The sub-systems

4.1 Rivers

4.1.1 Abiotic characteristics

Considered at large spatial scale level geology, climate and geomorphology are the main determining factors for the presence of species in, and the appearance of, fluvial ecosystems [Van Vierssen and Wind (1990)]. In the longitudinal direction of the river we can distinguish the upper course (head waters), the middle course and the lower course (Fig. 4.1).

The upper course is characterized by erosion and vertical incisions. The bed material consists of rock and stones. The head waters are relatively small streams with high flow velocities. The middle course can have braided and meandering sections. Whether a river is braiding or meandering depends on the river slope, the bed material and the bankfull discharge [Struiksmā and Klaassen (1988)]. Braiding channels usually have gravel beds and meandering channels sand beds. In the lower course a delta can be formed by sedimentation of silt. Near the mouth the river flow will be affected by the tides at sea. We limit ourselves to rivers without tidal influence. The hydrological time scales vary also from upper course to lower course. In mountainous

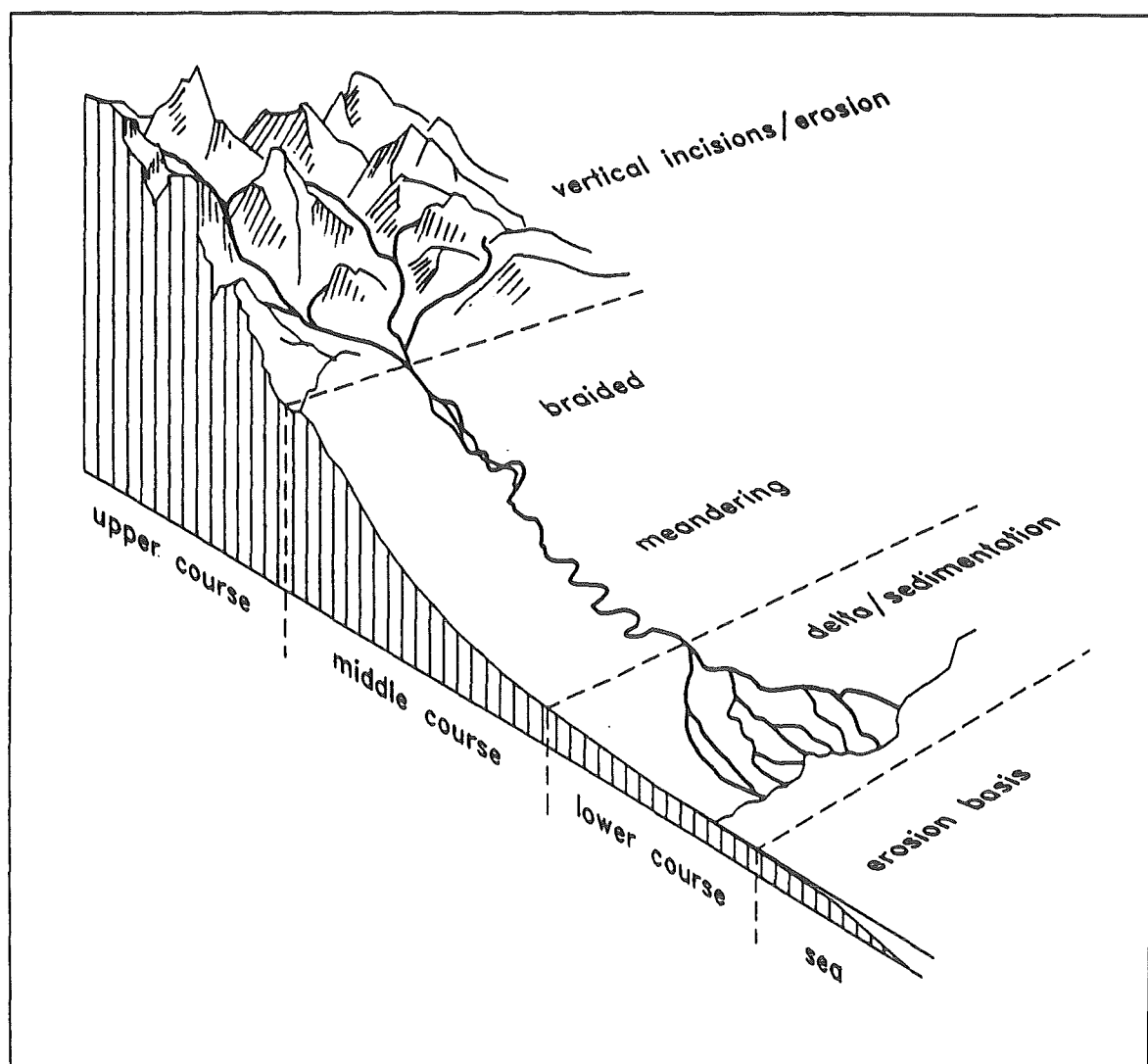


Fig. 4.1 Idealized longitudinal river profile (after De Vries, 1985).

regions the rivers react very quickly on changes in rainfall, which is the reason why the flood waves are rather flashy (flood-wave periods in the order of magnitude of hours) and the by groundwater flow determined base discharge rather low. In low-land rivers the flows do not react that fast (flood-wave periods in the order of days) and the base flow and peak-discharges are larger than in the upper courses. Besides, every hydrological variable has a seasonal component. The time scales of geomorphological processes (erosion and sedimentation) are much larger than the hydrological ones (periods determined by year-units). The morphological time scales depend on the spatial scale level of analysis. Roughly, three spatial scale levels can be distinguished:

<i>spatial scale</i>	<i>morphological time scale</i>
river basin (100–1000 km)	geological time scales (centuries to millions of years)
river branch (10–100 km)	10 to 100 years
local (1–10 km)	0.1 to 10 years

4.1.2 *Biotic characteristics*

Considering abiotic characteristics of the fluvial ecosystem it can be stated that these abiotic factors determine to a large extent the biotic components of the ecosystem. In the upper course of the river the riparian vegetation strongly affects the biological communities in the stream. The rivers which are rather small and steep are shaded by riverine forests. Due to low energy input from the sun the productivity of biomass is low while the biomass input (detritus) from the riparian forests is high. The biotic community is dominated by shredders and collectors. Grazers using primarily the biomass production of algae at various surfaces are of minor importance in the ecological energy dissipation process.

Downstream, in the middle course of the rivers, the biomass and energy output from upstream are used while the riparian detritus input is decreasing. Due to the increased solar energy input the primary productivity increases and surmounts often the community respiration. Also, the partly processed input from upstream regions is either already mineralized, or at least transformed into fine particulate organic matter. The biotic community is now dominated by grazers and collectors filtering the fine-grained particles from the water. Because of the solar energy input the daily and seasonal fluctuation of the water temperature is increased, which is also reflected in an increased biological diversity.

Going further downstream a gradual tendency towards heterotrophic conditions is observed [Fisher (1977)]. The high input of fine-grained organic matter and sediments from upstream causes turbidity which reduces the solar energy input. The biological community is dominated by grazers. Due to the decreased variation in temperature a well-adapted community with a smaller diversity is established.

4.1.3 *Human impact on river systems*

The characteristics described before are valid for natural rivers without human intervention. Human impact on rivers can be divided into two categories:

- impacts due to pollution of water and sediments;

- impacts due to river engineering works (dams, weirs, channel straightening, embankments, bank protection, river training works, etc.).

In natural streams the chemical composition of the water is determined by the geology of the catchment area and by biological processes. Pollution of the water by toxic chemicals and nutrients decreases the environmental quality and hence the health of the fluvial ecosystems. The impacts of water and sediment pollution on flora and fauna have not been investigated thoroughly yet. Current ecotoxicologic research is focussed on species in the water rather than on the functioning of entire ecosystems. The deterioration of the water quality of large rivers has a bad impact on the diversity of macrofauna and on fish production, but it is not the only cause. Due to river engineering works the diversity of habitats in both the main channel and the floodplain is usually strongly reduced [Brookes (1988)]. The migration possibilities for organisms in the longitudinal direction of the river have often been blocked by the building of dams, weirs and shipping locks.

The two types of human impact have dramatically modified the look and the functioning of the large river systems in Europe and America. That is why in recent years more and more river restoration schemes are being carried out or are subject of study. However, cosmetic landscaping, such as tree planting, without appropriate management of the hydrological and geomorphological processes, will not lead to sustained river restoration. Landscaping and forest management must be integrated with policies for flow regulation and for maintaining geomorphological and hydro-chemical processes if naturally dynamic and diverse river corridors are to be restored on a sustainable basis [Petts (1990)].

In the Netherlands the desire to enhance the nature function of the large rivers has also been gaining more and more attention recently. De Bruin et al. (1987) have proposed a number of measures to live up to this desire. Several of those measures have been adopted by the government of the Netherlands in the Third National Water Management Plan (1989). As a result, nature restoration schemes are being carried out in the floodplains of the Rivers Rhine, Meuse and IJssel. In this respect two important questions arise, namely:

1. How should we landscape the floodplains so as to create optimum conditions for sound riverine ecosystems?
2. What are the effects of the nature restoration schemes on the fluvial system and its other users (navigation, flood protection, etc.)?

In order to be able to answer these questions we need to link mathematical models for river hydraulics and morphology and ecological models.

4.1.4 *Matching hydraulics and ecology*

As an important example one can see that in the cross-sectional direction the ecotones, that form the dynamic land-water boundaries, are dominant features of rivers. Documentary evidence indicates that the corridors of most large alluvial rivers of the northern mid-latitudes were once forested [Petts (1990)]. Along large European rivers the forested river corridors were up to about 10 km wide. Typically, such alluvial forests display a general lateral zonation, reflecting the transition from aquatic to terrestrial environments. Topography is very important for the structure of the riparian forests. Slight differences affect the duration of inundation and waterlogging as well as vegetation species composition and distribution. Inundation of the floodplains is important for maintaining soil moisture levels, transporting sediments, carrying a nutrient subsidy, imparting hydraulic stresses and dispersing seeds. The forested and wetland ecotones

along natural rivers clearly have a major impact on the hydrology, water quality, primary stream productivity, channel morphology and habitat diversity. They also have exceptional value for wildlife conservation and are important for recreation and amenity.

Mathematical river models describe the main hydraulic and morphological fluvial processes and can be used to predict future developments of a river. They have proven their power and are widely used in the field of river engineering.

A selection of models, which can be useful for ecology, is mentioned here. Each model has its own spatial and temporal scales and level of detail. The accuracy of the models strongly depends on the availability of data for calibration and verification.

- The *one-dimensional models for river hydraulics* can be sub-divided in 1-D single channel river models, and 1-D network of river branched modelling, e.g. a braided section.

These models are based on the time-dependent St-Venant equations which describe the water movement. The variables have been averaged over the cross section of the river.

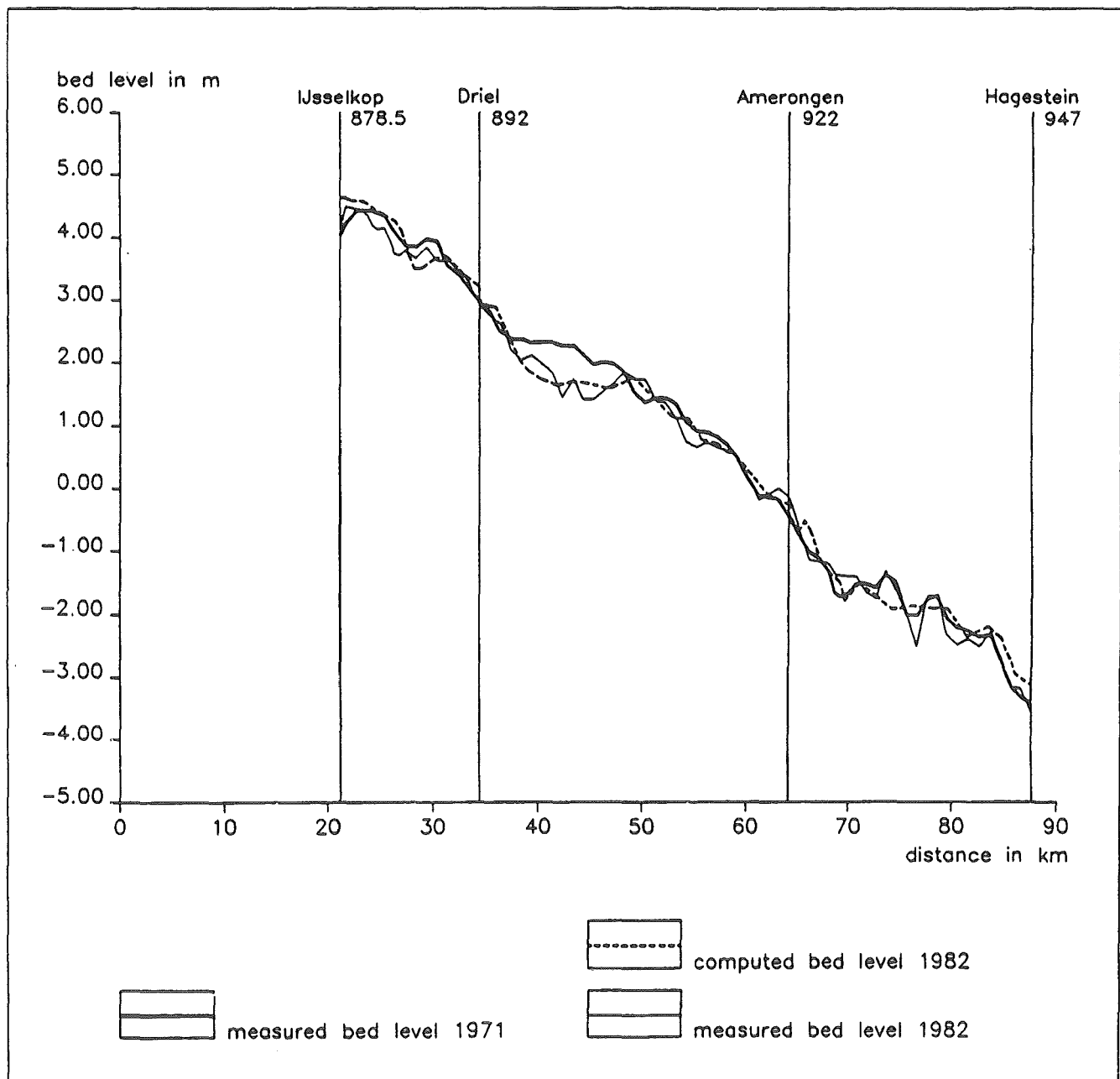


Fig. 4.2 Verification of model results of a one-dimensional morphological computation for the lower Rhine (Vermeer, 1989).

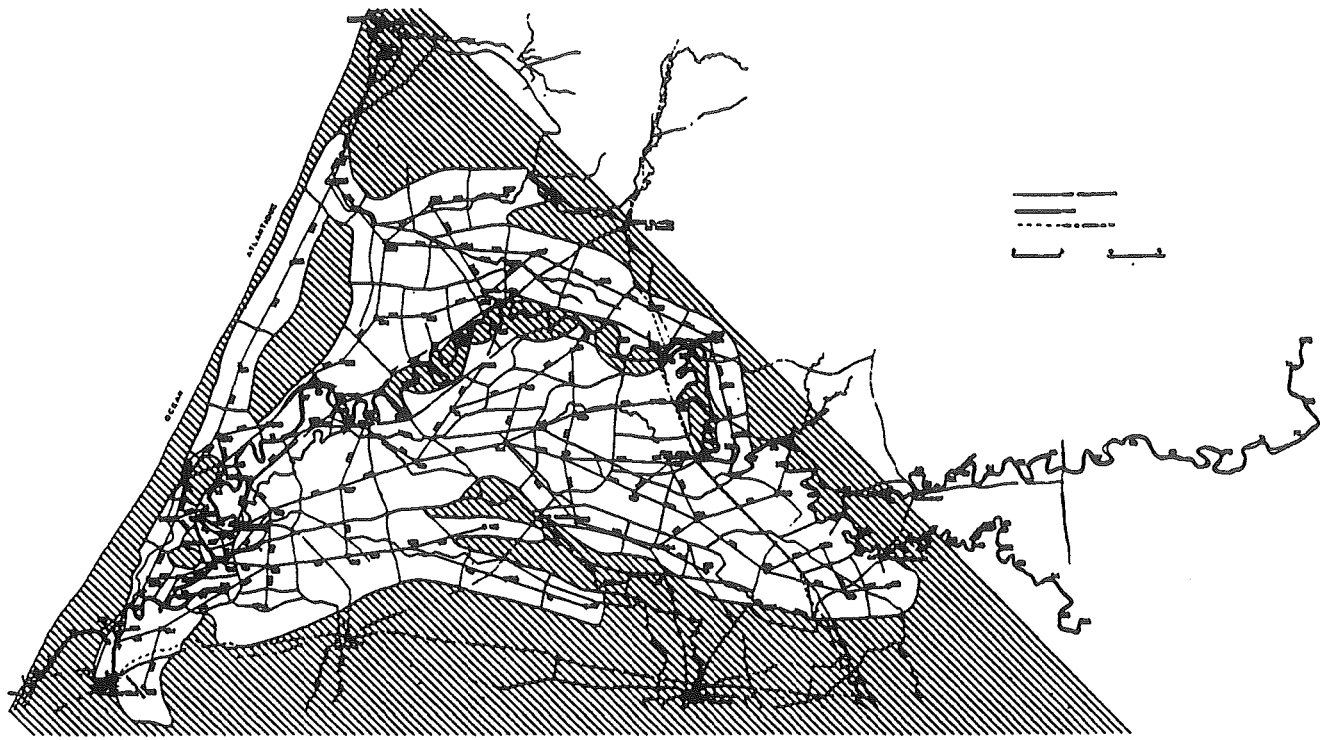


Fig. 4.3 Schematization Rharb plain, Morocco.

For morphological computations the continuity equation for sediment and a sediment transport formula must be added. The length of the modelled rivers may vary in the order of magnitude from 10^4 m to 10^6 m, and the space step may vary in the order of magnitude from 10^1 m to 10^3 m. For morphological computations the time step may be in the order of magnitude of days to months and for flood computations of minutes to days (Fig. 4.2 and 4.3).

- The *two-dimensional (horizontal) models (2-DH) for river hydraulics* are based on the two-dimensional depth-averaged momentum and continuity equations for river flows. These models can give far more details than 1-D models. They are often used for quasi-steady flow conditions and relatively short river branches (10^3 m to 10^4 m), because of computation costs (Fig. 4.4).
- The *two-dimensional (horizontal) models (2-DH) for river morphology* can be divided into two classes, namely models with fixed river banks and models with erodible banks. The first type of models is used to compute detailed bed topography in the main channel of a river (Fig. 4.5). A quasi-steady approach is followed, being an interaction between a steady water motion and a non-steady bed evolution (time step of the order of magnitude of days). This type of models is used for river branches of about 10^3 m to 10^4 m (computation costs). The second type of models is used to simulate the meandering process of a river (Fig. 4.6). Therefore, a bank erosion formula has to be included.
- The *two-dimensional (vertical) models (2-DV) for hydraulics and morphology* are applied when flow velocities or sediment concentrations in vertical direction are important. The application is, for instance, in the vicinity of hydraulic structures, dredged trenches (Fig. 4.7) or for the computation of sediment deposition in flood plains (length scale 10 m to 10^3 m).



