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Partnership in Sustainable Development

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Contents

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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 [Haimes 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.

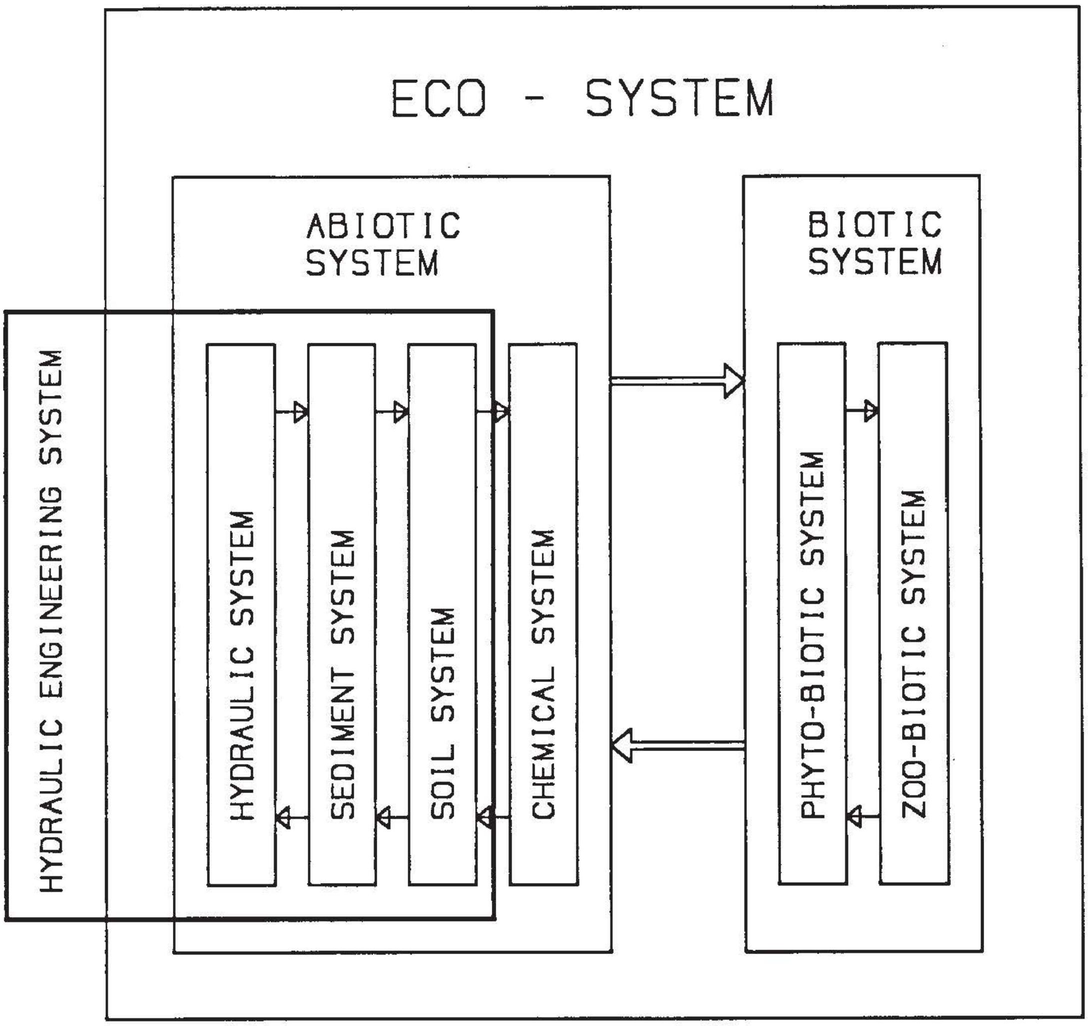

Fig. 2.1 Systems approach of ecology.