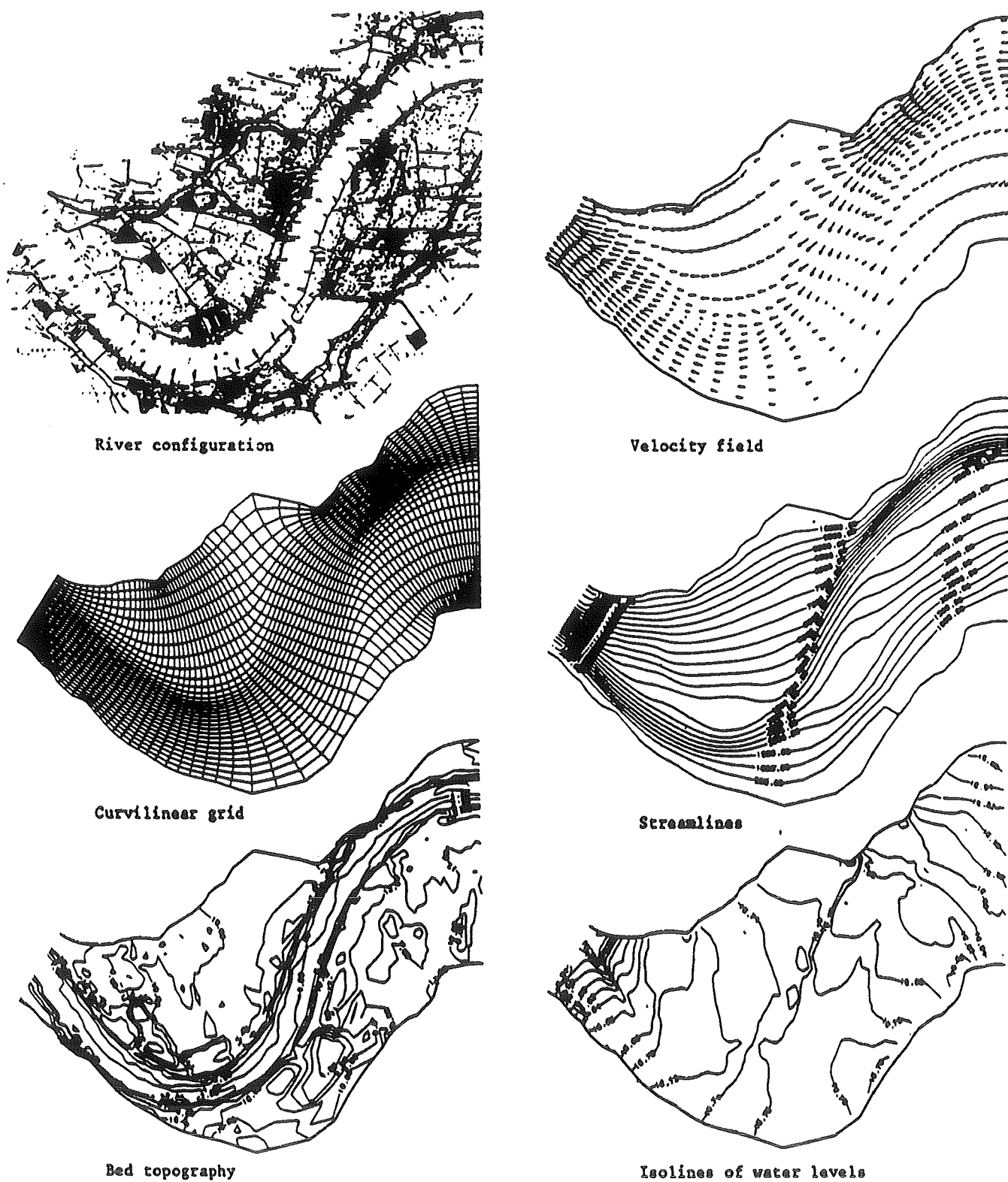


Fig. 4.4 Results of a two-dimensional hydraulic model for the River Waal upstream of Nijmegen (Wijbenga, 1985).

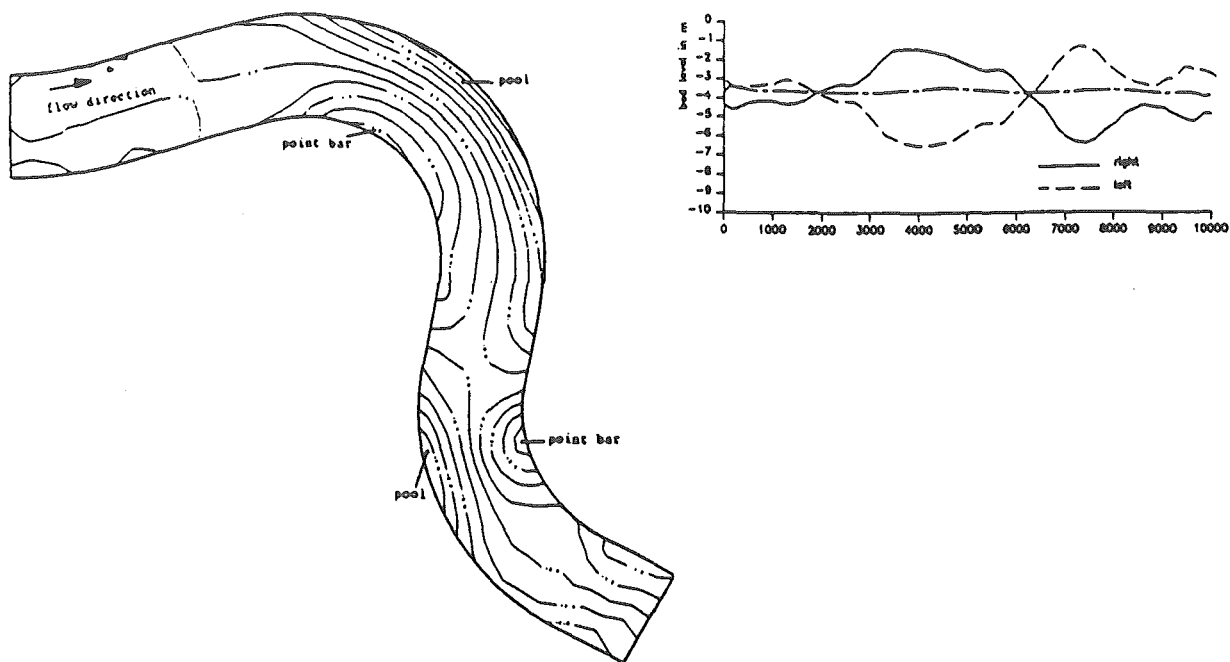


Fig. 4.5 Two-dimensional morphological computation for the River Waal near St. Andries in the Netherlands (RIVCOM model).

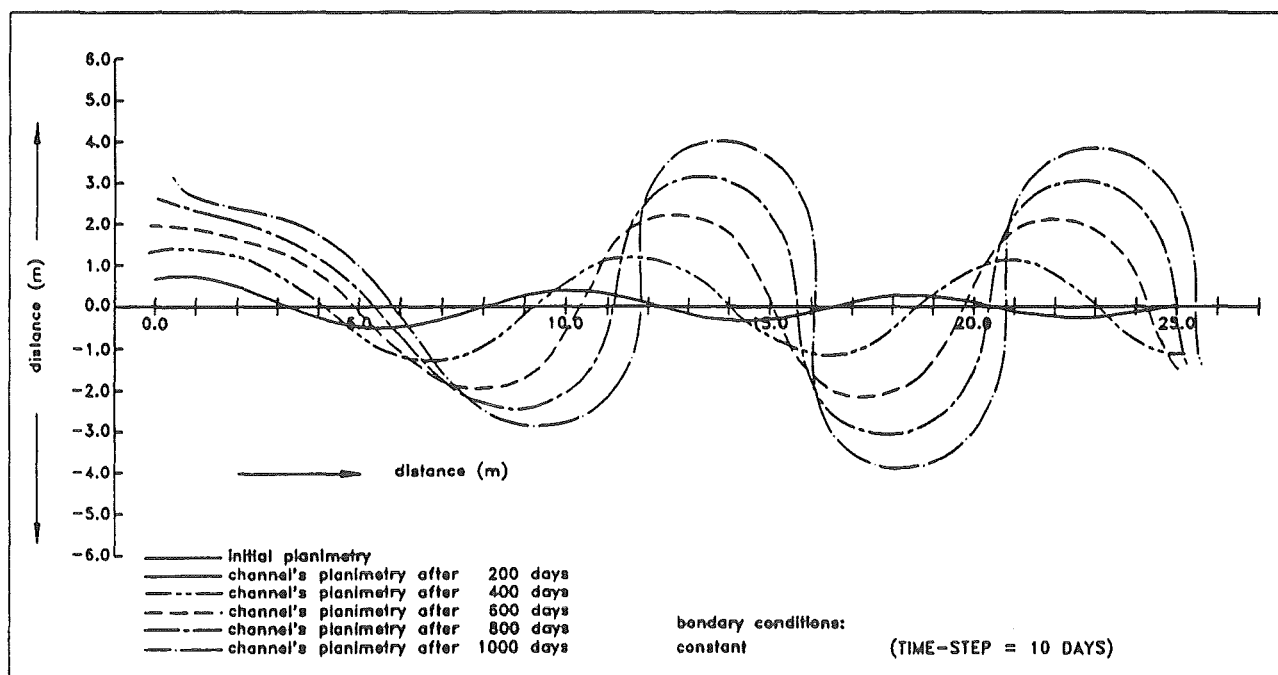


Fig. 4.6 Results of the simulation of the meandering process for a fictive case (MEANDRAS model).



(a) 1986



(c) 1986-1993



(b) 1986-1987



(d) 1986-2000

Legend: blue = Dhaleswari River alignment in 1986 from satellite image
white = Dhaleswari River alignment predicted with MEANDRAS

Fig. 4.6 Application of MEANDRAS mathematical model for prediction of alignment changes to Dhaleswari River, Bangladesh.

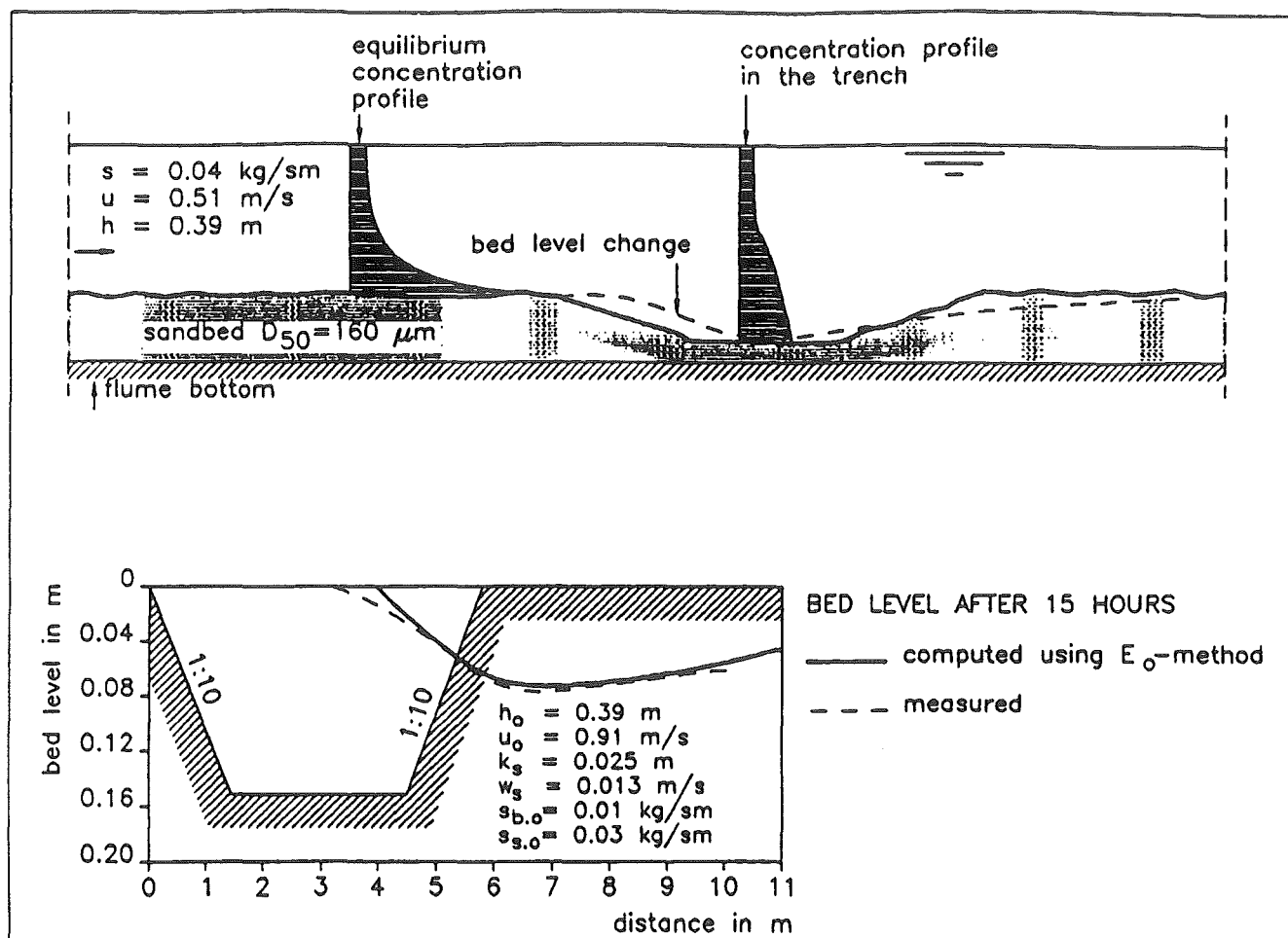


Fig. 4.7 Migration of a trench (SUTRENCH 2D-model).

Mathematical models are powerful tools to predict the consequences of certain policy measures. However, mathematical modelling in ecology is still in its infancy. Still, ecology is becoming more and more important in water management practices. This is not only true for nature restoration projects, but also for environmental impact studies for large projects. Therefore, three approaches to study fluvial ecosystems are described here.

In the *continuum concept* [Hynes (1970); Cummins et al. (1984); Vannote et al. (1980); Statzner and Higgler (1985)] the ecology of a river strongly depends on the gradient of physical conditions. The flow of water, the transport of organic matter and the energy fluxes are the driving forces of the ecosystem. The basis of the theory is given in the physical-streamnetwork concept [Leopold and Maddock (1953)] describing the relationships between abiotic stream parameters such as stream width, depth, slope, discharge and sediment transport. Biotic communities which can be described by the producer and consumer communities reflect as a biological analogon the hydraulic system and its way of using kinetic energy. As a consequence of this idea a river system in dynamic equilibrium exhibits an adapted biological system without any succession process in a given river reach. This conclusion is also justified by the short turn-over rate of streams, which is (averaged for all rivers of the world) about two weeks [Czaya (1981)]. Applying the continuum concept to a whole river network from the headwaters to the lower course, the gradients of the physical variables govern the biological system, which results in a continuously changing biological community along the river course [Statzner and Higgler (1986)].

The *ecotone concept* [Naiman and Decamps (1990); Pringle et al. (1988); Clements (1905)] focuses on discontinuities in the fluvial system. An ecotone is defined as a functional entity, having a set of characteristics and interactions, that depends on its transitional position between adjacent ecological systems uniquely defined in space and time scales [Holland (1988)].

As has been previously shown the ecological system of head waters is often strongly dependent on the riverine forests. Also, the exchange of nutrients between lowland rivers and its fluvial corridors, and the input and storage in both subsystems is of essential importance in understanding the processes within the biotic aspect system. A main feature of such terrestrial-aquatic ecotones is their natural spatial and temporal instability [Braga and Gervasoni (1983), Sedell and Froggatt (1984), Fortune (1988)]; and also their large biological diversity; the community is composed of species from both adjacent ecosystems plus specific species well adapted to this intermediary zone. The functioning of these ecotones is manifold. They absorb flood peaks and reduce the flow velocity. They extract, store and process nutrients from the river system and simultaneously they filter groundwater draining into the river [Jacobs and Gilliam (1985), Pinay and Decamps (1988)].

In the longitudinal direction of a river several discontinuities can be observed, too. The discontinuities are caused by tributaries, or are related to different geological structures. But even at a small scale level a sequence of instream ecotones can be identified, such as the riffle-pool structure and the mosaic-like pattern of substrate in the riverbed within a "uniform" river reach [Pringle et al. (1988)]. Each of these structural elements constitutes an instream ecotone characterized by a typical community.

It is evident that the ecotone concept is strongly related to the scale of analysis. Each level of ecotones has its characteristic space-time development and is controlled by the higher scale level. Considering the dynamics of biotic aspect of ecotones the driving force is the hydrological system described by the mean annual hydrograph and the superimposed random fluctuations such as floods or low flow periods. Riparian ecotones buffer the floods and contribute to a smoothed discharge but on the other hand their dynamics strongly depend on these fluctuations.

An *ecotope* [Leemans (1985); Duel (1991)] is characterized by a spatial homogeneous vegetation type with specific determining factors for that vegetation [Runhaar (1986)]. Examples of these vegetation determining factors are geomorphology, soil type, groundwater level, aeration of the soil, availability of nutrients, number of days of inundation, flow velocity, vegetation management (grazing, mowing), etc.

Duel (1991) presented a matrix model to predict changes in vegetation (in spatial units of 50 m × 50 m) due to the following measures:

- the removal of "summer dykes" to increase the hydro- and morpho-dynamics in the floodplains;
- to extensivate agricultural use of the floodplains;
- the heightening or lowering the bottom level of the floodplain.

Duel (1991) discerned 28 vegetation types, which he related to geomorphological elements, substrate type, number of days of inundation per year, isolation from the river and vegetation management. The model gives the expected vegetation in the final stage. It does not give predictions about the time it takes to reach the final stage. In fact, the model does not describe how the riverine ecosystem works. It is based on quantitative and qualitative correlations between the vegetation types and the environmental and management characteristics of the floodplains in the Netherlands.

For linking mathematical models for river hydraulics and morphology and ecological models it is

of the utmost importance that the river models and ecological models have equal space and time scales and accuracy.

According to Van Vierssen and Wind (1990) not all natural processes are equally important at every scale level. They discerned four scale levels (Table 4.1). Only at scale levels lower than the local level of table 4.1 it will be necessary to include factors like nutrient contents, soil aeration and biotic factors (predation, competition, etc.). They state that for the three main components of fluvial ecosystems (waterplants and fauna in the main channel, vegetation on the floodplains) hydrodynamics and morphodynamics are the most important processes.

But the scale level is also dependent on the kind of policy questions to be answered.