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

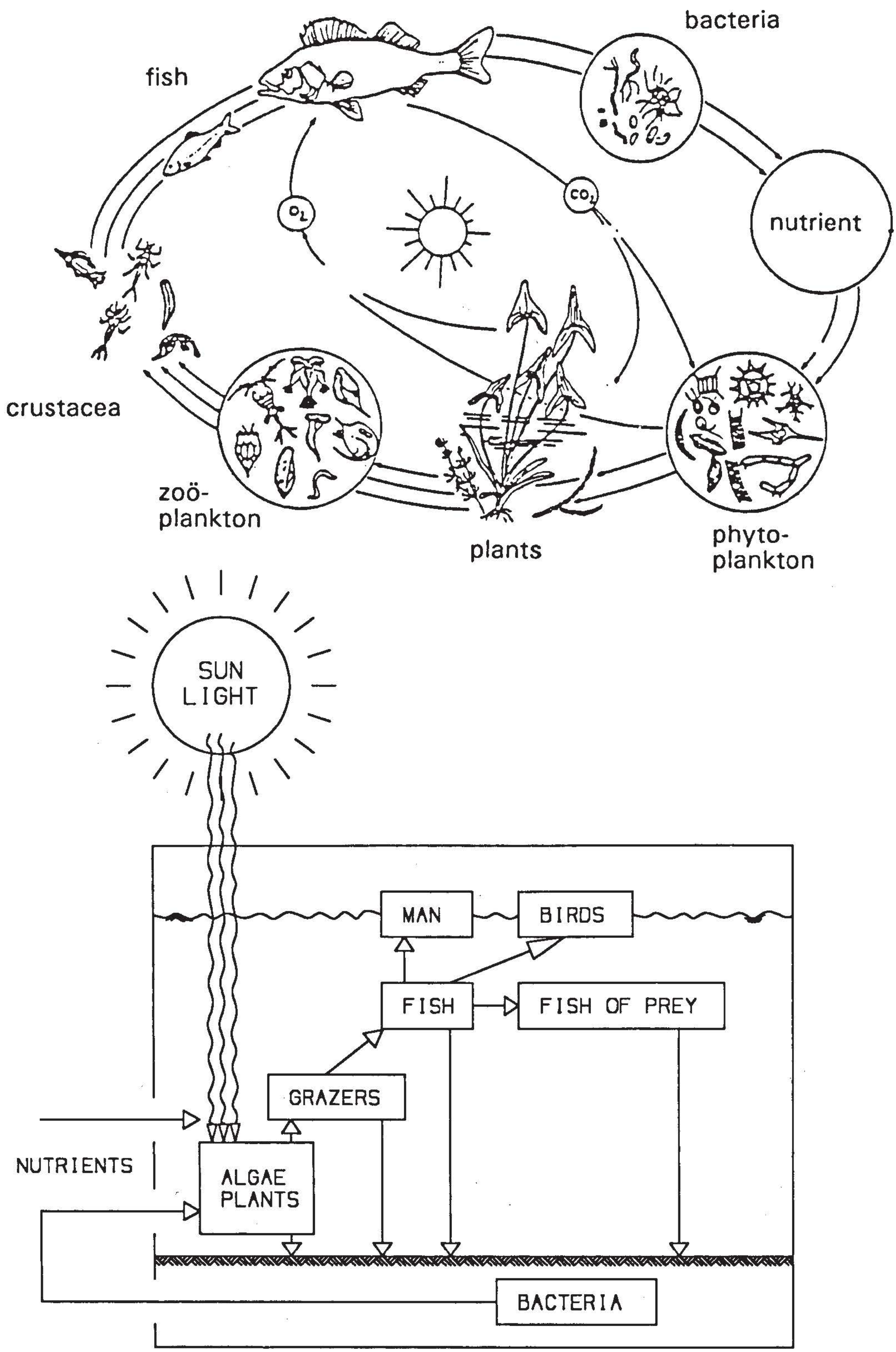

Fig. 2.2 The food chain as the structuring element of a simple eco-system; a picture and a system analysis.

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.

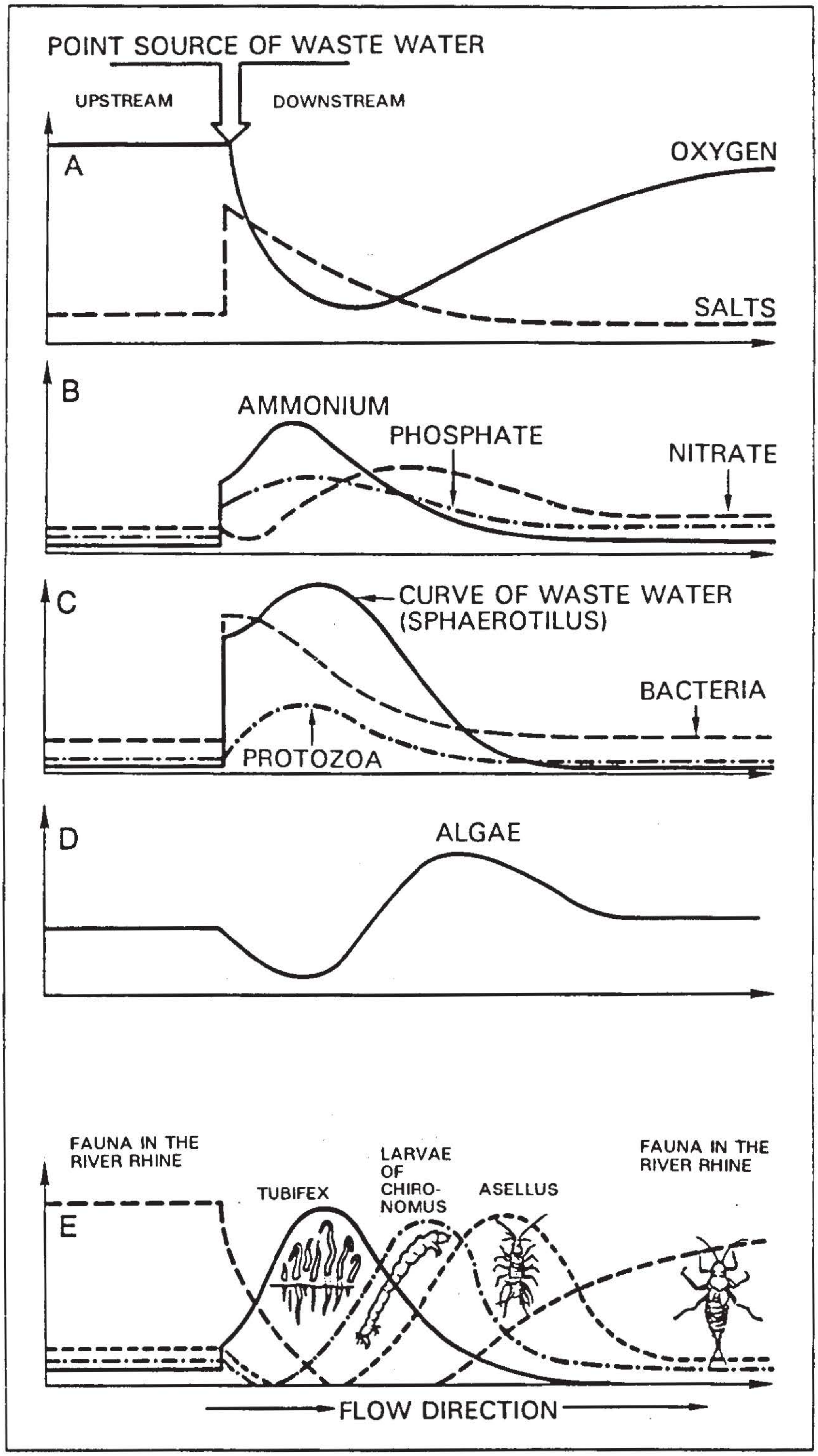

Fig. 2.3 The recovery of a river after an input of waste water.