Table 4.1 Scale levels and determining factors and processes for floodplain management [(Van Vierssen and Wind (1990))]

scale type	river basin	regional	local	ecosystem
level (km)	(100-1000 km)	(10-100 km)	(1-10 km)	(0.01 km)
example	R. Rhine	lower course (Rhine branches in the Netherlands)	landscape (nature restoration)	forest meadow pool
main ecological factors	climate geology human impact	geology climate human impact time	spatial variation of river dynamics	idem and biotic factors
management issues	guarantee water quality	idem, and landscaping	guarantee river dynamics	
decision making level	international	national	provincial	local (water boards)

In further research it seems useful to distinguish four important components of the fluvial ecosystem, namely flora and fauna in the water and flora and fauna on the floodplains. It should be remembered that the physical conditions (hydraulics and morphology) determine the biological system of a river. Stream communities are more physically than biologically controlled systems. The interaction of the aquatic system with the terrestrial system is essential for the biological diversity. This is also true for the variation of physical parameters at different scales in space and time. So, the spatial and temporal fluctuations of these parameters must be included in the analysis.

4.2 Lakes

4.2.1 Abiotic characteristics

Lakes constitute relatively closed ecosystems. The most important determinant for their evolution is the internal pattern of circulation [Imberger (1979)].

The internal circulation is a very complex phenomenon which is influenced by a number of exchange processes with the environment. They are responsible for changes in a lake's potential energy:

- The wind drag force on the lake surface. The wind energy creates large scale water circulation as well as small scale turbulence due to wave action [Bengtsson (1973)].

- The heat exchange processes across the lake surface have a decisive influence upon the development of thermocline and subsequently the vertical exchange processes [Svensson (1978)]. These processes are firstly the cause of expansion and contraction of the waterbody, and secondly of mass loss through evaporation.
- The solar radiation, which penetrates the surface and causes heating of interior water layers, a process that affects the water circulation by means of i.a. the creation of thermal barriers [Holström and Carlsson (1978)].
- The lake may be used as a water reservoir, which means that some kind of control structure has been installed at the outlet. The artificially controlled water levels may fluctuate in a way that significantly changes the biotic environment.

Furthermore there are the entrainment or epilimnetic mixing and hypolimnetic mixing.

Many physical processes are influenced by the bathymetry of the lake and its banks. Wind set-up by the wind drag force, velocity distribution and heat exchange are some examples.

The internal circulation may be reduced if the lake has a bathymetry which separates it into a number of relatively independent sub-basins.

It should also be observed that the lake may be separated into different regions according to the water-sediment interaction; in some areas there is predominantly erosive action, in other areas there are bottoms over which sediment is transported, and there are areas where sediment is predominantly deposited [Hakansson and Ahl (1976)]. In these latter areas, there is an accumulation of deposits that consume oxygen in their breakdown processes. In these areas, the internal stratification determines the rate at which the oxygen content of the lower layers can be replenished. Climate is also an important parameter. As lakes gain heat they become stratified into three layers: the epilimnion, the upper warm and circulating region; the metalimnion, or thermal discontinuity and the hypolimnion, the lowest colder region.

Lakes in cold climates usually have an annual cycle of stratification. During summer the upper layer floats on the colder, lower main body. This heating phase is followed by cooling of the surface layer during the fall and a general overturning before the surface once again freezes. In warm climates the complete overturning may not occur. In tropical regions the lake thermocline seems to be stable.

The strength of local winds is also important, especially in larger lakes in which the entire surface layer is sometimes blown to one side [Mellor and Durbin (1975)].

Lakes may also stratify because of density changes produced by chemical gradients, resulting from water inflow. As lakes cool, the density gradients breakdown permitting wind action to mix the whole water column.

One of the major difficulties in the hydrothermal analysis of lakes is the incorporation of turbulent transport phenomena.

Another important aspect is the residence time distribution or the exit age distribution of the water. It is evident that elements of fluid, taking different routes through a lake, may require different lengths of time to pass through the lake.

The residence time distribution gives us a rough indication about the time needed for a change in the quality of the water entering the lake to establish new equilibrium conditions in the lake. For a closed vessel one can distinguish between two ideal cases [Nauman and Buffham (1983)]; plug flow and completely mixed flow respectively.

In the plug flow case, the residence time is exactly the same for all water "parcels" leaving the lake. With complete mixing there is a residence time distribution which falls off exponentially from zero to infinity.

In reality, we have something in between these cases. There is no water with zero residence time, but there is a minimum residence time which may be called the breakthrough time, i.e. the time needed for a change in input composition to affect the output composition.

4.2.2 *Biotic characteristics*

Although a lake constitutes a relatively closed ecosystem, its chemical composition and hence also its biological composition depends strongly on the catchment area or drainage basin, that provides its water, inorganic mass and biomass input. These characteristics are obtained directly through the interaction of the geology, geography and cultural development of the catchment and the lake or, indirectly via inflowing rivers.

While the significance of the catchment area to inputs of inorganic nutrients (nitrogen and phosphorus) to lakes is well understood because of the research into eutrophication processes, its significance to inputs of dissolved and particulate organic matter is still largely unappreciated [Wetzel (1983)].

The open water area of a lake is referred to as the pelagial zone, while that shallower part of the bottom of a lake colonized by aquatic macrophytes (plants) is called the littoral zone. Lake sediments beneath the pelagial zone which do not support macrophyte populations are termed the profundal zone. Various groups of organisms live in each of these zones.

Plankton is a general term, which includes bacteria, plant and animal members, for organisms which are suspended in the water and have limited or no locomotory abilities. Planktonic organisms are subject to vertical and horizontal dispersal by turbulence and other water movements. The plant plankton are known as algae, or phytoplankton, while the animal plankton are referred to as zooplankton.

Phytoplankton are the primary producers in lakes and convert solar radiation and inorganic carbon into organic carbon via the process of photosynthesis. If a lake has large populations of floating or rooted aquatic macrophytes, these plant communities may be the dominant primary production by photosynthetic bacteria in saline lakes and in freshwater lakes with an aerobic-aneurobic interface occurring at a depth where light is still available.

The primary producers are grazed upon by the zooplankton. In lakes, the primary decomposers of organic matter tend to be the bacteria [Robarts (1986)] which in turn are also a food resource for zooplankton. Although the processes are not yet fully understood, it is now widely accepted that bacteria play major roles in the biogeochemical cycles of inorganic and organic nutrients and the transfer of energy in lakes.

As noted previously, in a lake a stratification can be discerned.

The epilimnion, depending upon water transparency (euphotic zone), is lighted and forms the region of photosynthetic production. Photosynthetic and growth processes can reduce the concentrations of essential growth nutrients to the point where they may become limiting to algal populations. Nutrients are replenished from the nutrient-rich hypolimnion by such processes as overturn events, vertical eddy diffusion, episodic deepening of the epilimnion and riverine inflows. Phytoplankton tend to sink as their main macromolecular constituents are denser than water [Reynolds (1984)]. Yet, most of these organisms have metabolic preferences to be in the lighted epilimnion. Buoyancy regulation, by gas production, is probably the only effective means of maintaining cells in the upper water column. The formation of diurnal mixed layers, which tend to be shallower than the euphotic zone, impart ecological advantages to phytoplankton capable for tracking these with buoyancy mechanisms and, therefore, influences successional events and

lake productivity [Zohary and Robarts (1989), (1990)]. The most prominent group of organisms associated with this process is the cyanobacteria, or blue-green algae, the characteristic bloom-forming algae found in nutrient-enriched lakes.

Zooplankton, like phytoplankton, are usually denser than water and tend to sink [Wetzel (1983)]. Turbulence and other water movement processes move the zooplankton in vertical and horizontal planes within a lake and create nonrandom dispersion of zooplankton throughout the pelagial zone. However, while generally subject to these physical processes in the open lake, many members of this group can move extensively in quiet parts and demonstrate marked diel (daily) vertical migrations [Wetzel (1983)].

According to Wetzel (1983) zooplankton tend to accumulate in the epilimnion at the leeward end of a lake and are rare at the windward end whenever a strong wind persists for extended periods. Zooplankton also accumulate in the region of upwelling in Langmuir cells, which occurs midway between zones of convergence. These concentrating effects on zooplankton affects the feeding behaviour of certain fish such as white bass [Wetzel (1983)].

According to Falkowski (1984) the shortest naturally occurring time scale of change in light fields relevant to phytoplankton is probably on the order of 10^{-1} s. This is called the flicker effect and is the variation in light intensity due to alternate focusing and defocusing of light by waves at the air-water interface.

Clouds passing in front of the sun create light variations in the order of 10^0 to 10^2 s, but the most important time scale to phytoplankton is diel (daily) variation which has a period of about 10^4 s [Falkowski (1984)]. Storm associated phenomena produce light variations of 10^5 – 10^6 s while seasonal variations in light patterns may influence physiological responses in phytoplankton [Falkowski (1984)].

4.2.3 *Human impact on lake systems*

The list of lake problems associated with socio-technical intervention is indeed very long. For the present purpose, however a few examples are sufficient to illustrate the possible effects of projects where hydrologic and hydraulic conditions have not been adequately taken into account:

- Lakes have been used as recipients for municipal waste water or stormwater assuming the lake to be well mixed. Thus, the capacity of the ecosystem of the lake to digest the pollution has been overestimated. The result is an accumulation of pollution in the lake. In many lakes, such accumulation has been allowed to take place for considerable periods of time. The remedy is to try to improve the mixing conditions in the problematic areas. However, experience shows that often one has to mechanically remove the contaminated sediment layers in order to achieve the desired lake rehabilitation.
- Lakes are important freshwater reservoirs. To make full use of the lake water, control structures are frequently installed at the lake outlet. If the discharge rules for the control structure are based on defective hydrologic or ecologic knowledge, they may create serious changes in the water level regime, which in turn will affect the biota of the lake.
- Lakes may suffer from non-point pollution sources. In such cases, a remedial action taken in the lake itself will treat the symptoms but not cure the disease. Eutrophication or acidification are prime examples. In these cases it is the land use and management practices in the upstream parts of the drainage basin that have to be revised.
- The shallower parts of the lake may be reclaimed, thus reducing the diversity in bathymetry and habitat.

4.2.4 *Matching hydraulics and ecology*

Lakes are not static structures, they have a "natural" evolutionary path. The speed of change or the direction of change may however, be dramatically shifted due to human intervention.

Shifts in the ratio of water input to output will affect the depth versus volume relationship in lakes which could potentially lead to changes in stratification patterns and the relative volumes of epilimnion versus hypolimnion and light versus dark regions. In addition the littoral zone communities of aquatic macrophytes, benthic (profundal zone) invertebrates and fish can be significantly impacted through loss of habitats suitable for growth, nesting and rearing. Wetting and drying cycles alter the leaching rates of inorganic and organic nutrients from soils [Wetzel (1983)]. River inflows enter lakes as density currents into the region of similar density. This can create aerobic zones in anaerobic regions, input particulate and dissolved inorganic and organic nutrients and substrates, entrain external microbial populations and lead to zones of increased microbial activity [Hubbard and Chrzanowski (1986); Robarts (1987)].

The balance between water inputs and outputs determines the retention time of inorganic and organic substances and will influence the concentration of these substances for both autotrophic (photosynthetic) and heterotrophic (predation and decomposition) growth and metabolism of microorganisms. Residence time is a fundamental concept in nutrient load models used by water managers in predicting water quality in different catchments.

The first attempts to model the internal structure of lakes were generally concerned with predicting the temperature of the outflow.

A useful simplification in this context is based on the observational evidence that most lakes with negligible inflow and outflow exhibit an almost horizontally homogeneous thermal structure. Accordingly, the one dimensional thermal energy equation is most commonly considered to describe lake temperature dynamics. When this equation is solved for the whole water body, the analyst faces the difficult task of specifying eddy diffusivities as a function of space and time or of providing equations that suitably describe the transport of turbulent quantities.

An attractive alternative has been offered by the upper mixed layer models. The justification for these models is, that during periods of strong stratification in temperate lakes, most turbulent activity takes place in a fairly homogeneous surface layer.

Recent modelling studies have concentrated on improving the modelling of the full range of mixing processes so that the models can better describe a wider range of water quality problems [Imberger (1979)].

Vertical mixing is usually studied by isolating various processes that change the potential energy in a lake. For this purpose one is interested in the time history of density and hence temperature profiles in the water body.

A mixing process is defined as an event that redistributes an element in the water body without changing the total content in the water column.

In addition to the solution of the heat conservation equation in the epilimnion an expression is required for the turbulent entrainment caused by wind stirring and convective instabilities. The relative importance of wind stirring and shear production may be evaluated in terms of the Wedderburn number [Patterson et al. (1984)].

Three examples of complications in lake modelling are:

- Many lakes at higher elevations and latitudes develop ice cover during winter. For continuous temperature and evaporation studies on such lakes, an algorithm for simulating ice cover is needed and some model processes have to be changed [Ragotzkie (1978)].

- Turbidity in the water increases the extinction of light below the water surface and concentrates the heat input distribution at the surface.
This affects the stratification and creates a feedback loop in which a water quality parameter, the turbidity, has an effect on the temperature distribution which, in turn, affects this parameter.
- The distribution, and therefore the availability of nutrients and chemicals is often controlled almost entirely by mixing. Consequently, a small change in the mixing conditions may lead to a large change in the size and distribution of the population of algae.

With respect to the time scale of hydrological processes, vertical and horizontal mixing processes in the epilimnion and hypolimnion of lakes have temporal scales of 10^3 to 10^8 s [Imberger (1985)]. They overlap the physiological time scales of bacteria, phytoplankton and other aquatic organisms, e.g. zooplankton have generation times of about 10^3 to 10^6 s, while fish have generation times of about 10^6 – 10^8 s [Allanson (1985)].

Physical processes in lakes with time scales comparable to the biological communities are obviously important in determining the structure and functioning of these communities.

4.3 Estuaries

4.3.1 *Abiotic characteristics*

Estuaries are essentially transition zones where fresh water and salt water meet. The pattern of mixing of fresh and salt water in an estuary is the dominant process within an estuarine system as it exerts a controlling influence on all other processes. Thus, the salinity distribution in an estuary affects physical processes (e.g. gravitational circulation, vertical mixing, flocculation and subsequent deposition and resuspension of fine sediment particles), chemical processes (e.g. the speciation and mobility of chemical substances) and biological processes (e.g. the distribution of aquatic biota). Moreover, as the dispersal and fate of pollutants is governed by the physical, chemical and biological regime of the environment into which they are introduced, the pattern of water mixing will ultimately control these phenomena also.

One of the most important parameters controlling water mixing is the topography of the estuary. Three basic estuarine topographical types exist and these exhibit a variety of circulation patterns [Pritchard (1955)]:

Coastal plain estuaries are drowned river valleys which have been formed by a rise in sea level relative to the land and subsequent flooding of the river valleys. They are the most common type of estuary, especially in northern, temperate waters. Their shape, in plan, generally retains the characteristic "V" shape of the parent valley as sedimentation is comparatively low. Typically such estuaries are characterised by extensive mudflats and saltmarshes cut by extensive systems of channels having a high depth to width ratio. They widen out progressively as they approach the sea coastal plain estuaries and tend to merge gradually with the marine environment. This feature makes it difficult to consider them in isolation from the surrounding coastal waters.

In those coastal plain estuaries in which river flow is large and the tidal range is small a poorly mixed salt wedge develops. In such situations a layer of salt water extends landward, in the form of a wedge, beneath the less dense outflowing freshwater. Frictional forces operating between the different water masses and between the sea and the estuary bed provide the primary force for mixing and there is typically a marked vertical discontinuity (halocline) in salinity between the two water masses.

In estuaries with a relatively high tidal range the interface between the fresh and salt water is

broken down to varying degrees and a partially mixed condition results. The vertical halocline is less sharp than in a salt wedge estuary.

Where the tidal currents are strong enough to completely mix the water column, the estuary is vertically homogeneous throughout although the longitudinal salinity gradient still exerts an important influence on water circulation.

Bar estuaries occur most commonly in the tropics, but can be found on any coastline of active deposition where shingle and sand bars may form parallel to the coastline. If such bar formation occurs across the mouth of an estuary it typically results in the formation of a large, relatively shallow body of water (lagoon) which is semi-enclosed and characterised by wind-induced mixing processes. Moreover, because the bar can severely restrict water exchange with the adjacent sea the salinity of bar estuaries can often be much higher or lower than the salinity of seawater depending upon factors such as freshwater inflow and evaporation rate.

Fjords are glacially overdeepened valleys into which seawater penetrates. They are generally characterised by the presence of a sill at their mouth which may reach relatively close to the water surface although the fjord itself can be extremely deep. Consequently, interchange of water with the adjacent sea is often confined to the volume lying above the level of the sill and the volume within the fjord lying below this level can be effectively isolated and become, on occasion, stagnant. Fjords are also subject to sudden exchanges of water caused by meteorological disturbance.

Although examples of these three basic estuarine types can be readily identified in nature, not all estuaries can be conveniently fitted into one or other of these categories. In practice naturally occurring estuarine types form a continuum from one category to another and water mixing patterns form a continuum from completely mixed to occasionally stagnant.

All of the significant mixing processes (e.g. tides, winds, river inflows) are dynamic ones which oscillate according to various *timescales*. Thus, in any given estuary the pattern of mixing will exhibit both temporal and spatial changes in extent and magnitude. Tidally-induced mixing processes, for example, operate on a short term time scale with the semi-diurnal tidal cycle, on a medium term time scale with the neap/spring tidal cycle and on a long term time scale with the annual tidal cycle. Moreover meteorological cycles, acting on comparable timescales, serve to influence and modify tidal mixing processes. During the tropical wet season, for example, regions of low salinity and the turbidity maxima tend to be displaced seaward from their position in the estuary during the dry season because of the dramatically increased freshwater outflows. Consequently at different stages of the tide during a single day and at different times of the year any given point in an estuary will be subject to different salinity regimes. Because the regime governs the nature of other physical, chemical and biological processes occurring in the estuary as described above, it follows that these parameters will also fluctuate, on similar timescales, at any given location.

The essential feature of the estuarine environment, therefore, is that it is a habitat of rapidly fluctuating physio-chemical conditions which vary over short, medium and long-term timescales.

4.3.2 *Biotic characteristics*

Few living organisms are adapted to cope with the stresses imposed by such a dynamic environment. Consequently, estuaries are characterised by a comparatively low biotic diversity, i.e. few species are present. This effect is compounded by the comparative uniformity of estuarine

habitats (i.e. primarily mud or sand flats) and their relatively short life-span in geological terms which has provided only a comparatively short period for colonisation by living organisms [Wilson (1988)].

Despite this relatively low diversity, however, those species which are able to exist in estuarine habitats often occur in extremely high numbers. This is partly due to the reduced level of competition prevailing, but mainly due to the profuse food supply (generally in the form of detritus). River inflows and the tides play a major role in maintaining available food levels by continually importing nutrients and detritus from the land and the surrounding sea. This constant input of foodstuffs serves to support very high levels of productivity. Indeed, estuarine systems rank among the most productive of aquatic systems. To the non-expert this productivity is most readily apparent in terms of the large numbers of permanent and migratory wading birds and wildfowl which utilise estuarine tide flats as feeding grounds. Many species of fish and invertebrates benefit from the productivity of estuaries too. Indeed, it has been estimated that species responsible for 66% of the world's fisheries are dependant upon estuaries for their survival at some stage or another of their life cycle [McHugh (1966)].

4.3.3 *Human impact on estuarine systems*

Estuaries are utilised by man for a wide range of uses including fisheries, recreation, transportation, sites for urban and industrial development, abstraction of cooling water for power stations, and repositories for the discharge of domestic and industrial wastes [Wilson (1988)].

It is readily apparent that many of the uses to which estuaries are put by man can be damaging to the estuarine environment if pursued to excess. Moreover different uses are often incompatible with one another. As the impacts of man's actions upon estuarine systems are diverse and wide ranging, careful management, based upon the accurate prediction of the possible effect(s) of changes to the system, is required in order to maximize benefits and minimize negative impacts in both the short and long-term, i.e. sustainable development should be a primary management objective.

In order to co-ordinate the conflicting uses to which estuaries are put, mitigate the potential for adverse environmental impacts and optimise utilisation of the estuarine resource it is necessary to have an appropriate management strategy. Rational management can only be based on an objective understanding of the system to be managed. Consequently, the first priority of any management plan for an estuarine system must be to identify and quantify, wherever possible, the fundamental physical, chemical and biological processes governing the natural functioning of that system. Given information on hydraulic mechanisms, chemical behaviour and mobility, for example, the disposal and ultimate fate/concentration of a specific chemical pollutant can be predicted provided that the input loading is known. These concentrations can then be judged in terms of stated environmental quality standards which have been set to safeguard prescribed environmental quality objectives (based on the use to which the estuary is to be put) to assess whether or not a proposed discharge should be allowed.

Thus, the management process requires the consideration of a wide range of interacting hydraulic and ecological features such as:

- Water levels and velocities;
- Salinity distributions;
- Morphological development of the estuary;
- Type and features of embankments;

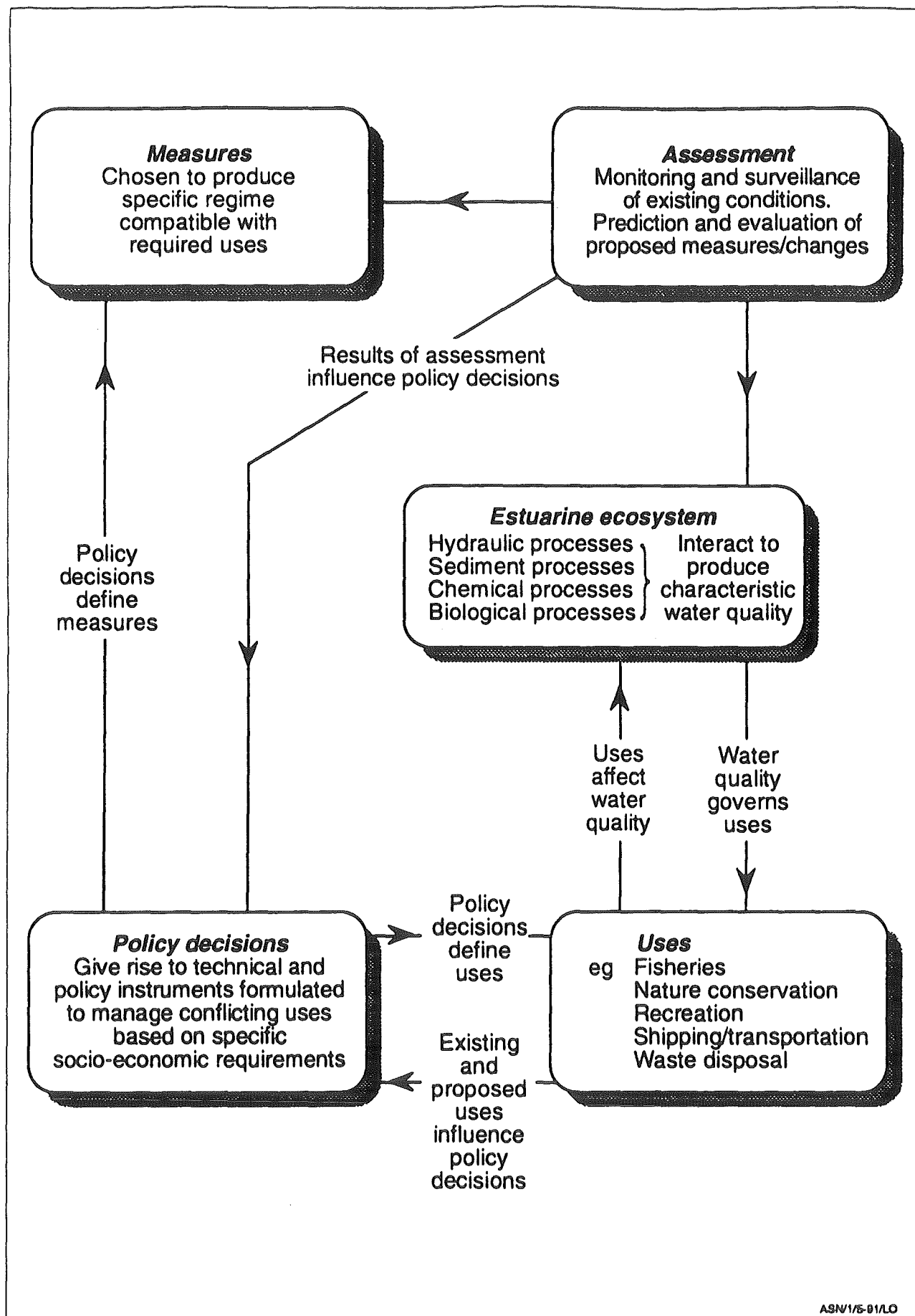


Fig. 4.8 Schematic representation of a system's approach to estuarine management.

- Ratio of exposing tide flats to total estuarine surface;
- Sand/silt distribution and pattern of sediment transport;
- Water quality;
- Nature of biota.

Depending on the specific problem and the level of approach to that problem it might be possible to consider hydraulic and ecological aspects separately, but, because of the close linkage between hydraulics and ecology described above, it is most often necessary to adopt a systems approach to estuarine management. This requires hydraulics engineers and estuarine ecologists to provide systems analysts with information on existing hydraulic and ecological conditions so that the likely effects of different options for estuarine development can be fully evaluated in terms of hydraulic impacts, ecological impacts and socio-economic impacts. A schematic representation of the systems approach to estuarine management is illustrated in figure 4.8.

4.3.4 *Matching hydraulics and ecology*

Hydraulics and ecology should be considered both in order to solve management problems of estuaries. However, the number of inter-acting physical, chemical and biological processes, that need to be analysed to resolve even the most straight forward problems of estuarine management, is large. Moreover, consideration must be given to the extent and magnitude of spatial and temporal variation of these processes, as described above, on short-term, medium-term and long-term time scales. The only way in which such large numbers of fluctuating variables can be satisfactorily integrated to facilitate the solution of practical management problems is by the use of mathematical modelling techniques as tools for integration. Examples of the use of mathematical models to integrate hydraulic and ecological processes are presented in Figs. 4.9 and 4.10. Mathematical models of estuarine systems represent their physical, chemical and biological behaviour in terms of sets of inter-linked mathematical equations which relate the estuaries major processes (state variables) to those external variables which influence those processes (forcing functions).

The way in which this is done depends on the nature of the estuary to be modelled, the problem(s) to be resolved and the assumptions made about the processes involved. Consequently, a general model for estuaries does not exist and it is always necessary to take account of those features specific to the system being studied. In all cases the model should be calibrated and validated against wholly independent sets of data obtained from the estuary of interest.

Despite the need for site specific information, however, the basic structure of mathematical models of estuaries (indeed, of all aquatic systems) contains the same essential elements. Thus, mathematical models are typically based on the conservation of mass and momentum into and out of each segment of a water body. The modelling process, therefore involves dividing a water body into segments. The size of these governs the resolution of the model.

Mathematical models can examine water bodies in one, two or three dimensions (paragraph 4.1.4). One dimensional models are often adequate for representing well-mixed, vertically homogeneous estuaries, but three dimensional models provide the most sophisticated representation of the spatial differences in physical, chemical and biological processes in stratified estuarine systems.

Any model designed to link hydraulic processes with the ecological interactions of an estuarine system must incorporate all four of the basic sub-models available for simulating these processes in aquatic systems.

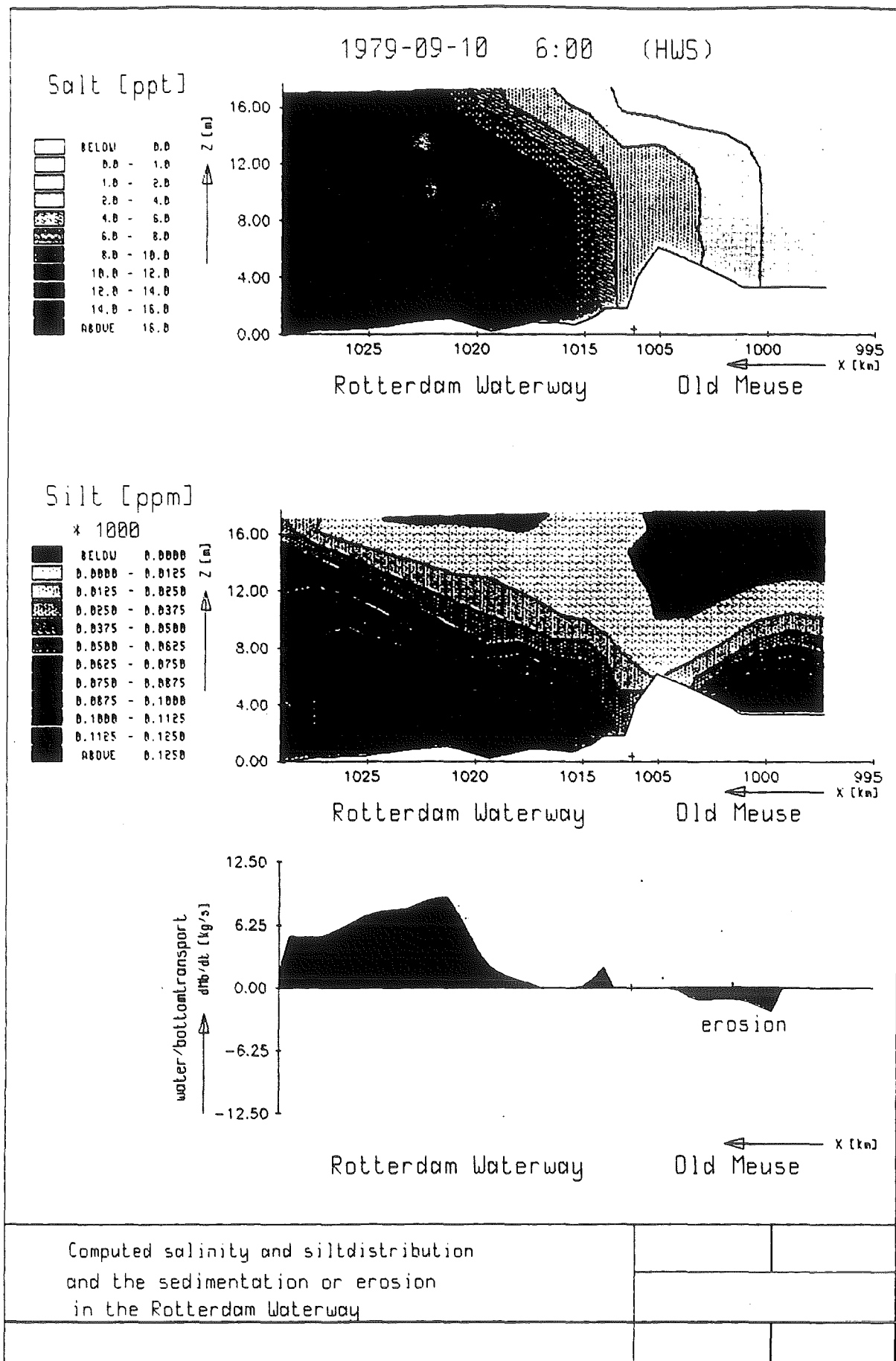


Fig. 4.9 Example of mathematical model integration of tidal flows, salinity distribution and silt transport.

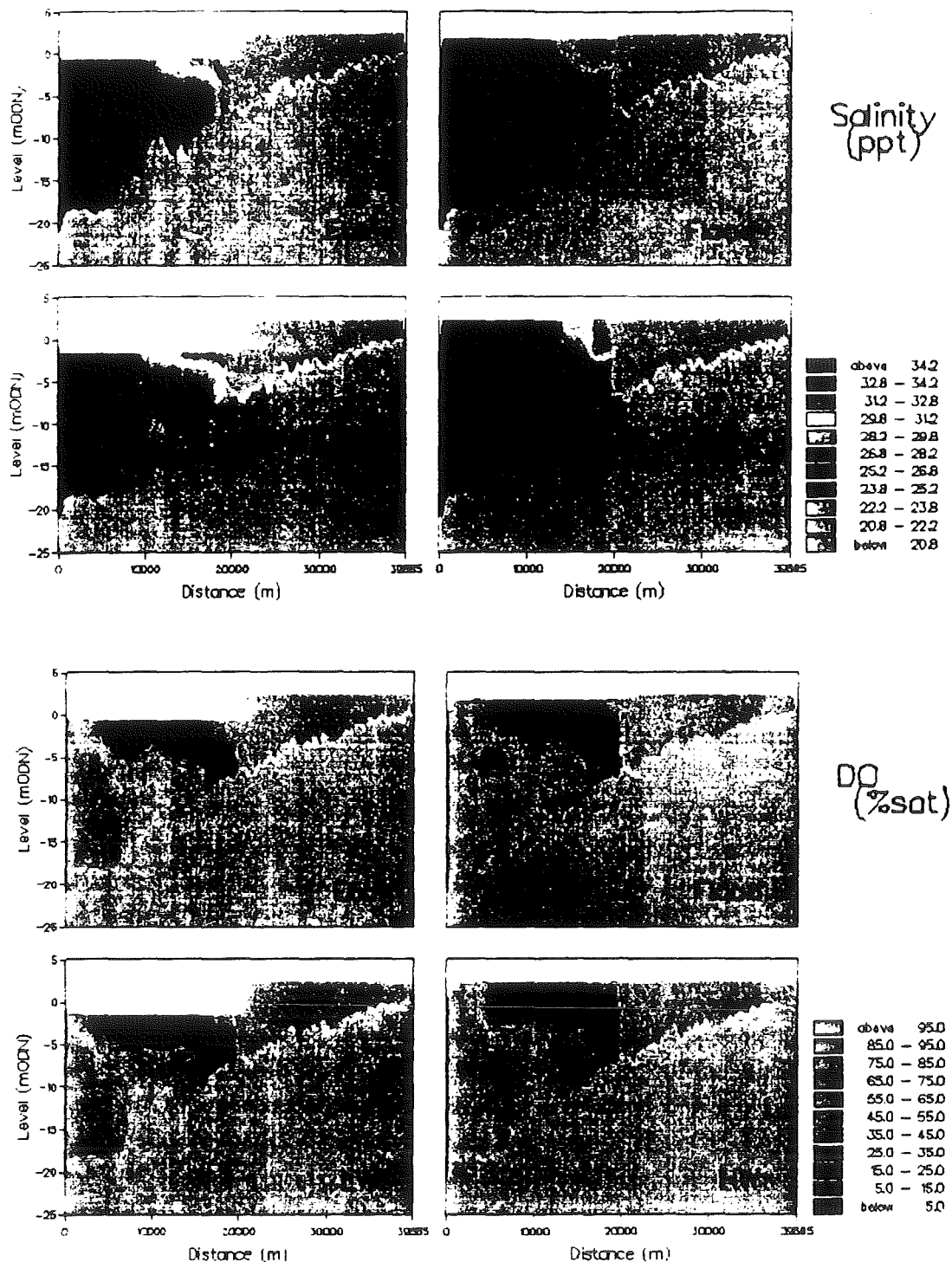


Fig. 4.10 Mathematical modelling simulation of the effects of a proposed barrage on salinity and dissolved oxygen levels in a highly stratified estuary.

These are:

1. The hydraulic sub-model which comprises a mathematical representation of the relevant hydraulic processes and calculates the movement of water through the various segments into which the water body has been divided. It is based on the physical characteristics of the water body and the relevant driving forces.
2. The physical transport sub-model which mathematically represents the processes governing the movement of inorganic mass (e.g. salt, sediment and pollutants) in water and combines them with the driving flows derived from the hydraulic sub-model to calculate the quantity of material transported into and out of each segment of the water body. It requires information on loadings and diffusion coefficients.
3. The chemical/biochemical reaction sub-model which mathematically represents chemical reactions occurring in the water body. It requires information on the initial concentration of the substances of interest and the reaction kinetics which affect the chemical transformations each substance undergoes.
4. The ecological sub-model which combines information on birth/death rate constants and the initial concentration of specific organisms or species groups together with data provided by the other three sub-models into mathematical equations representing the relevant ecological processes. It calculates changes in biomass or concentrations of organisms within a water body.

It is not stated here that the inclusion of many processes in a mathematical model will lead to a more precise simulation of the real condition. Each parameter employed must be derived in the first instance from an experimental measurement which will have an associated range of uncertainty. Thus, the inclusion of increasing numbers of parameters, each with its own range of uncertainty, will increase the overall uncertainty of the model output. It is essential, therefore, to ensure that only those processes of significance to the problem being addressed are incorporated in the model structure. This will require close co-operation between the various disciplines (e.g. hydraulic engineers, ecologists and policy makers) involved.

Various 1-D, 2-D and 3-D mathematical models of hydraulic processes in estuaries and coastal waters have been developed and successfully employed to drive water quality and ecosystem models. They may be driven in a tidal or tidally-averaged mode to simulate periods of weeks or years and can simulate and predict a wide variety of physical processes which can exert significant influence on ecological interactions. These include tides, coastal currents, longitudinal gravitational circulation driven by fluvial flows and/or thermal effects, wind driven circulations, evaporation and hypersalinity.

The inputs driving these models include water levels at boundaries, fluvial inflows, rainfall, insolation, wind speed and direction and humidity. Output data on water levels, 3-D flows, dispersive mixing fluxes, salinity and temperature is typically stored and used to drive matching ecosystem models. A generalised procedure for linking hydraulic and ecological processes in an estuarine system by using mathematical simulation models is described in Fig. 4.11.

While the hydraulic component of the model structures provides the capacity for advanced simulation and prediction of hydraulic processes, however, some of the ecosystem components are described in general terms. This is because of the fact that the understanding of hydraulic processes is much more complete and better quantified than that of ecological processes. Thus, it is to be hoped that future developments will enable a wider range of ecosystem processes to be modelled in greater detail. This will require a considerable amount of field and laboratory study and necessitate the development of improved sampling techniques especially in the areas of automated instrumentation and remote sensing methodologies.