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

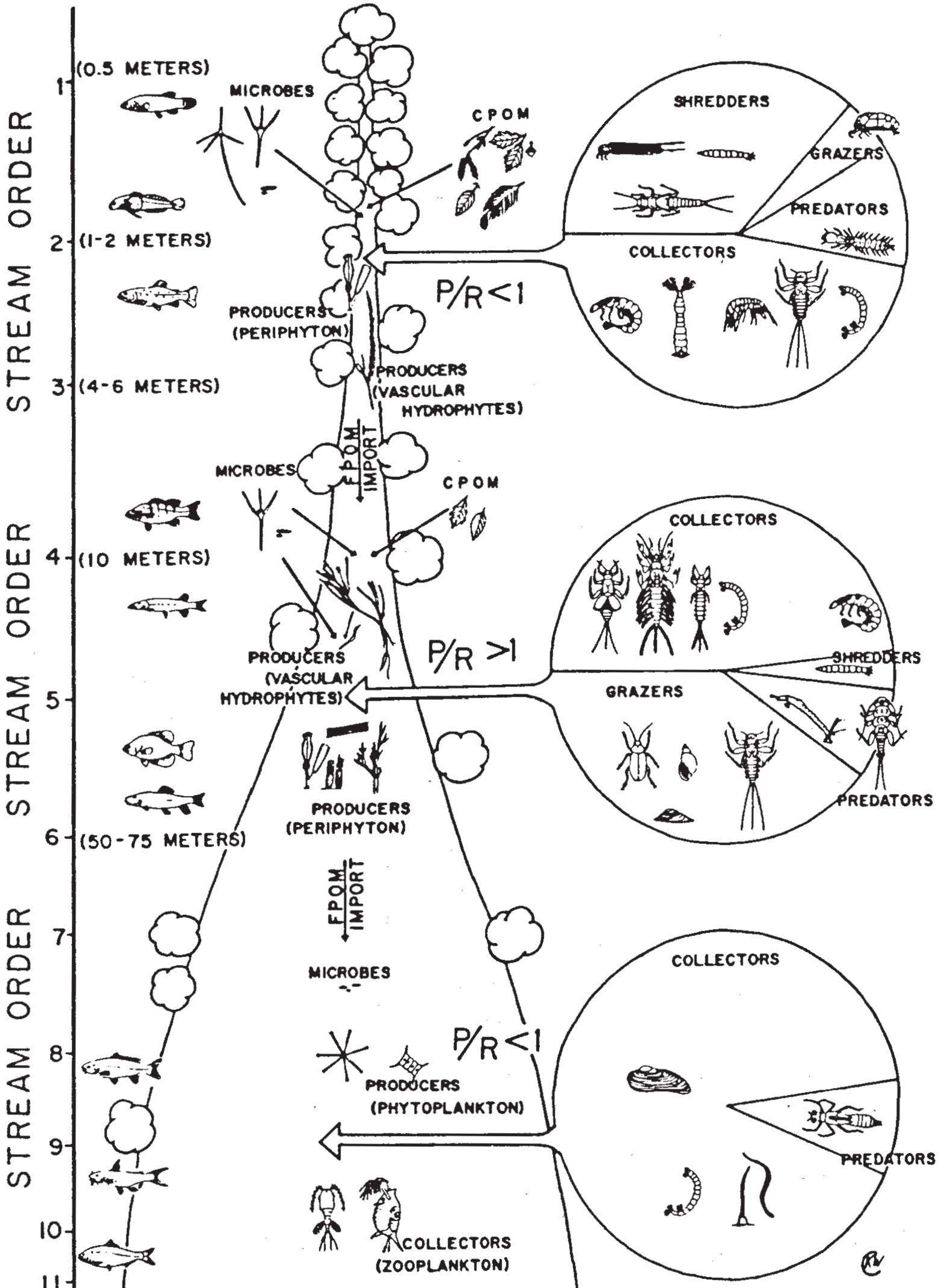

Fig. 2.4 Stream communities in the fluvial eco-system.

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 previusly 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