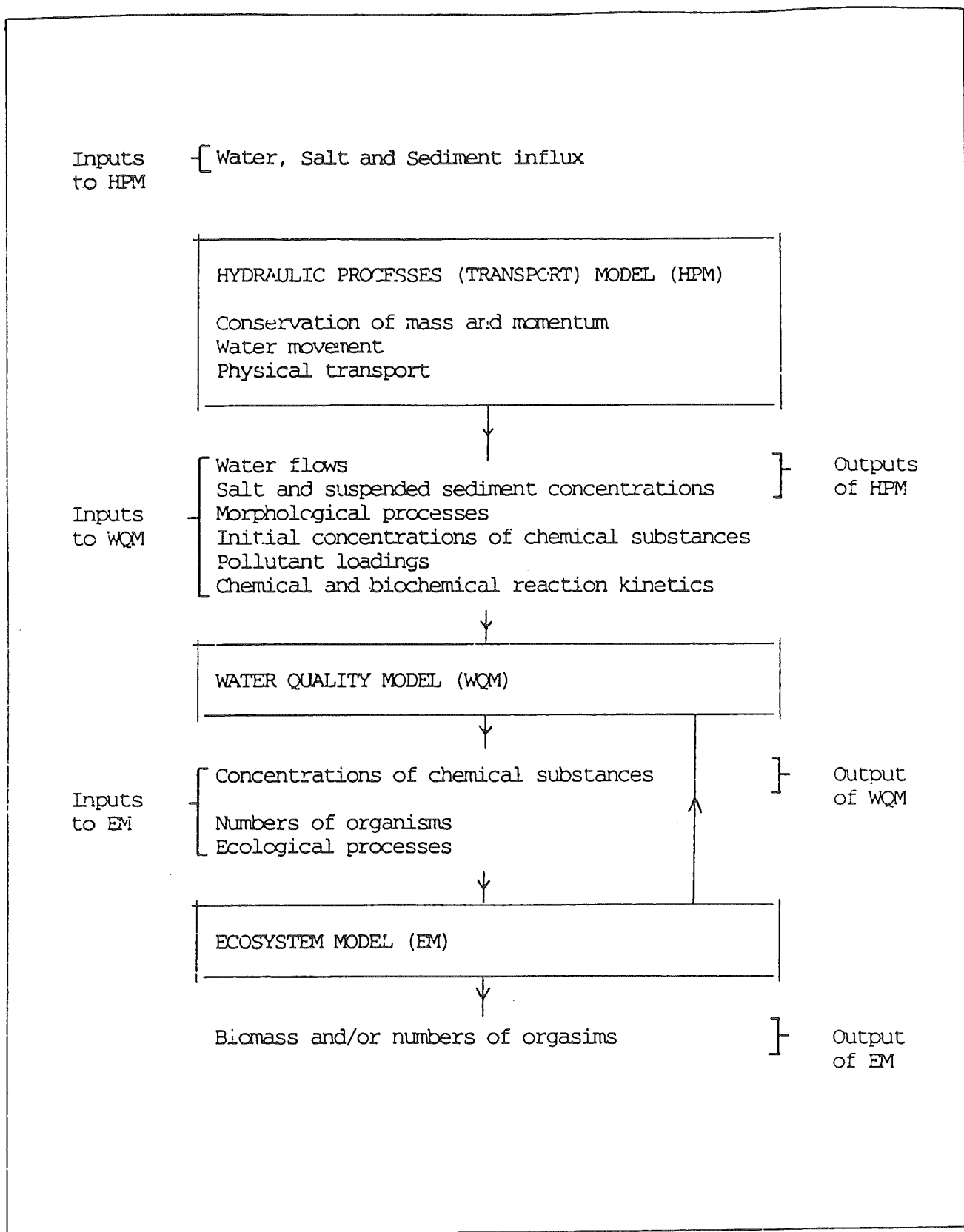


Fig. 4.11 Generalised mathematical simulation modelling approach to linking hydraulic and ecological processes in an estuarine system.

4.4 Groundwater

4.4.1 *Abiotic characteristics*

Groundwater constitutes the most important freshwater resource of the earth, it is two orders of magnitude larger than the total water volumes of rivers and lakes. It is a renewable resource, characterized by stability of its chemical composition and stability of temperature. Percolation of water through the subsurface has a good purification effect due to the combined action of filtration, sorption, chemical reactions and microbiological processes.

Groundwater is utmost important as drinking water resource, since it is less prone to pollution than surface waters due to the protection effects of the covering layers. However, industrial and agricultural activities have led to groundwater pollution problems which are sometimes irreversible and in any case very difficult and expensive to recover. This endangers the long-term use for drinking water supply, and any efforts for sustainable development have to consider the vulnerability of groundwater resources to pollution, which shows great regional diversity, by suitable groundwater protection efforts.

In a general way, we can define the groundwater system as an open subsystem which is inter-related with other aquatic and terrestrial subsystems as well as with adjacent groundwater compartments as is shown in Fig. 4.12. Across the open boundaries of the system, fluxes of water, matter (nutrients, contaminants) and energy can take place either in both directions or sometimes only in one direction.

Groundwater systems show extremely great variety depending upon the geological formation of the aquifers. Groundwater circulation systems in sand and gravel aquifers, in fissured rock aquifers or in karstic aquifers exhibit very different flow and transport characteristics. Depending upon the hydrological and hydraulic conditions, the saturated groundwater region and the unsaturated soil water zone have also to be distinguished in addition. Hence, it would be inappropriate to think of an undifferentiated groundwater system. Even though these distinctions are made on purely physical criteria, they are also of great ecological significance, since they define the physical frame of the subterranean ecosystems.

The *hydraulic characteristics* of groundwater circulation systems are described by huge water bodies, very small flow velocities (meters per day to meters per year) and hence extremely long exchange times. Groundwater circulation is extremely slow, with residence times ranging from a few years to thousands of years for natural aquifers. Groundwater is recharged by rainfall (minus evaporation and surface runoff), by percolation through the unsaturated zone, as well as by infiltration from surface waters during high stages (wet periods). The recharge rates are low compared to the large volumes of the aquifers. In the hydrological cycle, the groundwater nourishes the surface waters at low stages (dry periods), thus providing the base flow in rivers. Groundwater basins have a damping effect on the extremes of hydrological rainfall variations (reduction of peak flood flows, maintenance of low flows in rivers). Between upper and lower groundwater compartments, the exchange is always stable and usually limited unless disturbed by human activities.

Groundwater hydraulics considers quantitatively the flow of water and transport of substances in porous and fractured subsurface systems. Fractured rock systems require more complex concepts. Classical applications include calculations of regional or local flow velocities, piezometric heads, discharges or draw down effects of wells, water balances, etc.

The *biogeochemistry* of groundwater systems deals with questions like: What are the temporal and spatial variations of concentrations of chemicals? How do they behave and what species

differentiations occur? How and how fast do chemicals react with and without mediation of microorganisms? And finally, where are the sources and sinks of chemicals?

We may define pH and the redox potential (pE) as the master variables which govern the biogeochemical processes in groundwater. pH and pE in "natural groundwaters" are controlled by microbiological decomposition of dissolved organic matter infiltrating from rivers, lakes and the unsaturated zone and the resulting $\text{CO}_2\text{-HCO}_3\text{-CO}_3^{2-}$ -system. However, in groundwaters contaminated by infiltration from highly eutrophic lakes and rivers, paddy soils or leachates from organic-rich domestic and industrial waste, pE and pH are controlled primarily by the C-N-S-Fe-Mn-system. Organic non-natural substances, which may be introduced through the interface from e.g. refuse dumps, from pesticide applications or from accidents involving chemicals, will be transported with the groundwater more or less like a tracer if they are small non-ionic or negatively charged. However, positively charged organic substances will be strongly adsorbed to the matrix by cation exchange.

Finally, nonpolar organic substances, especially those of greater molecular volume, are sorbed onto the matrix by hydrophobic interaction or are partitioned onto organic coatings or organic colloidal matter.

The behaviour of trace metals in groundwater depends on the physio-chemical properties of the individual species, the formation of which is related predominantly to the master variables pE and pH and to the availability of complexing ligands. Adsorption by iron and manganese hydroxides predominantly controls the transport of trace metals in groundwater, as this process keeps the concentration below the solubility equilibria of commonly occurring oxide/hydroxides, carbonates or sulfides of trace metals. As with organic non-natural substances, anionic trace metal species are less likely to be adsorbed than cationic species.

Finally, within a range of pores of different size, we will also observe a range of different chemical

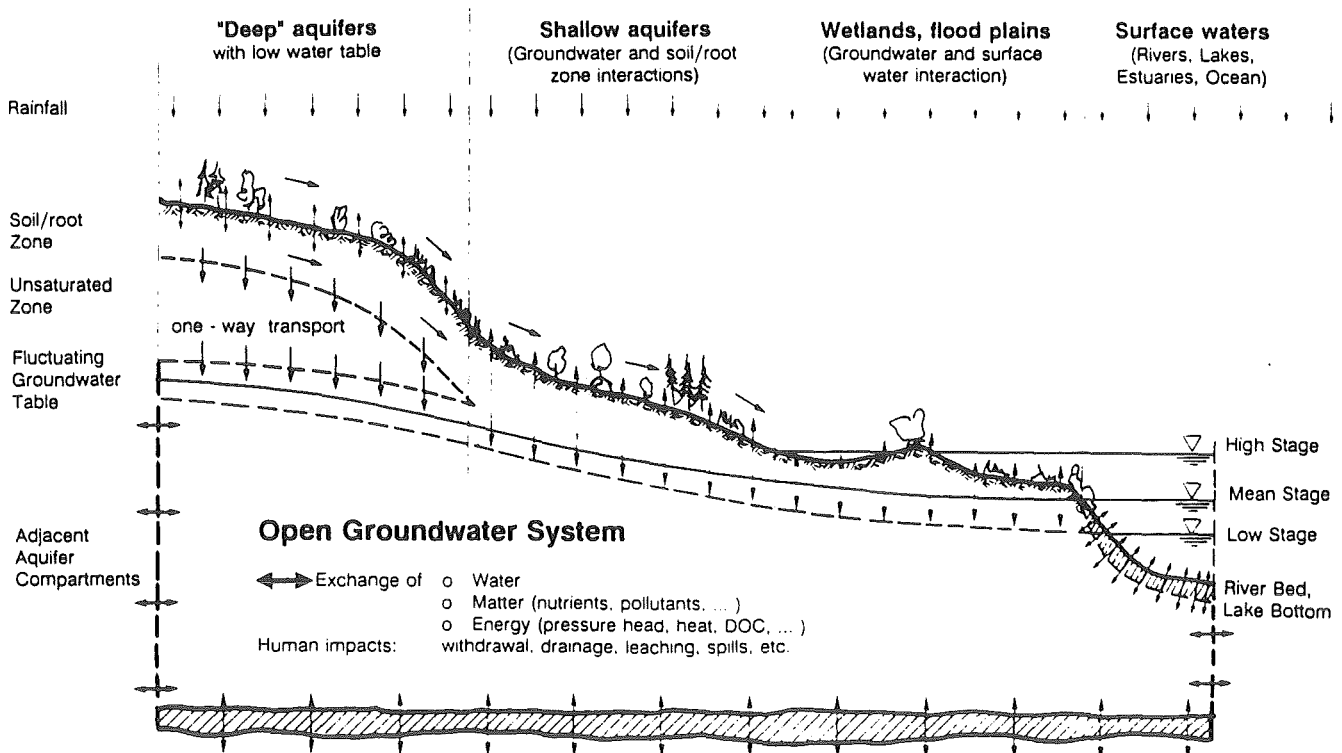


Fig. 4.12 The groundwater system.

reactions. Thus the transition on a "microscale" from one pore size distribution to another may cause a dramatic change in chemical reactions.

In connection with groundwater pollution problems, calculations of the regional transport of substances have gained great importance. However, the prediction of transport processes requires a much more detailed knowledge of the flow field as well as a good representation of dispersive spreading effects. Dispersion, as the combined action of differential convection and molecular diffusion, occurs at the pore/grain size scale as well as due to local inhomogeneities and due to geological formations (macrodispersion).

We have just considered groundwater bodies by themselves. In an environmental perspective it is also necessary to consider how they can affect other media and ecosystems. Groundwaters are related to the surface terrestrial and aquatic ecosystems in many ways (Fig. 4.12).

All intentional (drainage, water abstraction) or fortuitous (leakage) actions lowering or raising the water level have ecological and/or environmental impacts which may be dramatic. Some authors point out such disturbances as a possible cause of desertification processes. All over the world, the ecologists are generally very interested in wetlands which are often the target of development projects. In any case, the control of groundwater hydraulics appears to be a necessary condition to protect and possibly to manage the surface ecosystems.

A particularly intimate interrelationship exists between surface water bodies and the associated groundwater. The direction of interchange varies usually with the hydrological conditions, and fluctuations in surface water levels cause corresponding groundwater level variations. Of particular significance for these interactions is the role of the river bed or lake bottom, which may have quantitative effects on the exchange (clogging by filtering, biological growth or chemical reactions, or clearing by river sediment transport) as well as strong effects upon the water quality due to biogeochemical processes. Of similar significance are the transformation processes in the zone of groundwater table fluctuations with frequent changes between saturated and unsaturated conditions, and particularly areas such as flood plains or wetlands.

4.4.2 *Biotic characteristics*

In order to define the *ecological characteristics* of groundwater systems, we have to redefine the definition of an ecosystem in this contexts. We define an ecosystem here as a community of biological species living and dying in a physical frame subject to external stimulations which govern fluxes of energy and matter. Karsts, which can be visited and also have macroscopic populations, have first been recognized as genuine ecosystems; but this was only some ten years ago. However, a conceptual jump has to be made to conceive aquifers, especially deep ones, as ecosystems, because here it is useless to treat in the same way the classical physical factors of an ecosystem: light which does not penetrate, temperature in a quasiisothermal medium and humidity in a saturated body! Bacteria are the significant form of life in groundwater, as far as the increase in geothermal heat with depth allows bacterial life. We still are in an early descriptive stage of these media seen as bacterial ecosystems, but we already know from scattered works that the nature and abundance of bacteria depend on temperature, water movement, distribution of organic matter, chemical composition and physical properties of the aquifer. In return microorganisms may cause important chemical effects as described in the previous paragraph.

Thus, we consider groundwater as an open system which may receive chemical energy such as DOC through open interfaces like the sediment/water interface of lakes or rivers or the groundwater table, which functions as the interface between the unsaturated zone and the aquifer.

4.4.3 *Human impact on groundwater systems*

Human impacts upon groundwater systems can be grouped in 3 categories: direct uses of groundwater and the problems associated with it, impacts due to hydraulic schemes of surface waters upon the groundwater, and groundwater contaminations due to numerous other human activities. Groundwater use concerns primarily the domestic drinking water supply from groundwater wells, from springs, from bank infiltration near surface waters, as well as industrial water supplies and possibly industrial waste or heat water discharges. In many parts of the world, groundwater is used for irrigation. Groundwater management includes the use of subsurface heat energy (groundwater driven heat pumps, etc.) as well as seasonal groundwater storage and recharge systems and seasonal heat storage in aquifers. Also, many groundwater resources can be used as mineral waters, and in specific cases also for medical uses (spa's).

The problems related to groundwater uses include overexploitation, drop of groundwater table and water deficit as well as problems of land subsidence and effects of changes in subsurface pressure distribution. Excessive irrigation can cause salination problems, and in coastal areas problems of salt water intrusion are encountered (shifts in the underground freshwater/saltwater interface, intrusion due to groundwater use). Problems of thermal effects of groundwater uses or recharges are less pronounced. Direct effects of changes in groundwater tables upon the vegetation and the terrestrial ecosystem can also be observed.

The impact of hydraulic schemes of surface waters upon groundwater tables and groundwater quality results from the direct hydraulic interaction between both systems.

An example was given by the developments on the upper Rhine in Chapter 1. Related to this example is the present day key issue in Germany that illustrates the concept of "matching hydraulics and ecology".

Due to the loss of all major flood plains, the flood wave propagation of the Rhine, in interaction with its tributaries, causes serious flood problems that have led to considerations about the construction of "polders" along the river as artificial retention volumes. This, in turn, raises many questions about the possible effects to be expected upon the ecology, upon the regional groundwater tables, and upon the resulting groundwater quality. At this point, the interests of flood protection, the preservation of ecologically sensitive areas and forests near the Rhine, and the concerns about the water quality of public water supply works in the Rhine valley have to be matched in order to design a hydraulic operation scheme considering ecological constraints.

Groundwater contaminations have developed into one of the key environmental issues in most of the industrialized countries. Regional-scale contaminations have been discovered due to numerous different sources. Industrial contamination sources include waste sites, leakages, accidental spills, abandoned industrial sites, storage and transport of hazardous substances, etc. Nuclear and/or chemical contaminations may result from nuclear and fossil power plants and gasification plants. Pipelines and traffic systems, roads and railroads serving the transport of hazardous substances also possess a groundwater contamination potential. The same holds for septic tanks. Agricultural contamination sources include animal farming as well as fertilizer applications (nitrates) and the use of herbicides and pesticides. Finally, air pollution contributes by deposition, etc.

The enormous dimension of subsurface and groundwater contaminations and the engineering challenge for cleanup technology is easily illustrated by the various national efforts and programs in the industrialized countries (e.g. "Superfund" in USA). Cleanup technologies undergo rapid

developments in all branches. However, technical application at high costs are more often than not based on mechanisms not sufficiently understood, and the “efficiency” of cleanup efforts can only rarely be assessed. There is a tremendous need for basic and applied research in this area. Groundwater uses do normally not require engineering structures apart from boreholes and wells. Groundwater management, therefore, usually enters into infrastructure-decision processes in one or two ways:

- The assessment of environmental impacts of groundwater uses. This concerns mainly groundwater balances, effects of drawdown near wells upon the terrestrial ecosystem, subsidence problems, interactions with surface water bodies, or water quality.
- The assessment of all kinds of other human activities (industrial, traffic, agricultural, surface waters, air pollution, etc.) for groundwater contamination risks.

Fig. 4.13 illustrates the dual roles of scientists, engineers and water resources managers in the necessary decision making process on the one hand and in the definition and execution of the research needs required for a better decision-making basis in the future, on the other hand. It is obvious that, due to the large time scales involved and due to the enormous costs of cleanup efforts, prevention by groundwater protection is of utmost importance. For example, in the State of Baden-Württemberg, Germany, 25% of the total land area are declared groundwater protection zones with various restrictions on land use. However, in political decisions on land use, groundwater usually is only a side issue in the decision process. Therefore, groundwater protection is a defensive battle in highly populated and industrialized countries against many political and economical pressures. In this combat, hydraulic engineers responsible for good drinking water and ecologists are in the same boat against the conflicting interests of infrastructure, industry or agriculture and others.

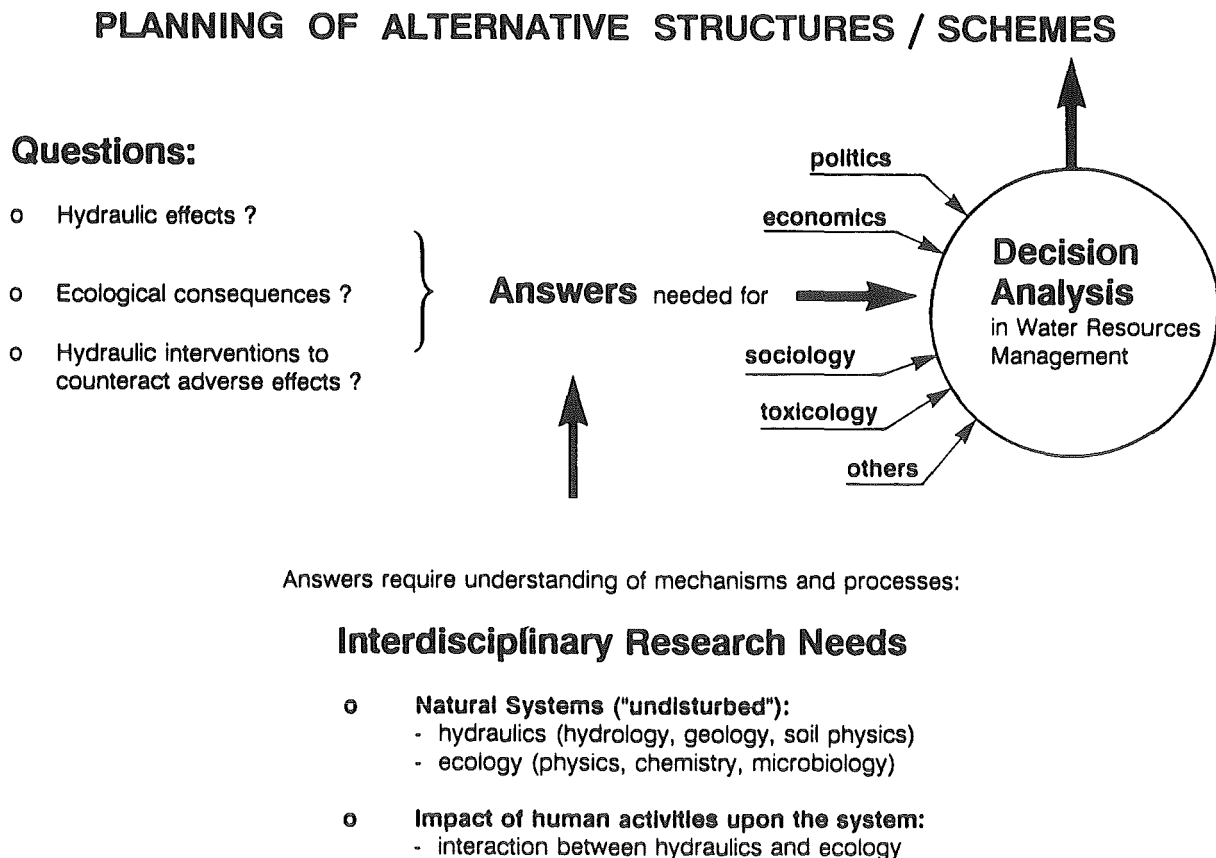


Fig. 4.13 Groundwater planning, decision processes and research needs.

4.4.4 *Matching hydraulics and ecology*

The idea that an interdisciplinary approach that couples hydraulics and ecology is needed, has to gain ground in hydrogeology and in groundwater engineering to avoid disappointments that originate from misconceptions, e.g. about an aquifer as an inert object, rather than a body resulting from a geological history, subject to further evolution originating from natural or non-natural causes. For instance, subsidence phenomena are an evidence of such evolutions: as a flood may modify the bed geometry of a river, water abstraction from a groundwater body may affect the internal structure of an aquifer.

Incorporating hydraulics and ecology in groundwater systems implies first to identify all the physical, chemical and biological processes occurring within an aquifer and secondly to understand how these processes are related. So it will be seen that their hierarchy and organization may be different, according to the geological, hydrological, thermal and other special features of the aquifer, leading to a particular association of species and giving the groundwater body a specific quality. Furthermore, the organization and hierarchy of these processes is not given forever, but their progress under natural or man-influenced conditions may affect the groundwater body itself, possibly in an irreversible way.

Understanding the medium is a first step. It allows us to model and helps any decision making process. A very important effort of basic research gathering hydrologists, hydraulicians, chemists and microbiologists remains to be done in order to achieve this goal.

The identification of model components and governing parameters requires a characterization of the microbiological population of aquifers, understanding of the basic mechanisms and processes leading to the transformation of substances (such as convection, adsorption, filtration, chemical processes, etc.) and also identification of suitable parameters for describing such transformation processes. In the end, engineers are interested in simple bulk parameters for "stability", "resistance", "resilience", "vulnerability", "critical contamination load", etc. for practical application, but suitable definitions for such summarizing parameters are still far away.

One essential problem that interdisciplinary groundwater research has to face is the question of incommensurability of scale (Fig. 4.14). If the hydraulic parameters of an aquifer are known, numerical modelling of groundwater flows at an integral scale allows predictions from regional down to local scales. However, due to the high underground variability, classical groundwater hydraulics allows only predictions for sufficiently large volumes, but not for local details (e.g. a local spilling area, the details of which determine the spreading process). Groundwater hydraulics is based on a fictitious continuum averaging over a sufficiently large number of pores and grains (representative elementary volume) and yields no information on the microscale flow and transport processes within the pore system. However, for the biogeochemistry, these local flow and transport conditions are of utmost relevance (local flow velocity and reaction kinetics, dead end pores, specific surfaces and surface films, etc.).

For instance, for the description of dispersion processes modelling concepts exist, but it is difficult to generalize the associated parameters and hence to predict dispersive effects in nature. Transport modelling furthermore requires due consideration of adsorption characteristics, chemical interactions, microbiological effects, etc. A major limitation for practical applications is the lack of suitable and sufficiently detailed field data.

The current developments towards a comprehensive modelling of groundwater flow and transport processes are gaining practical relevance for the design of integrated monitoring schemes of groundwater quality and also for the development of methods for environmental impact assessments.

SCALES OF GROUNDWATER FLOW AND TRANSPORT PROCESSES

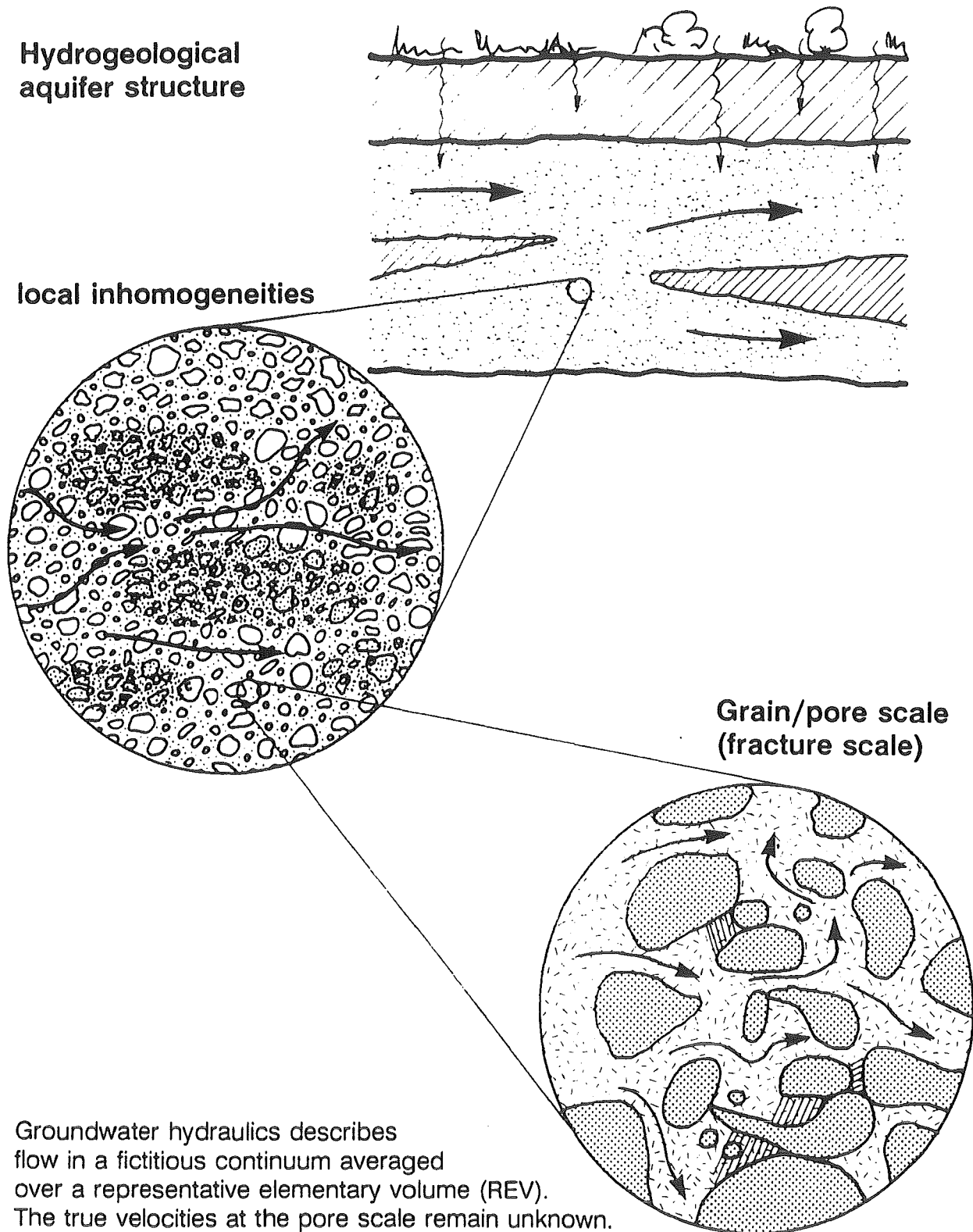


Fig. 4.14 Scales of groundwater flow and transport processes

Groundwater protection is a high stake: because of the very large time scales involved, it can be the proof for our society on its efforts for sustainable development. However, it is not an easy task to create awareness for the high priority of groundwater protection as an ecological issue, because - unlike river or lakes - groundwater cannot be seen, heard or felt. It can only be observed through the narrow keyhole of boreholes and geophysical logs, or through the quality of the water drawn from it. The conception of groundwater as a subsurface "water body", harbouring an ecosystem is difficult and not yet well developed. The efforts today are geared towards maintaining groundwater systems as the most valuable drinking water resource and the undeniable supporter of terrestrial ecosystems. In the framework of sustainable development, this is a major responsibility of our society for future generations.

5 The uncompromising involvement of ecology

This publication is a preliminary step to defining the main requirements for matching hydraulics and ecology.

Human needs and economic considerations are generally the driving forces which bring about proposals for water resources projects. In the past, economic interests dominated and dictated how water bodies would be developed and used. In present times however, it has become very clear that considering only the technical and economic aspects of water resources projects may often give rise to unexpected environmental problems. The increasing number and scale of these problems is seen by some to pose a threat to human life. With the ongoing pressures to meet the needs of growing populations, there are continuing demands to develop the remaining natural land and waters for industrial, urban or agricultural uses. Healthy ecological systems are becoming scarcer.

The growing awareness of the conflict between economic demands and the natural environment led to the concept of sustainable development: humanity has to ensure that its present day development "meets the needs of the present without compromising the ability of future generations to meet their own needs" [Brundtland report (1987)].

This should mean that the ultimate goal of every civil engineering project and especially those concerning water resources, should include in its design the preservation of the environment, comprising the living system of air, water, soil, flora and fauna with mankind as the top-component. In some cases, it is conceivable that the higher values assigned to ecological systems will lead to civil engineering projects where the fostering or the restoration of the environment is the primary goal.

Conceptually, the broadening of the design and decision making process to encompass at the outset of a project the added dimensions of sustainability and environmental health, could be realized by adding the environmental values to the typical cost/benefit analysis. In practice, however, some barriers have to be overcome.

Firstly, there is a disciplinary barrier. Hydraulicians, hydrologists and biologists are largely ignorant of each other's science. Communication is difficult because of a difference in terminology, definitions and academic background.

Secondly, there is a difference in precision of analysis and prediction between the technical disciplines and the life sciences. Hydraulic and other engineers are able, by mathematical or scale models, to establish quite reasonably the future physical regime of the project. In contrast, ecology must confront a complex biotic system interacting with the physical or abiotic environment. A major difficulty is the lack of a suitable methodology to measure biological events with the same resolution as physical quantities. At this moment there is no scientific definition of the health of an ecological system or general theory that connects cause and effect in the case of changes induced by hydraulic regime alterations. The prediction of ecologists is based on both a general understanding of biological systems and a knowledge of local biota. Often the ecological data is quite limited which increases the uncertainty of prediction.

Thirdly, there is a problem of scales. Often the discussion between engineers and ecologists is hampered by the implicit use of vastly different time and space scales. The basis of the biological development depends on local properties of water and soil and on local short term changes of

temperature, flow or turbulence. The hydraulician often limits himself to temporally and spatially averaged variables (e.g. average velocity and depth).

The creation of a better understanding between the different disciplines must be pursued on three planes: education, execution of projects and research.

It is essential for existing and future hydraulicians, hydraulic and water resources engineers to expand their horizons to include some basic knowledge of the life sciences. Equally, aquatic ecologists should probably take more cognizance of the principles and the approach of the engineering sciences [Wetzel (1991)]. This exchange of basic knowledge should preferably start during specialist training of both scientific groups and be further fostered by training provided by employers.

The technical and operational design of water resources and related projects must be undertaken by a multi-disciplinary group containing not only hydraulicians and civil engineers, but also ecologists, hydrologists, economists, etc. Moreover, the involvement of environmental pressure groups, civilians and political decision makers in the design and decision processes should be part of the design and implementation process. An Environmental Impact Analysis should be the preferred approach because it provides for the full integration of hydrological, ecological, technical, economical and other significant values. The close cooperation of the relevant disciplines and a timely involvement of all interested parties is a condition for the social and political acceptance and successful implementation of the project.

Working with multi-disciplinary teams will improve mutual understanding among the disciplines and provide ways and means to ensure the planning of sustainable and ecologically sound development.

In short, hydraulicians should become more familiar with the fundamental concepts of ecology and be aware of the relevant characteristics of the water body under study. It should be noted also that the water body may already have been altered from its "natural" state owing to development. It is also evident that the aquatic ecologists must also in their turn make an effort to understand the principles of hydraulics and the skills which can be brought to bear to describe and quantify the physical conditions of the water body.

Organizing a workable entente between ecological and engineering disciplines is no easy task in the practical world of a complex river basin with its mixture of natural and altered water bodies, with its interactions of surface and groundwaters, with its basin changes, with its agricultural practices and with its demographic distributions.

Hydraulic engineers accustomed to work with systems should be able to collaborate with life scientists to adapt and expand their skills in systems and data manipulation in order to provide a frame work for effective collaborative interdisciplinary analysis and prediction. Interdisciplinary research jointly working in hydraulics and ecology must be stimulated in order to facilitate and to improve an integral approach to projects.

From the point of view of the engineer, research in the joint realms of hydraulics and the life sciences remains virtually unexplored. Some ideas for research topics are listed below which might be considered as a preliminary list for an integrated water resources research programme.

- Conceptual models of the entire ecosystem in a project area.
- Criteria to define the health of an ecosystem.
- Methods to gauge and monitor the health of an ecosystem.
- Mathematical models to predict the change in an ecosystem as a consequence of changes in the hydraulic regime.

Possibly, research along these lines could be adopted as a study requirement for future projects primarily aimed at the restoration, preservation or development of ecological systems.

A necessary first step in the process is to inform engineers of some of the ecological effects induced by hydraulic engineering works.

For example, hydraulicians should know that aquatic ecological systems are profoundly influenced by temperature gradients and the accompanying density variation of the water mass. In standing water, the water becomes stratified owing to the surface warming. The aquatic biota are adapted to this stratification. Flowing water, or wave action in shallow lakes which brings about strong turbulent mixing, makes the mass isothermal, destroying density gradients, which in turn means that the aquatic ecology is different from standing water. In running water, the mass of water is not only moving rapidly but also the bottom sediments may be transported vigorously from time to time, but in lakes and reservoirs the bottom sediments remain virtually undisturbed and may have a substantial benthic fauna community. There may also be quite strong influences on the chemistry of the water by interactions with the sediment. Groundwater flows may play an important role on benthic chemistry. River bottoms, except in their lower reaches, tend to be granular rather than muddy which in turn supports a different benthic community. Each of these physical regimes in standing and flowing water develops its own ecological system.

Consequently, any water resources project which converts one system to another, e.g. creation of a reservoir, brings about a major change in the aquatic ecology. The final outcome in the new regime is a matter of expert conjecture by the biologist because there are few models available and usually not much data.

But there are not only changes at the site of the project itself. The site is part of a larger system. For example, the creation of a reservoir can be the cause of changes in groundwater tables and fluxes and in downstream sediment and nutrient supplies.

Furthermore, hydraulic construction works are not only the cause of the conversion of the system but may also be directly disruptive especially to interface zones which are ecologically very important. Therefore, hydraulic structures should try to maintain the continuum in the ecological system and to preserve gradients in the physical parameters and to avoid sharp discontinuities.

Close cooperation of scientists and engineers will improve mutual understanding and provide the means to ensure sustainable and ecologically sound development.

The 21st century presents a challenge to all scientists and engineers who are working on water resources projects. Hydraulicians and civil engineers must adapt and develop their skills to understand and involve their colleagues in life sciences. Such a step is needed to meet the future and to be able to support responsible, ecologically sound planning for developments in order to have a sustainable life style for this and future generations. It is equally important that aquatic ecologists receive training in hydraulics, hydrology and engineering as part of a comprehensive and integrated training programme [Wetzel (1991)].



6 Conclusions

The preceding chapters and comments lead to the following conclusions:

1. The organization of the decision making process, which contains the design process as a sub-process, should guarantee the involvement of all relevant societal interest groups from the initial stage. If their role is neglected, delicate situations may arise, that can act as a brake for economic development.
2. Methodologies, to compromise the conflicting goals of ecology and economic development, must be developed more fully and applied consistently in the analysis and the organization of the intertwined design and decision process.
3. A systems approach by which the engineering and the ecological aspects of a development are basically considered in one step, must be introduced into the planning, execution and operation of water resources projects. The two step approach of first designing the engineering project and then considering the ecological effects should be phased out.
4. Distinct problems, which inhibit matching hydraulics and ecology are linked to inconsistencies, that may be identified as follows:
 - the difference in time and space scales for ecological and hydraulic processes
 - the higher development of modelling and schematisation skills in hydraulics compared to ecology
 - the limitation of the predictive capabilities in ecology by the state of data and the complexity of the biological system.
5. Innovative schemes at three planes: education, research and execution of projects, are required to initiate ways for scientists, engineers and economists to collaborate and to consider the hydraulic, the ecological and the economical needs simultaneously.
6. As the political decision making process is inclined to short term priorities, it is the responsibility of the scientific community to clearly present and create awareness of the impacts of human action, which are characterized by very long time lags, poor visibility, and serious consequences for groups that are indirectly involved.
7. The recognition of the above conclusions sets the scene for a sustainable development of water resources.