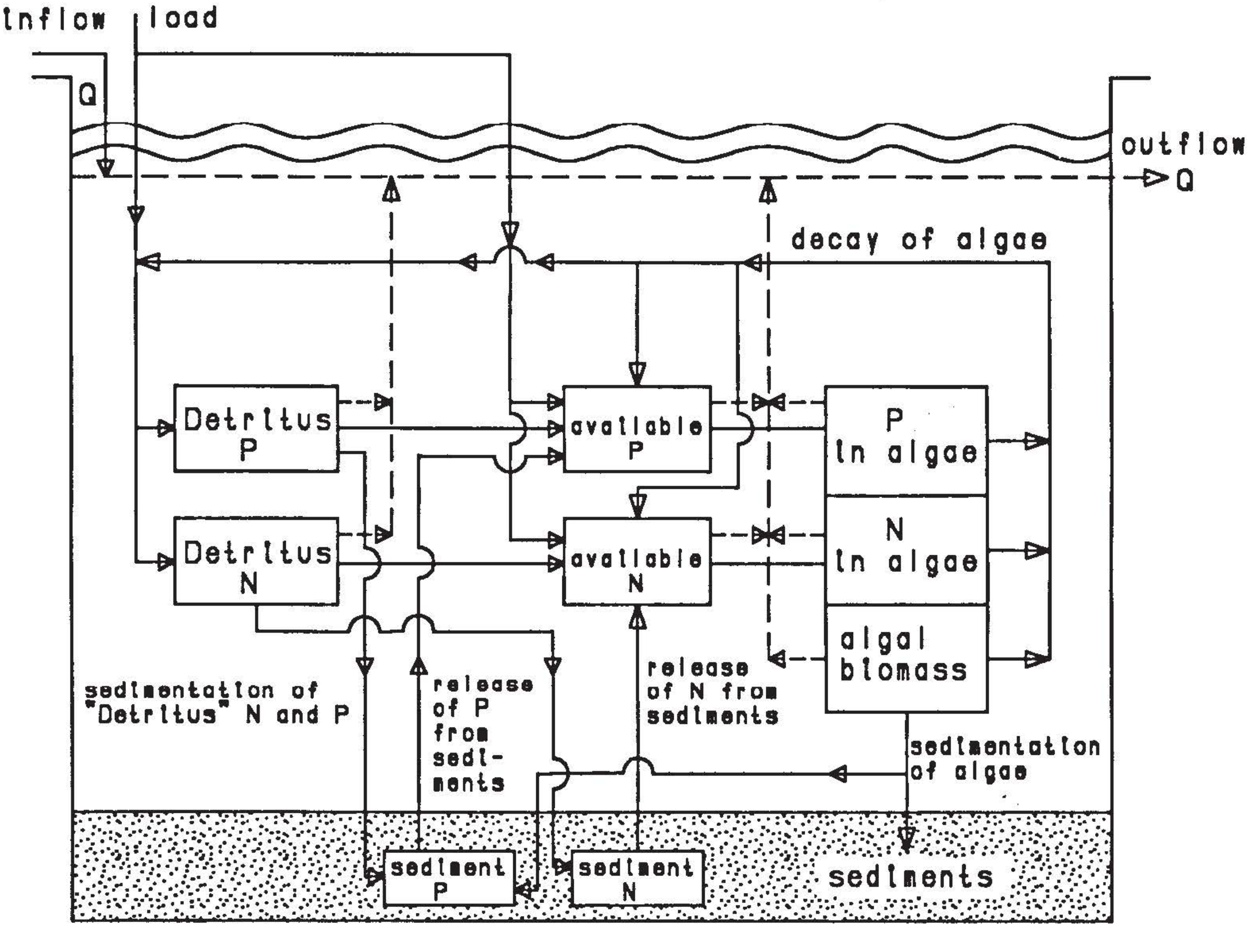

Fig. 2.5 A box diagram of the Lavsoe model (Nyholm, 1978).

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 of 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

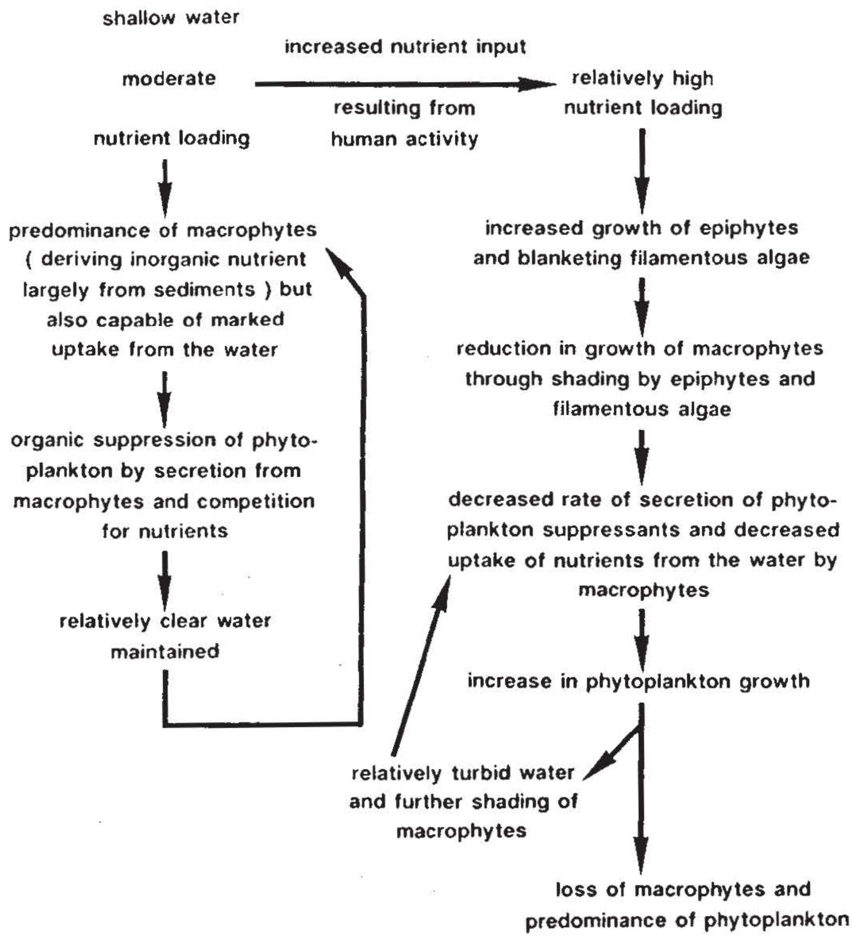

Fig. 2.6 Hypothesis to account for decline in macrophyte populations when estuaries are fertilised.

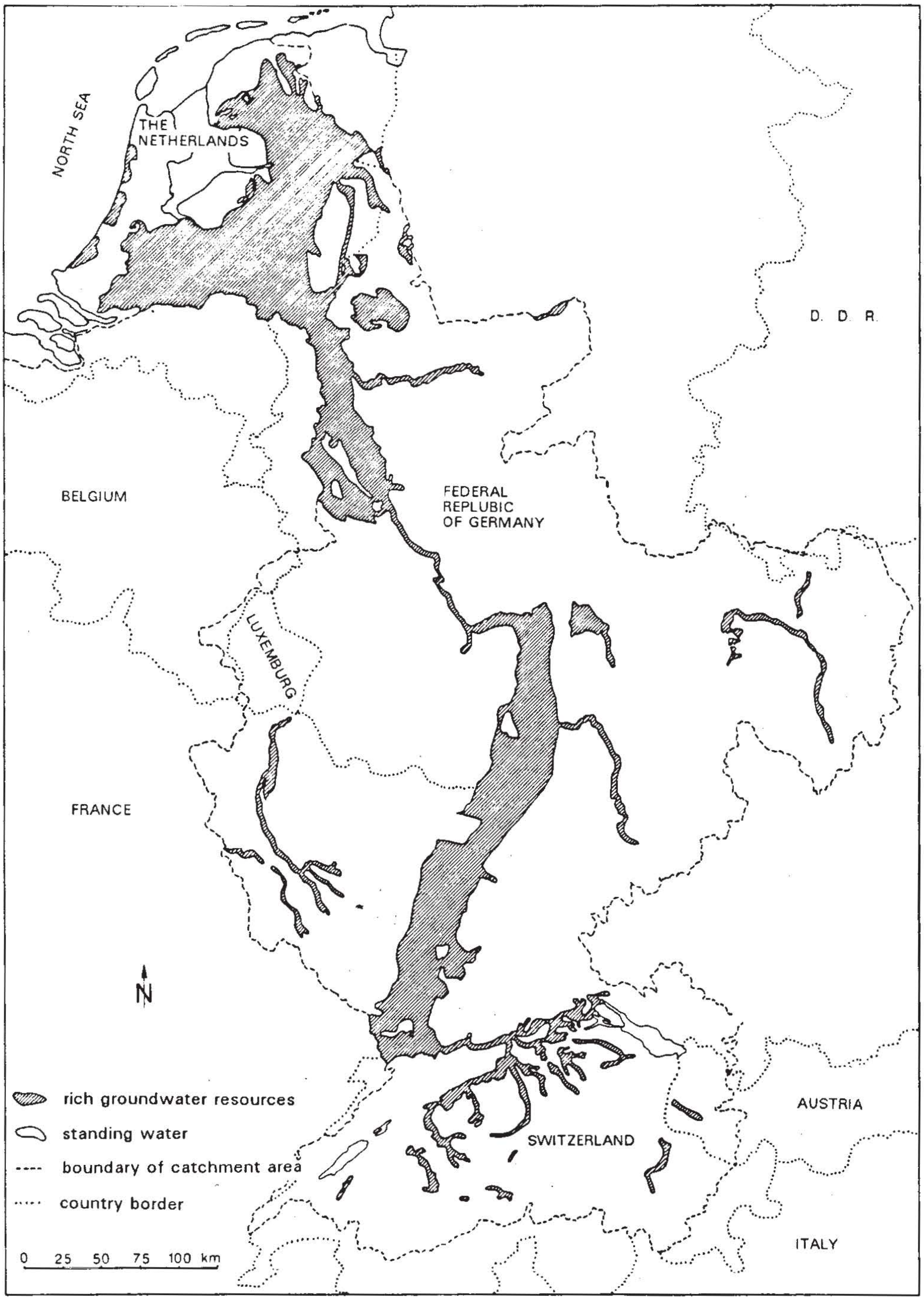

Fig. 2.7 Groundwater bodies of the Rhine basin.

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, fracturated, 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 baterial 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.