7 An annotated bibliography on case studies

Introductory comments

From the following short list of annotated case studies related to the problem of matching hydraulics and ecology it is possible to draw some conclusions:

- it is of paramount importance to nominate a team consisting of hydraulicians and ecologists in order to make in advance an evaluation of possible environmental consequences in the short as well as in the long run;
- data and necessary information must be available to perform an environmental impact assessment (EIA) - many projects have failed because of lack of primary data;
- sometimes it is necessary to look upon the consequences in a very wide perspective as should have been done for instance at the Aswan Dam project. Such a project will have far reaching societal consequences not so easily revealed if not a very careful analysis is done in advance;
- in making analyses it is sometimes important to consider those consequences which are due to human influence and those which are assignable to natural environmental changes. They may counteract or concur;
- making an EIA is sometimes expensive. Decision making without a reliable assessment can - in the long run - be a much more expensive affair.

Case studies

Abracos, R. and Ortolano, L., "Lessons from EIA for Bicol River development in Philippines". - Water Resources Planning and Management, Vol. 114, No. 5, 1988.

The study describes the development of the Bicol River basin (started in 1975) by providing integral projects for rural development. An environmental assessment study was performed but the outcome was quite inadequate and it really failed to predict negative impacts of the followed project implementation. This was especially true for the Lake Buhi vegetation project. The author claims that this situation in which an adequate assessment was followed by unanticipated adverse effects, is, unfortunately not unique. The reason for this failure stems both from the limited resources allotted for the EIA and the absence of effective review to spot deficiencies in environmental assessment documents. The author claims that if the EIA process had been adequately funded and used as a practical planning tool, it would have been possible to avoid some negative impacts by redesigning portions of the project and implementing mitigating features.

Bonetto, A. K., Wais, J. R. and Arquez, G. S., "Ecological considerations for river regulation of the Del Plata Basin according to flatland characteristics". - Water International, Vol. 13, No. 1, 1988.

In the northeastern region of Argentina there is an abundance, diversity and complexity of large rivers with 85 percent of the surface water of the country. However, paradoxically, the use of this vast amount of water has to be restricted because of large floods. Consequently it is necessary to optimize efforts to adopt measures which will allow an efficient development of the area. On the large lower Del Plata basin flatland there are dams mainly for hydroelectric purposes that may

cause ecological disturbances in the alluvial floodplains. During floods important hydrochemical and biological interactions taking place, affecting in the long run fish as well as plankton. When the river level falls the main stream receives remaining water from the flood plain which has considerably changed its physical, chemical and biological characteristics. According to ecological model studies these changes are related to the intensity of bioproductivity, especially fisheries. Because of the natural complexity of the different environments of the flood plains, with very particular ecosystems with a very complicated ecological functioning it is necessary to perform multidisciplinary studies of connections among physical, chemical and biological variables. The authors particularly conclude that the dams already built on the rocky reaches of the Del Plata basin do not represent any greater ecological risks than those already well-known as a consequence of this type of dam. However, the problems will occur when dams are constructed for the plain area or as the authors claim "In the plain area it would be more important to regulate the flow volume to prevent floods than to obtain hydroelectricity".

Card, J. R., "The Peace Athabasca delta, Canada" in "Hydro-environmental indices: a review and evaluation of their use in the assessment of the environmental impacts of water projects", Unesco 1984.

This paper deals with the consequences of a large hydro-electric dam on the Peace river in north-western Canada, which was supposed to create significant changes on a large inland delta, some 1200 km downstream. The dam was completed in 1967 and the filling of the reservoir took place during the next three years. Since it had been claimed that the biological regime of the delta should be affected a study was undertaken in order to assess the impacts and to recommend remedial measures.

However, not until the completion of the dam and the filling of the reservoir had been made the downstream problems became apparent in the delta, encompassing an area of 6000 km². The vegetation and the landscape of this delta has been the habitat and food supply of many wildlife species and the delta has served as a retreat in years of drought for continental waterfowls. The water level of the delta is controlled by the Lake Atkabara and the river Peace where the dam is situated, is controlling the outflow from the lake. Changes in this river due to operation of the dam was studied. A hydrological model was derived as well as one for the biological system. It became evident that the potential biological changes in the delta, due to the dam operation, were unacceptable. So, consequently alternative questions of the dam had to be chosen in order to restore the natural characteristics of the Peace river and to recreate the biological conditions in the delta. However, this has not been quite feasible because the models were rather crude and therefore more knowledge would have been desirable.

Cummins, J. D., "The Anacostia river restoration: a case study". - Coastal Zone 89, ASCE.

The Anacostia river is a tributary to the Potomac river, flowing through large metropolitan communities in Maryland and the District of Columbia. Within the Anacostia basin the aquatic habitats are diverse with meandering coastal flood-plain streams, marshes, wetlands, and tidal waters, etc. However, large portions of the basin have undergone urbanization and moreover the remaining rural area is increasingly subject to development. The quality of water in the Anacostia has been bad due to urbanization. The fish population has also declined between 1948-1972. However, in 1984 a watershed restoration was decided and measures were taken to reduce the effects of sewage systems, urban runoff etc. Modern technique was applied by using peat-sand

filters in association with retrofitted and storm water detention ponds. The aim of these filters is to reduce nutrient and toxic burdens from suburban runoff. The author of this paper claims that the Anacostiana river represents an excellent case study for the restoration of an urban watershed. The success of this environmental engineering task is very much based on innovative technology and interagency cooperation.

Gasser, M. M. and Mohamed Ibrahim Abdou, "Nile water management and the Aswan High Dam". - Water Resources Development, Vol. 5, No. 1, 1989.

Mahmoud Abu Zeid, "Environmental impacts of the Aswan High Dam. A Case Study. - Water Resources Development, Vol. 5, No. 3, 1989.

One of the most spectacular hydraulic engineering works in our time is the Aswan High Dam that now has been operation during 20 years. The negative and positive impacts of the Dam has also been discussed frequently during these years.

The difficulty in identifying the various effects of the High Dam has to a rather big extent been depending on the fact that we do not have had sufficient access tot data. According to the recent paper, mentioned above, we now have these operational data which furthermore indicate that the objective evaluation shows that the effect of the dam has been overwhelmingly positive even though it has contributed to some environmental problems. According to the authors of the first paper the importance of the High Dam is unquestionable as to the social and economic development of Egypt. Especially they claim that by controlling now the flow of the River Nile, damage due to floods and droughts has now been mostly eliminated. How important the dam has been - and still is - for the water management in Egypt can be judged from a speech by Dr Tolba (UNEP): "The real question is not whether the Egyptians should have built the Aswan Dam or not - for Egypt realistically had no choice - but what steps should have been taken to reduce the adverse environmental impacts to a minimum".

Jong, J. de and Roelofs, J. H., "Ecology and the Zuiderzee project". - Water, Science and Technology, Vol. 16, Rotterdam, pp. 171, 1984. See also: "Dams and Environment - The Zuiderzee damming". ICOLD Bulletin 66, 1989.

The former Zuiderzee, a large estuarine area over 500,000 ha located in the northwestern part of the Netherlands has undergone great changes due to the execution of the Zuiderzeeproject. Within the framework of this project 375,000 ha of the area has been dammed and excluded from the influence of the sea. The waters in the area were turned into stagnant, eutrophic freshwaters by using the water from the river IJssel. In the dammed off region also four polders, having a total area of 165,000 ha have been reclaimed. A fifth polder of 41,000 ha is planned, but not yet decided upon. The execution of this project was started in 1919 and is still not yet finished.

In the beginning of the execution of the project, due to the social and economic conditions of that time, only limited attention has been paid to ecological expects of the project during planning, execution and initial management. However the ecological changes, that would occur, were regarded to be very important from a scientific point of view. As a result both the original situation and the changes in the aquatic ecosystem have been monitored. Also transient high ecological values of the new polders have been well documented by the scientists.

As a result, when social and economic conditions changed after the second world war and especially in the period after about 1965, a sound basis of biological and ecological knowledge was

present and incorporated in the state authorities involved, to enable the additions of ecological considerations into the development of both polders and lakes.

Due to the flexibility of the Zuiderzee project, where the project is executed polder after polder, in the two polders, that have been made after the second world war, large areas of forest and nature reserves have been realized next to other means of land use such as agriculture, infrastructure, recreation and urbanization.

By this way changing views of society reflect upon the way of development and management of both land and lakes.

Nowadays, both lakes and polders provide on a international level high ecological values, especially for birds, in spite of drastic ecological changes.

A careful planning, execution and management by state organizations, assisted by continuous research, prove to be essential factors to realize these results.

Knoester, M., Visser, J., Bannink, B. A., Colijn, C. J. and Broeders, W. P., "The Eastern Scheldt Project". – Water, Science and Technology, Vol. 16, Rotterdam, pp. 51, 1984.

In the planning of the Delta-works, carried out in the Southwestern Netherlands, the Eastern Scheldt was the largest and therefore the last tidal basin to be fully closed mainly to protect the area from floods. Increased recognition for the natural value of estuaries and a strong lobby from nature conservationists and shellfish producers led to a reconsideration of original plans, confirmed by a series of governmental decisions. Per consequence execution of the present plans will result in a storm-surge barrier at the entrance of the tidal basin together with two partitioning dams, separating the (reduced) tidal Eastern Scheldt from a new freshwater lake. Attention is paid to the present values in the Eastern Scheldt and briefly to changes involved by the project. The decisionmaking process described and discussed: In the course of the project the majority of decisions taken were prepared by teams of ecologists, civil engineers, hydrologists and financial experts, using policy-analysis methods. For guidance of developments in the influenced area the local government accepted a policy plan, in which human uses are regulated. Operations of the barrier are designed such that safety from flooding is guaranteed, while adverse effects for the tidal ecosystems are minimized.

La Bounty, J. F. and Sartoris, J. J., "The influence of environmental data on the design and construction of the M.T. Elbert Pumped-Storage powerplan". – Waterpower 81, An international conference on hydropower. US Army Corps of Engineers, Washington DC, 1981.

Many problems that occur as consequences of conflicts between hydraulicians and ecologists may be traced back to a negligence of pre-investigations of the actual project. However, there are also situations where the premises are very well investigated like the one presented in this paper. The pumped storage plant located on Twin Lakes central Colorado is a peaking-type facility in that it will generate for only a few hours per day. A research project was started in 1971 to study the effect of the pumped-storage operations in the Twin Lakes, especially the physical, chemical and biological consequences for the lakes. The potential or suspected effects fall into three categories: disruption of the thermal regime, disturbance of the bottom sediments, and mortality of aquatic biota. Considerable efforts have been expended to keep flow velocities in the tailrace low and to divert the generating discharge along the shoreline in order to minimize effects of thermal stratification. However, water will be pressed back and forth through the powerplant

resulting in some thermal loading. This may lead to a change of the species composition of the plankton population.

This general study of the ecological effects gave rise to a good co-operation between environmental researchers and design construction engineers. The authors point out that these studies made it possible for the engineers to incorporate many research findings in the finished project.

Messieh, S. N., "Human-induced damage to coastal marine ecosystems". - Coastal Zone 89, ASCE.

This paper deals with three case studies in the Maritime Provinces of Canada representing coastal zone habitat problems. The coastal projects range from small-scale modifications such as those caused by small dams and causeways to large-scale dredging or hydro-electric power development. Particularly interesting in Messieh's paper is the analysis of the causeway built across the Strait of Canso in order to connect Cape Breton Island with the mainland Nova Scotia whereby St. Georges Bay was separated to the North and Chedabecto Bay to the South. The strait is 27 km long, less than 2 km wide, and from 30 to 60 deep. The causeway was built without impact studies, however influenced by economic and political decisions. Dramatic changes were caused by the construction. For instance, there was a change in the cyclonic circulation in St Georges Bay resulting into anti-cyclonic circulation with severe biological consequences. From this and other consequences the author concludes that the only way of avoiding such ecological problems is to integrate resources planning with habitat and fisheries management objectives.

Ruxton, T. D. and Downing, A. L., "Integration of ecological and engineering investigations over recent years in England and Wales and the far East". - Water Science and Technology, Vol. 16, 1984.

This case study concerns several feasibility studies - requiring ecological investigations - that have been carried out in England and Wales. Three examples are referred to in this paper, namely the Dee estuary, The Bay of Wash on the east coast of England, and the Severn estuary. It appears from these case studies that a considerable benefit has been gained from having been able to develop a small core group of engineers and ecologists, who worked together over several years. Certainly this co-operation meant that the participants of the team had reached a good insight into a discipline outside their own. The authors particularly remark that the teamwork has helped to "overcome the problem of polarised positions whereby on the one hand biologists and other scientists knowing the complexity of ecosystems are reluctant to have them described by equations which are often at best crude generalizations; and at the other engineers and system analysts habitually inclined to formalize the behaviour of systems in algebraic expressions are reluctant to see the difficulties of deriving adequate ones for living systems".

Smedile, E., "The thermo-electric power station Porto Tolle (Delta of the river Po, Italy)" in "Hydro-environmental indices: a review and evaluation of their use in the assessment of the environmental impacts of water projects", Unesco 1984.

The subject of this study was the consequences for the area surrounding a thermo-electric power station utilizing cooling waters from the river Po and from adjacent lagoon known as Sacca del

Canarin. The used water will be returned either into the river or into the Adriatic Sea. The area affected by the installation of the power station involves three main types of environment: the stretch of the river, the coastal lagoons connected with the river and the adjacent marine area. Environmental effects may be salt water intrusion, changes in water quality due to rising temperature and on aquatic, biological communities and vegetation. The study was performed as a description of the complete system during the pre-operational phase in order to make possible comparison with the situation when the power station has come into operation. The study was carried out using environmental indices and a special attempt was made to distinguish between indicators caused by operation of the plant and those caused by natural changes. This approach gives additional dimensions to the task of matching hydraulics and ecology by emphasizing the necessity to include also natural changes of the environment, besides those caused by man, in solving conflicts.

Szekely, F., "Environmental impact of large hydro-electric projects on tropical countries". - Water Supply and Management, Vol. 6, No. 3, 1982.

This is a more general case study with examples taken from the Kainji dam on the Niger River in Nigeria, the Volta dam and dams in Latin America. The author's general comments on how to match hydraulics and ecology are very interesting. Like other authors he stresses the need of preparing environmental impact studies prior to the construction and operation of a hydroelectric project. When discussing hydro-electric dams in developing countries it is of fundamental importance to consider also diseases caused by the high dam which may impose high social costs. With respect to the irreversibility of certain effects associated with the building and operation of large hydroelectric systems as for instance the degradation of the ecosystem, the author emphasizes that it is cheaper to plan by taking into account the variable environment then by trying to solve problems post mortem. Therefore he also recommends a new type of development-ecodevelopment - which seeks to balance the interrelation between man and the environment, a challenging task for hydraulicians and ecologists.

UNESCO/UNEP, "The impact of large water projects on the environment". - UNESCO/UNEP, Paris 1990.

This document containing 46 papers in more than 550 pages form a symposium organized by Unesco/UNEP in co-operation with IIASA and the IAHS in 1986 is a valuable book promoting a better understanding of the conflicts that may develop between hydraulic engineers and ecologists if projects are not properly prepared. The book is divided into five themes covering impacts of various hydraulic projects - small as well as large - on the environment, methodologies for assessment of impacts, public information and participation in the decision making process etc.

There are a lot of conclusions and recommendations presented in the book based on findings of the participants at the Symposium. The following opinion may for instance be quoted: "water resources projects have a dual-objective nature, namely, to serve both socio-economic development and ecological-environmental development. These dual, but sometimes conflicting, objectives require trade-offs between them". To find an appropriate solution of this conflicting situation one has to make compromises between the dual objectives. A solution may be found by an

environmentally sound management of the water resources projects which should be oriented towards the establishment of a long-term dynamic equilibrium between the water project and its environment.

Another aspect that has been stressed in the book is that the costing of environmental impact management as identified by EIA has to be integrated into the planning procedure already when identifying project alternatives. Such a dual view should continue throughout the whole planning cycle to include an external review of the assessment document and involvement of the public.

8 Literature

- ALDAMA, A. A., D. R. F. HARLEMAN and E. E. ADAMS, (1989), Hypolimnetic mixing in a weakly stratified lake, *Water Resour. Research*, 25, 5, pp. 1014-1024.
- ALLANSON, B. R., (1985), Thermal characteristics: chairman's summary, *Hydrobiologia*, 125, pp. 71-73.
- BARENDREGT, A. and J. W. NIEUWENHUIS, (1991), Identification of ecological parameters for application in sustainable ground-water management, In Nachtnebel H. P. and Kovar K. (eds.) Proc. of IAHR Conference on "Hydrological basis for ecologically sound management of soil and ground-water", IAHR Press, Wallingford, Oxon, UK.
- BENGTTSSON, L., (1973), Wind Stress on Small Lakes, Report No. 16, Series A. Dept. of Water Resources Eng., University of Lund, Sweden.
- BLEED, A., H. P. NACHTNEBEL, I. BOGARDI and R. J. SUPALLA, (1990), Decision making on the Danube and the Platte, *Water Resources Bull.* 26, 3, pp. 479-487.
- BRAGA, G. and S. GERVASONI, (1983), "Evoluzione storica dell'alveo del fiume Po nel territorio Lodigiano", *Atti convegno naz. Il suolo come risorsa*, 60: pp. 59-69.
- BROOKES, ANDREW, (1988), *Channelized rivers, perspectives for environmental management*, Chichester, Wiley, 326 p.
- BRUIN, D. DE, D. HAMHUIS, L. VAN NIEUWENHUIJZE, W. OVERMARS, D. SIJMONS and F. VERA, (1987), Stork; the future of the riverine area, (In Dutch, Ooievaar; De toekomst van het riviereengebied), Arnhem, Stichting Gelderse Milieufederatie, 128 p.
- BRUNDTLAND, G. H. (ed.), (1987), *Our common future*, Oxford University Press, p. 43.
- CANTER, L. W. and L. G. HILL, (1981), *Handbook of variables for environmental impact assessment*, Ann Arbor Science Publ., Michigan.
- CARD, J. R. and P. LEENTVAAR (eds), (1984), *Hydro-Environmental Indices: A Review and Evaluation of their Use in the Assessment of the Environmental Impacts of Water Projects*, IHP-II Project A3, 2, UNESCO, Paris.
- CLAPHAM, W. B., (1973), *Natural Ecosystems*, Mac Millan Press, NY.
- CLEMENTS, F. E. (1905), *Research methods in ecology*, Univ. Publ. Co., Lincoln, NE.
- CUMMINS, K. W., G. W. MINSHALL, J. R. SEDELL, C. E. CUSHING, and R. C. PETERSEN, (1984), "Stream ecosystem theory", *Verh. Int. Ver. Limnol.* 22: pp. 1818-1827.
- CZAYA, E. (1981), *Ströme der Erde*, Dentuer Verlag, Köln, BRD.
- DANIELOPOL, D. and P. POSISIL, (1991), Ecological basic research with potential application for ground-water management, In Nachtnebel, H.P. and Kovar, K. (eds), Proc. IAHR Conference on Hydrological basis for ecologically sound management of soil and ground-water, to appear 1991, IAHR, Press, Wallingford, Oxon, UK.
- DAVID, L., (1986), Environmentally Sound Management of Freshwater Resources, *Resources Policy* 12(4): pp. 307-316.
- DE ANGELIS, D. L., (1980), Energy flow, nutrient cycling and ecosystem resilience, *Ecology* 61, pp. 764-771.
- DECAMPS, H., M. FORTUNE, F. GAZELLE and G. PATOU, (1988), Historical influence of man on the riparian dynamics of fluvial landscapes, *Landscape ecology* 1: pp. 163-173.
- DUEL, H., (1991), Nature restoration of floodplains, (In Dutch: Natuurontwikkeling in uiterwaarden), research report INRO-TNO, Delft 91/NE/005, 206 p.
- DYER, K. R. (1973), *Estuaries: A physical Introduction*, Wiley, London and New York.

- DUCKSTEIN, L., A. TECLE, H. P. NACHTNEBEL and B. F. HOBBS (1989), Multicriterion analysis of hydropower operation, *J. of energy Engineering, ASCE*, 115, 3, pp. 132-153.
- FALKOWSKI, P. G. (1984), Physiological responses of phytoplankton to natural light regimes, *J. Plankton Res.*, 6, pp. 295-307.
- FISHER, S. G. (1977), "Organic matter processing by a stream-segment ecosystem, Fort River, MA.", *Int. Rev. Hydrobiol.* 62, pp. 701-727.
- FORTUNE, M. (1988), "Historical changes of a large river in an urban area: the Garonne river, Toulouse, France". *Regulated rivers*, 2: pp. 179-186.
- GERSHON, M. E. and L. DUCKSTEIN (1984), A procedure for selection of a multi-objective technique with application to water and mineral resources, *Applied Math. and Computation* 14, 3, pp. 245-271.
- GOICOECHEA, A., D. HANSEN and L. DUCKSTEIN (1982), *Multi-objective Decision Analysis with Engineering and Business Applications*, John Wiley and Sons, New York, New York.
- GOODMAN, A. S. and R. J. TUCKER (1971), Time varying mathematical model for water quality, *Water Res.* 5, pp. 227-241.
- HAIMES, Y. and D. J. ALLEE (1982), *Multi-objective Analysis in Water Resources*, Proceedings of the Engineering Foundation Conference, ASCE, New York, New York.
- HENDERSON-SELLERS, B. and A. M. DAVIS (1989), Thermal stratification modelling for oceans and lakes, In Tien C. L. and T. H. Chawla (eds.), *Annual Review of Numerical Fluid Mechanics and Heat Transfer*, Vol. II, Hemisphere Publ. N.Y.
- HERZIG, A. (1989), Limnologische Veränderungen im Ökosystem Donau durch das Donaukraftwerk Altenwörth, In Hary N. and H. P. Nachtnebel (eds.), *Ökosystemstudie Donaustau Altenwörth*, p. 95-120. Veröffentlichung des Österr. MaB Programmes, ÖAW, Bd. 14, Universitätsverlag Wagner, Innsbruck.
- HAKANSSON, L. and T. AHL (1976), Lake Vättern - Recent sedimentary deposits and sediment chemistry (in Swedish with English summary), SNV PM 740, The National Swedish Environmental Protection Board, Sona, Sweden.
- HOLLAND, M. M. (1988), "SCOPE/MAB technical consultations on landscape boundaries, Report of a workshop on ecotones, *Biology International*, special issue 17: pp. 47-106.
- HOLSTRÖM, I. and B. CARLSSON (1978), Hydrologi - Storsjöarners hydronamik, In Vänern - en naturresurs, The National Swedish Environmental Protection Board, Solna, Sweden.
- HUBBARD, J. G. and T. H. CHRZANOWSKI (1986), Impact of storms on heterotrophic activity of epilimnetic bacteria in a southwestern reservoir, *Appl. Environ. Microbiol.*, 51, pp. 1259-1263.
- HYNES, H. B. N. (1970), *The ecology of running waters*, Liverpool Univ. Press.
- IMBERGER, J. (1979), Mixing in reservoirs, In: Fischer H. B. (ed.), *Mixing in inland and coastal waters*, Academic Press, New York.
- IMBERGER, J. (1985), Thermal characteristics of standing waters: an illustration of dynamic processes, *Hydrobiologia* 125, pp. 7-29.
- JACOBS, T. C. and J. W. GILLIAM (1985), "Riparian losses of nitrate from agricultural drainage waters", *J. of Env. Quality*, 14: pp. 472-478.
- JAEGGI, M. (1985), Die flußbauliche Bedeutung alternierender Kiesbänke, *Wasser, Energie, Luft*, H. 1/2. p. 14-18. Baden, Schweiz.
- JOERGENSEN, S. E., L. A. JOERGENSEN, H. F. MAJOR and L. KAMP-NIELSEN (1982), A water quality model for the upper Nile lake system, pp. 631-639, In Lauenroth, W. K., Skogerboe, G. V. and M. Flug (eds.), *Analysis of Ecological Modelling, Developments in Environmental Modelling*, Vol. 5, Elsevier Scientific Publ. Comp., Amsterdam.

- JONG, J. DE and J. H. ROELOFS (1983), Ecology and the Zuiderzee project, Water, Science and Technology, Vol. 16, Rotterdam, pp. 171, 1984. See also ICOLD Bulletin 66, 1989.
- KNOESTER, M., J. VISSER, B. A. BANNINK, C. J. COLIJN and W. P. BROEDERS (1983), The Eastern Scheldt Project, Water, Science and Technology, Vol. 16, Rotterdam, pp. 51, 1984.
- LAUENROTH, W. H., G. V. SKOGERBOE and M. FLUG (eds.) (1983), Analysis of Ecological Systems: State of the Art in Ecological Modelling, Elsevier Scientific Publ., Amsterdam.
- LEEMANS, J. A. A. M. (1985), Research on the relation between vegetation, sand mining and river regime in the floodplains of Gelderland, (In Dutch: Onderzoek naar de relatie tussen vegetatie, ontgrondingen en rivierregime in de Gelderse uiterwaarden), Provincie Gelderland, Dienst Landinrichting en Landbouw, Afdeling Natuur en Landschap, januari 1985, 118 p.
- LEOPOLD, L. B. and T. MADDOCK (1953), The hydraulic geometry of stream channels and some physiographic implications, USGS Prof. Paper 252, 57 p.
- LINDEMAN, R. L. (1942), The Trophic dynamic aspect of ecology, Ecology, 23, pp. 399–418.
- LITTLE, A. F. (Inc.), Report on Channel Modifications, Vol. I, Prepared for the Council of Env. Quality, USA.
- MARMONIER, P. and M. J. DOLE (1986), Les amphibodes des sédiment d'un bras court-circuite du Rhône, Science de l'eau 5, pp. 461–486.
- McHUGH, J. L. (1966), Management of estuarine fisheries, In: A symposium on Estuarine Fisheries American Fisheries Society Special Publication No. 3.
- MELLOR, G. L. and P. A. DURBIN (1975), The structure and dynamics of the ocean surface mixed layer, Journal of Physical Oceanogr., 5, pp. 718–728.
- MICHAELIS, W. (ed.), (1990), Estuarine Water Quality Management (Monitoring, Modelling and Research) Coastal and Estuarine Studies, No. 36, Springer-Verlag, Berlin, Heidelberg, New York, London, Paris, Tokyo, Hong Kong.
- MITSCH, W. J., M. STRASKRABA and S. E. JORGENSEN (eds.), (1988), Wetland modelling, Developments in Environmental modelling 12, Elsevier, 227 p.
- NACHTNEBEL, H. P. (1989), Hydrologische Veränderungen durch das Kraftwerk Altenwörth, p. 26–91. In Hary N. and H. P. Nachtnebel (eds.), Ökosystemstudie Donaustau Altenwörth, Vol. 14, Man and Biosphere Program, Austrian Academy of Sciences, Universitätsverlag Wagner, Innsbruck Austria.
- NAIMAN, R. J. and H. DECAMPS (eds.), (1990), The ecology and management of aqua-terrestrial ecotones, Man and Biosphere Series, Vol. 4, UNESCO, Paris.
- NAUMAN, E. B. and B. A. BUFFHAM (1983), Mixing in continuous flow systems. Wiley - Interscience, New York.
- NEWBURY, R. W. (1984), Hydrologic determinants of aquatic insect habitats, In: Resh V. H. and D. M. Rosenberg (eds.), The ecology of aquatic insects, Praeger, NY, pp. 327–357.
- NIEUWKAMER, R. L. J. (1991), Development of a decision support system for river planning and management, DELFT HYDRAULICS and University of Twente, report Q1065.
- NYHOLM, N. (1975), A simulation model for phytoplankton growth and nutrient cycling in eutrophic shallow lakes, Ecol Modelling 4, pp. 279–310.
- OBENG, L.E. (1981), Man's impact on tropical rivers in LOCK, M. A. and D. D. Williams (eds.), Perspectives in Running Water, pp. 263–288, Plenum Press, NY.
- OCTAVIO, H. K., G. H. JIRKA and D. R. F. HARLEMAN (1977), Vertical Heat transport mechanisms in lakes and reservoirs, Techn. Rep. 227, Ralph Parsons Lab. MIT, Cambridge, USA.
- ODUM, H. T. (1957), Trophic structure and productivity of silver springs, Florida, Ecological Monographs 27, pp. 44–112.

- PATTERSON, J. C., P. F. HAMBLIN and J. IMBERGER (1984), Classification and dynamic simulation of the vertical density structure of lakes, *Limnol. Oceanogr.*, 29, pp. 845-861.
- PERKINS, E. J. (1974), *The biology of Estuaries and Coastal Waters*, Academic Press, London and New York.
- PETTS, G. E. (1984), *Impounded rivers, Perspectives for ecological management*, J. Wiley & Sons.
- PETTS, G. (1990), "Forested river corridors: a lost resource", Chapter 2 in D. Cosgrove and G. Petts, *Water, engineering and landscape*, Belhaven Press.
- PINAY, G. and H. DECAMPS (1988), "The role of riparian woods in regulating nitrogen fluxes between the alluvial aquifer and surface waters, A conceptual model", *Regulated rivers*, 2: pp. 507-516.
- PRINGLE, C. M., R. J. NAIMAN, G. BRETSCHKO, J. R. KARR, M. W. OSWOOD, J. R. WEBSTER, R. L. WELCOMME and M. D. WINTERBOURNE (1988), "Patch dynamics in lotic systems: the stream as a mosaic", *J. North Amer. Benth. Soc.* 7: pp. 503-524.
- PRITCHARD, D. W. (1955), *Estuarine circulation patterns* American Society of Civil Engineers 81, pp. 717/1-717/11.
- RAGOTZKIE, R. A. (1978), *Heat budgets of lakes*, In: A. Lerman (ed.), *Lakes: chemistry, geology, and physics*, Springer, New York.
- REYNOLDS, C. S. (1984), *The ecology of freshwater phytoplankton*, Cambridge University Press, Cambridge.
- RIDLEY, J. E. and J. A. STEEL (1975), *Ecological Aspects of River Impoundments*, In: B. A. Whitton (ed.), *River Ecology*, pp. 565-587, Blackwell Scientific Publications.
- ROBARTS, R. D. (1986), *Decomposition in freshwater ecosystems*, *J. Limnol. Soc. Sth. Afr.*, 12, pp. 72-89.
- ROBARTS, R. D. (1987), *Effect of rainstorms on heterotrophic bacterial activity in a hypertrophic African lake*, *Hydrobiologia*, 148, pp. 281-286.
- RUNHAAR, J. (1986), *Assessment and evaluation of effects on the natural environment*. (In Dutch: Voorspelling en beoordeling van effecten op het natuurlijk milieu), DELFT HYDRAULICS and Universiteit Leiden CML, rapport T195, mei 1986.
- SEDELL, J. R. and J. C. FROGATT (1984), "Importance of streamside forests to large rivers", *Verh. Int. Ver. Limnologie*, 22: pp. 1828-1834.
- SEWELL, W. R. D. and A. BISWAS (1986), *Implementing Environmentally Sound Management of Inland Waters*, *Resources Policy* 12: pp. 293-306.
- STATZNER, B. and B. HIGLER (1985), "Questions and comments on the river continuum concept", *Can. J. Fish. Aquat. Sci.* 42: pp. 1038-1044.
- STATZNER, B. and B. HIGLER (1986), "Stream hydraulics as a major determinant of benthic invertebrate zonation patterns", *Freshwater Biology*, 16: pp. 127-139.
- STRASKRABA, M. and A. GNAUCK (1983), *Aquatische Ökosysteme*, Gustav Fischer Verlag, Stuttgart.
- STREETER, H. W. and B. PHELPS (1925), *A study of the pollution and natural purification of the Ohio river*, *Publ. Health Bull.* 146, pp. 1-25.
- STRIKSMAN, N. and G. J. KLAASSEN (1988), "On the threshold between meandering and braiding", In: W. R. White (ed.), *Int. Con. on River Regime*, J. Wiley & Sons, pp. 107-118.
- SVENSSON, U. (1978), *A mathematical model of the seasonal thermocline*, Report No. 1002, Dept. of Water Resources Eng., University of Lund, Sweden.
- UNEP & UNESCO (1990), *The impact of large water projects on the environment*. UNESCO, Paris.

- UNESCO (1987), Integrated Environmental Evaluation of Water Resources Development, Methodological Guidances, Paris, France.
- VANNOTE, R. L., G. W. MINSHALL, K. W. CUMMINS, J. R. SEDELL and C. E. Cushing (1980), "The river continuum concept", *Can. J. Fish. Aquat. Sci.* 37: pp. 130-137.
- VERMEER, K. (1989), RIJNMOR, morphological model of the branches of the River Rhine in the Netherlands, (In Dutch: RIJNMOR, morfologisch model van de Nederlandse Rijntakken), DELFT HYDRAULICS, report Q 938, november 1989.
- VIERSSSEN, W. VAN and H. G. WIND (1990), Rivieren, natuurlijk dynamisch, Eindrapport externe advisering Rijkswaterstaat, DBW/RIZA, opdracht DB-586, IHE Delft, Universiteit Twente, april 1990, 181 p.
- VISSMAN, W. and K. E. SCHILLING (1986), Social and Environmental Objectives in Water Resources Planning and Management, Proc. Engineering Foundation Conference, ASCE, New York, New York.
- VOLLENWEIDER, R. A., W. RASS and J. KERESKES (1980), The phosphorous loading concept and great lakes eutrophication, In: Loehr R. C., C. S. Martin and W. Rast (eds.), Phosphorous management strategies for lakes, pp. 207-234, Ann Arbor Science Publ. Michigan.
- VRIES, M. DE (1985), Rivers, (In Dutch: Rivieren), Lecture notes f8N, Delft University of Technology, Faculty of Civil Engineering, 129 p.
- WAIDBACHER, H. (1989), Veränderungen der Fischfauna durch Errichtung des Donaukraftwerkes Altenwörth, In: Hary N. and H. P. Nachtnebel (ibid).
- WARING, R. H. (1989), Ecosystems: Fluxes of matter and energy, In: Cherrett, J. M. (ed.), Ecological Concepts, Blackwell Scientific Publ., pp. 17-41, UK.
- WETZEL, R. G. (1983), Limnology, Saunders College Publishing, Philadelphia.
- WETZEL, R. G. (1991), On the teaching of limnology: Need for a national initiative, *Limnology and Oceanography* 36: pp. 213-215.
- WIJBENGA, J. H. A. (1985), "Determination of flow patterns in rivers with curvilinear co-ordinates", Proc. of the 21st Congress of the International Association for Hydraulic Research, Melbourne, Australia.
- WILLIS, R., D. R. ANDERSON and J. A. DRACUP (1975), Steady State Water quality modelling in stream, Proc. ASCE. J. of Env. Eng. Div. 101, pp. 245-248.
- WILSON, J. G. (1988), The Biology of Estuarine Management, Croom Helm, London, Sydney and New York.
- ZOHARY, T. and R. D. ROBARTS (1989), Diurnal mixed layers and the long-term dominance of *Microcystis aeruginosa*, *J. Plankton Res.*, 11, pp. 25-48.
- ZOHARY, T. and R. D. ROBARTS (1990), Hyperscums and the population dynamic of *Microcystis aeruginosa*, *J. Plankton Res.*, 12, pp. 423-432.

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10 Vocabulary of aquatic ecosystems

aquatic	growing, living, or found in water (adj.)
terrestrial	living or growing on the land (adj.)
biota	the plant and animal life of a particular region or period
biotic	of or relating to living organisms (adj.)
abiotic	related to absence of life (adj.)

Classification of aquatic biota according to their mode of life:

plankton	what inhabits the surface layer of the water	
	zooplankton	floating animals
	phytoplankton	small floating plants (e.g. algae)
	haliplankton	sea plankton
	limnoplankton	lake plankton
	potamoplankton	river plankton
nekton	what swims in the water at middle depths	
benthos	what lives at the bottom	
	zoobenthos	animals that live at the bottom
	phytobenthos	plants that live at the bottom
neuston	what floats on the surface film of the water	
benthic	living at the bottom	
lotic	living in running water	
lentic	living in standing water	
rheophilic	loving running water (lotic)	
stagnophilic	loving standing water (lentic)	

Classification according to size:

macro	big
meio	middle
micro	small

The major zones in lakes:

littoral zone	shallow water region where light penetrates to the bottom, typically occupied by rooted plants
limnetic zone	open water zone up to the depth effectively lighted by the sun
euphotic zone	the total illuminated stratum (littoral + limnetic zone)
profundal zone	bottom and deep water zone beyond the effective penetration of sun light

Regarding thermal stratification during summer in temperate regions:

epilimnion	upper warm water layer
hypolimnion	deep cold water layer
thermocline	layer, separating the epi- and the hypolimnion, where the water-temperature drops

The major zones in streams:

rapids zone	shallow water where the current velocity is high enough to keep the bottom clear of loose sediment
pool zone	deeper water where the velocity is reduced and sediment settles to provide a soft bottom

Classification of biota based on the position in the food chain:

nutrients	chemicals needed to form living organisms (e.g. phosphorus, sulfur, nitrogen, calcium, silicium, etc.)	
	macronutrients	nutrients required in large amounts for healthy growth
	micronutrients	nutrients required in minute amounts for healthy growth (trace elements)
flora	plants producing organic matter from sunlight and nutrients by photosynthesis	
fauna	animals consuming plants, other animals or detritus	
herbivores	animals consuming plants (primary consumers)	
carnivores	animals consuming other animals (secondary or tertiary consumers)	
omnivores	animals consuming plants and other animals	
detritus	dead organic matter	
grazers	herbivores; primary consumers grazing primary producers (e.g. zooplankton grazing phytoplankton)	
autotrophic	feeding from internal sources by photosynthesis (primary producers)	
heterotrophic	feeding from external sources (consumer)	
	biophages	organisms consuming other organisms
	saprophages	organisms consuming dead organic matter (detritus)
eutrophic	well fed, rich in nutrients	
oligotrophic	poorly fed, poor in nutrients	
crustacea	animals with shells and jointed legs	
molluscs	shellfish	
ecology	the science studying the totality or pattern of relations of organisms with their environment (living as well as dead)	
ecosystem	a system involving the interactions between all elements of flora and fauna and the physical environment	
ecotone	transition between two ecosystems e.g. land and water or forest and grassland	
biology	the science of living organisms	
biomass	the total mass of living organisms in a certain space	

Some chemical variables:

pH	measure of proton activity
pE	measure of electron activity, redox potential
DOC	dissolved oxygen concentration
BOD	biological oxygen demand

